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Comparative analysis of nitrogen accounting models with particular reference to agriculture

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Executive Summary

Background

Agriculture accounts for the second largest proportion of greenhouse gas emissions in Scotland[1], particularly through the use of fertilisers, livestock manures and other organic materials such digestate or compost. One approach that could help to reduce these emissions is the use of nitrogen accounting tools. Here we compare available nitrogen accounting tools to assess their potential application focusing on Scottish agriculture.

With a focus on input-output models, we evaluate the strengths and weaknesses of different models, their practical potential for application to Scottish farm businesses, and their potential to support policy decisions.

Key Findings

- Generally, there are common knowledge gaps across many of the tools assessed. This includes a lack of detailed description for nitrogen parameters such as deposition, gaseous losses (particularly ammonia losses), fixation rates (based on legume type and coverage), content in feed, machinery use and wider. Gaps were also found in evidence for the use of novel technologies on farms, efficiency differences from livestock breeding programmes and how the nitrogen accounting tools link more widely, for example with sectors such as industry, transport, human consumption and waste.
- We found that the tools available have been designed for specific (different) purposes that vary in spatial scale and which differ in complexity, both in how easy they are to use and in the details describing nitrogen pathways in agricultural systems.
- At the national and regional scale from the identified tools, the model by Vogt and the UK Smart Inventory shows the greatest potential to be developed into a national level policy monitoring tool. On the other hand, Farmscoper and IMAGE would be suitable to explore alternative scenarios in the near and further future, respectively.
- The tool evaluation process determined that, of the tools reviewed, PLANET, MANNER-NPK and potentially FarmAC are most suitable for Scottish application for calculating farm-level

[1] https://www.gov.scot/publications/scottish-greenhouse-gas-emissions-2017/

budgets at this time. However, the OverseerFM tool provides the most holistic coverage of farm level management practices influencing nitrogen inputs, transformations, storage and outputs from a farm.

Recommendations

Of the 10 tools assessed, we recommend two tools for further evaluation as a farm-scale tool: PLANET and OverseerFM.

Due to large financial investments into the development of OverseerFM tool by the New Zealand Government, there is an easy to use interface and the potential to centralise farm-level data compilation on fertiliser, manure and supplement usage as well as livestock movements on and off the farm and overall productivity. As data can be privately shared with advisors and government agencies, there is the opportunity for the compilation of data (anonymised if necessary) for national-level reporting and decision making.

To characterise nitrogen inputs and outputs across the range of Scottish agricultural (arable, livestock and grassland) systems, we recommend that OverseerFM is either a) adapted for Scottish use or b) PLANET is developed further using OverseerFM as a template.

To obtain a national roll-out of a Scottish-wide nitrogen-accounting tool for farming activities, there is likely to be a need for financial investment to further develop and tailor tools to better suit current and future policy needs.

At a national scale, we suggest further discussions on the specific objectives of such a tool, including if the main goal is monitoring or scenario exploration, and also exploring the feasibility of data sharing between a farm-level tool and a national tool. Furthermore, as activities other than farming also substantially contribute to nitrogen flows (e.g. transport, wastewater, natural areas, water bodies), it is important to note that a national level tool might consider these wider connections.

Content

Introduction

How a nitrogen (N) budgeting approach for farming activities might support the delivery of GHG emission reductions in practice depends on several factors, including the nature of the available data, the underlying assumptions and potential accounting boundaries, and, importantly, the practical potential for application for farm businesses in Scotland. Agricultural N budgets should comprehensively quantify inputs and outputs to estimate and evaluate nutrient use efficiency and the tools needed to achieve this must be suitable, competent, and have the potential to identify effective measures that can achieve reductions in nitrogen emissions.

Here we evaluate the strengths and weaknesses of different models and their potential for practical application to Scottish farm businesses, and to support policy decisions. Our detailed methodology is reported in Appendix 1.

Results

Summary of models

Holos

Holos is a Canadian farm-level greenhouse gas calculator. Holos was designed as an exploratory tool to test possible GHG mitigation scenarios before implementation. There are two versions of the model that are available for use; Holos-Classic and Holos-Research. Holos-Classic is a tool providing an easy to use interface comprising drop down menus to describe a farm and default parameters underlying the selections made. In Holos-Research the user has the ability to delve deeper behind the selections made to change the default parameters to figures that better suit the farm or to conduct scenario testing.

Accessibility & Ownership:

Holos is free to use and accessible to all with no registration required. The software and model can be downloaded directly from the Agriculture and Agri-Food Canada (AAFC) website[2]. The model can be run offline and is not visible to anyone else (unless copied and sent deliberately).

Coverage:

The Holos models are designed for use in Canada and requires the user to identify an eco-district (on a map of Canada) which are predetermined and use 30 year average climate data in each area. Climate, livestock feed, reducing tillage or including perennial forages in rotation area covered in the tool.

Robustness:

According to the AAFC website, Holos is continually being updated with new data and improved features. In May 2017, Holos Version 3.0 was released, which included new features such as basic economics cost/benefit analysis sub-component and use of imperial units of measure. The model is based on IPCC Tier 2 methodology and national climate 30 year data so can be updated alongside inventory data. Details of the underlying assumptions are not available.

Practicality:

Holos includes 4 soil types (note that these do not cover the range of soil types in Scotland), 18 major crop types and 5 livestock types, which covers the majority of farm types in Canada. Some can be translated to Scottish farms but the climatic and soil type data would need to be compiled and

[2] http://www.agr.gc.ca/eng/science-and-innovation/agricultural-research-results/holos-software-program/?id=1349181297838

included. Holos estimates greenhouse gas emissions for the whole farm that can help the user identify ways to reduce farm emissions. This includes carbon dioxide, nitrous oxide and methane emissions on a monthly and annual basis. Sources of emissions, such as enteric fermentation and manure management, cropping systems and energy use are provided. In addition carbon storage and loss from lineal tree plantings and changes in land use and management are also estimated. The Holos-Classic model is designed for farmers and producers so that minimal data input is required and easy to use. However, as Holos-Research runs in the background there is the potential to be as detailed as the user needs.

FarmAC

FarmAC is used to simulate greenhouse gas emissions and nitrogen (N) losses from farming systems and looks at both carbon (C) and N processes and can be used to generate a farm N balance. Simulations of crops and soils is dynamic whereas livestock simulations are static. It can be used to test management scenarios to alter the flows of N on farm and help the user to identify where emissions/losses could occur.

Accessibility & Ownership:

The model is available to use for free online on the internet browser and requires a log in name and password. There is one available for users to trial the model and a personal log-in can be requested from the model developers and owners at Aarhus University, Denmark. User guidance is available and should be read before using the model as this explains the steps in running the model. FarmAC parameter files are available for download which can be altered and become reflected in the model, although this requires experience in changing html codes. If the model is run incorrectly or there is an error in the definition of the farm an error page will appear with html and stack code errors.

Coverage:

Arable, livestock and mixed farms can be simulated in FarmAC and the main agricultural land uses are represented across the model. An appropriate agroecological zones can be selected to simulate flows of N at local climate level making the tool useful in farming systems across different climatic regions.

Robustness:

The main calculations are from the IPCC and are laid out in the available guidance documents which also states assumptions used throughout the model. Tier 2 (emissions) and Tier 3 methodologies are used. Academic literature is also referenced in the guidance document.

Practicality:

The model is extensive in its consideration of N flows across the farm. Inputs include cropping sequences and rotations, production of primary and secondary products, N mineral fertiliser use and composition, manure/slurry application and incorporation methods. Livestock numbers and feed rations can also be entered and the model is capable of producing N outputs from milk and meat for livestock categories. Gaseous and leaching losses of N are also considered along with N deposition. The crop choice includes legumes and thus N fixation and the losses associated with N are simulated. Detailed reports can be produced which show comprehensively the flows of N in a large range of sources across the farm. The nitrogen pathways and processes used in the model are detailed throughout the guidance document. The model could be extended to include other livestock types such as chickens; pigs are included in the code but not currently functioning in the user interface. Currently, the model does not include the effect of P, K and pH on the soil processes.

Farmscoper

Farmscoper is a tool mainly designed for multi-pollutant assessment of farming systems in England and Wales. In its current form (the latest version is Farmscoper v4) it can evaluate the environmental impacts of standard agricultural activities regarding nitrate and phosphorus leaching, sediment load, nitrous oxide, methane and ammonia emissions, release of plant protection products, effects on biodiversity, and energy and water use. It has over a hundred technologies (mitigation options) built in, with their effects in these environmental areas. The tool is based on emission factors derived from process-based models and, in the case of greenhouse gas emissions, from IPCC methods. A N budget is not an explicit output of the tool, but it estimates the three key reactive N losses (nitrate leaching, ammonia and nitrous oxide). It can be run for built-in typical farm types, or a custom farm, or a group of farms in a catchment (up to 10 farm types, upscaling the results). A cost module is also part of the tool, making it possible to calculate an optimal set of technologies for a required emission reduction.

Accessibility & Ownership:

The tool is developed by ADAS and it is freely available for download. A detailed user guide contains information on how to use it. Though it is easy to use, it is not completely self-explanatory, so requires some computer literacy from the user (but not specific training). However, understanding the results requires a good understanding of the technologies, which is provided in separate documents, and, as far as we could see, not part of the tool itself.

Coverage:

Farmscoper covers 17 farm types (based on the June Census Robust Farm Types). The underlying models had been run for England and Wales (aggregated to 3 soil types and 6 climate regions), therefore it is applicable in those countries.

Robustness:

The tool is well documented, the underlying models have been described in peer reviewed scientific papers and the underlying nutrient and sediment models have been validated. Farmscoper is not expected to accurately predict the pollutant losses for any specific catchment, but the outputs should correlate with observed data across catchments and at national scale. However, the database with the emission factors derived from the models (for the various technologies) is not available and documentation detailing these values have not been found.

Practicality:

Farmscoper can easily be used by researchers and by interested farmers and advisors. As the tool was designed to evaluate pre-determined technologies, representation of the farm management is not detailed at the level of input data, and therefore, as well as due to reasons mentioned above, is it best suited for catchment or larger scale assessment,

Image

The IMAGE (Integrated Model to Assess the Global Environment) is an integrated assessment model that simulates the environmental consequences of human activities worldwide, considering interactions between society, the biosphere and the climate system. It assesses environmental issues such as climate change, air pollution, land-use change, biodiversity loss, and water scarcity. The model is calibrated to the year 2005, and all years beyond that (up to 2100) are modelled internally (including e.g. land use, livestock numbers, and fertiliser inputs) based on future changes in demography, economy and policy. Technological details (e.g. fertiliser spreading, manure storage) are not represented, but the model includes natural as well as managed land use systems and the wastewater system, therefore describing the full terrestrial N flow process.

Accessibility & Ownership:

The tool has been developed at PBL (Netherlands Environmental Agency), and is a complex set of models, therefore only suitable for use by the developer team. There is no publicly available version. However, scenario results from previous modelling exercises are available online.

Coverage:

IMAGE covers all main production systems over the world, and also natural terrestrial systems.

Robustness:

The tool is well documented, the sub-modules are published in peer-reviewed scientific papers. The tool has been extensively used for assessments global and European funded by agencies (e.g. IPCC, OECD, EU).

Practicality:

IMAGE gives a detailed representation of global processes; and reflects the regional N flows so that world regions and different future scenarios are comparable. However, details of management and lack of the use of current statistical data does not make it suitable for country level use, but can provide a guide of how N flows would evolve in the region given certain future pathways.

https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0

UK Smart Inventory/Agricultural Emission Inventory for ammonia and greenhouse gases

Accessibility & Ownership:

The model is very complex and currently only useable by the consortium producing the annual agricultural UK emission estimates for Defra (Rothamsted Research lead, partners ADAS, CEH, Cranfield University, SRUC contributions). It requires a very high level of expert knowledge and information and is not suitable for use by farmers or policy makers.

Coverage:

The model covers all UK farm types (with sub-types, e.g. higher and lower intensity dairy systems), and estimates summary nitrogen emissions to the atmosphere and other budget terms (E.g. fertiliser use by type) at the devolved administration level. Emissions of agricultural ammonia and nitrous oxide (N_2O) to the atmosphere are freely available by detailed sectors and as summary 1 km grid emission maps via the UK National Atmospheric Emission Inventory naei.beis.gov.uk. The model covers all agricultural land uses (crops, grassland and livestock production).

Robustness:

The model builds on large amounts of detailed survey data/statistics and peer reviewed information, including the IPCC and emission inventory guidelines. It is documented in detail and all input/output undergoes regular international reviews.

Practicality:

All main agricultural activities relating to nitrogen emissions are covered, with available details taken account of at an individual holding level, where possible. For example, livestock numbers and crop/grass areas are used from the annual agricultural census/survey, with other information (agri-climatic information, soil data) at a 10 km grid resolution, and other data, such as the British Survey of Fertiliser Practice, at a devolved authority level. The model is run annually for the UK national inventory, with outputs made available. Thereby, while regional variability within Scotland is taken into account as much as possible, the model is mainly intended at the DA scale. Some of the output (emissions to air) is available at a 1 km grid resolution across Scotland, but not a farm or farm type level, and is anonymised to meet confidentiality agreements with the Scottish Government for use of the high-resolution holding level agricultural statistics.

Ndicea

Ndicea was developed to assist farmers and advisors to effectively manage nitrogen dynamics in a crop rotation. It simulates soil water dynamics, nitrogen mineralization and inorganic nitrogen dynamics demand on a daily basis, in relation to weather and crop. It can therefore be used to calculate the N balance through a crop rotation. The model includes organic and inorganic fertilisers; however, it does not describe nutrient flows in livestock.

Accessibility & Ownership:

The model is freely available to download (http://www.ndicea.nl/indexen.php). The model was developed by Louis Bolk Institute, The Netherlands. User guides are part of the software.

Coverage:

Organic and inorganic crop rotations can be simulated by Ndicea. Defaults for The Netherlands, England, Denmark and Spain are included. However, the user can build their own climate files, although care needs to be taken to ensure that evapotranspiration is calculated using the methodology required by Ndicea.

Robustness:

The nitrogen flows within the soil and crop are based on dynamic deterministic descriptions of the processes. The rate of mineralisation of the manures, crop residues, green manures are dependent on the weather and soil type. Data collected over more than 15 years by the Louis Bolk Institute (http://www.louisbolk.org) has been used to develop and test the model.

Practicality:

The model is extensive in its consideration of N flows within a rotation, and the soil is described in terms of soil texture for the top and subsoil. The user also enters the pH for the topsoil. For the rotation, ploughing is defined as conventional, reduced or no till. Inputs include cropping sequences, projected yield and inputs of organic and inorganic fertilisers. The crop choice is extensive including legumes and vegetable crops. The model includes green manures and composts as well as manure and fertilisers. N deposition is also an input. Leaching, denitrification, fixation and changes in the soil organic matter are described in the model. Although the model describes denitrification, nitrous oxide is not an output from the model. The model also describes P_2O_5 and K_2O balances. Summary reports which include graphical outputs are available for download. The graphical outputs make it easy for the user to see what happens over the years. Scenarios can be set-up within the tool, and the graphical outputs allows the user to compare the results of two scenarios. The model does not consider livestock or the losses occurring during the storage of manures.

MANNER-NPK

MANNER-NPK (MANure Nitrogen Evaluation Routine) is a simple and easy to use calculator software that provides a field scale nutrient balance for organic inputs. It produces an immediate estimation of N, phosphate (as P_2O_5) and potash (K_2O) availability to crops from manures, slurries and other organic materials. The model was last updated in 2013 but there is no on-going support for it. It incorporates Nitrate Vulnerable Zone (NVZ) legislation which is embedded, and the model will present warnings of potential breaches of NVZ rules to help with management decisions. The model can be used across the UK in England, Wales, Scotland and Northern Ireland. Since its last update there have been considerable advancement in our understating of nutrient availability from organic inputs and this has not yet been incorporated into the model.

Accessibility & Ownership:

The model and related technical and user guidance is currently accessible and available to download for free from the internet, although registration is required to obtain a copy. ADAS is the owner and developed the model with support from a consortium of funders but currently there is no funding to support users of the model. MANNER-NPK is easy to use and the user can move through the 5 tabs in any order without any restrictions, to easily change the scenarios or values and get immediate estimations.

Coverage:

The spatial scale of this model is field level. It can be used to provide estimates on N availability, cost and use efficiency for any farm type where manures, slurries or organic materials are applied. It covers most crop types grown in the UK but does not take manufactured fertiliser application into account nor does it consider soil test results.

Robustness:

The main calculations come from the NVZ rules and legislations which are embedded within the model. Industry recommendations (RB209 for England & Wales and SAC Technical Notes for Scotland) are also embedded for providing advice. These recommendations have been updated since the model development, and so any future development would need to update values based on new fertiliser and management recommendations.

Practicality:

The aim of MANNER-NPK is to provide a quick calculation and estimation at the field scale of nutrients available from organic sources and on how efficiently they are being used. As the focus is on organic imports, however, the model does not cover an extensive amount of detail of on-farm activities. Therefore, for what it is, the areas covered make sense: crop and grass characteristics can be specified as these are relevant to producing a crop availability estimate. Climate characteristics can be specified, such as excess rainfall amount and wind, as this will allow the model to consider potential additional applications of N where the rules allow, and to highlight specifically where N is being lost. Leaching losses are considered within the model as part of the NVZ rules and therefore values cannot be edited; rainfall is taken into consideration. Topsoil and subsoil type can be selected from a range of options, but it is unclear if these are official definitions used in the NVZ literature, as soil type can restrict N application and certain management practices in an NVZ area. A default N (and P and K) contribution from manure, slurry and other organic materials is included in the model, but is easy to alter in the user interface if laboratory analyses is available. The application method for applying these materials can be selected, as this affects the N flows in the field. Ploughing frequency, type and depth is indicated through the incorporation methods of these materials and up to three applications can be included in the estimate. Livestock characteristics such as grazing type or intensity and numbers cannot be entered. The tool does not estimate crop yield or grain N, nor does it estimate gaseous N losses directly which is an area that the model could be improved on. Manure storage characteristics are not considered. Legumes and estimates of N fixation are not available directly. MANNER-NPK is embedded within PLANET Scotland, however, the stand-alone MANNER-NPK presents different information (that can be edited) regarding nutrient balances for NPK. The calculator does not include mineral fertiliser N sources nor incorporation methods, but the prices of N fertilisers can be entered, so that the potential value of N from the manure, slurry and organic materials can be compared.

OverseerFM

OverseerFM (Overseer Farm Model) launched in June 2018, is a tool for farmers and advisors for the purpose of increasing nutrient and financial efficiency on-farm. OverseerFM was developed from previous OverseerFM software to be more user-friendly and to allow practitioners to have more control over their farm data, assess flows of nutrients and support farm management decision making and planning.

Accessibility & Ownership:

Anyone can use OverseerFM, through there is a subscription fee of $200 (NZD) per farm account per annum. Once subscription is paid, the owner of the account (typically the farmer) can allow other people to access the account. This may include other workers, consultants and local authorities/regulators (e.g. for compliance purposes). The owner can choose how much access additional users can have, for example could allow full access to farm workers so that raw inputs of data can be made (these can also be directly linked to invoices and accounts) whereas local authorities (if invited) might only be able to view a read-only file of the farm's year-end account and overall nutrient budgets. To access additional information registration with Overseer Ltd (separate to subscription to the model), is free and just requires an email address - https://www.overseer.org.nz/overseer-explained/technical-description-of-overseer.

Coverage:

OverseerFM is designed for use in New Zealand. The model works by selecting an area of land from a map (your farm), then within that you draw blocks to identify the different land uses that comprise the farm overall. Once blocks are selected, the model will automatically provide soil data (pulled from the Landcare IS Soil maps that the model is linked to), for up to 3 soil types (if more are detected and comprise a substantial contribution to the overall land unit, it is advised to break up the area into smaller blocks), however, this data can be overridden if necessary (e.g. if you have Soil Test data). Other factors within the model allow for flexible description of a farm, or fields within a farm and cover similar pasture, crops and livestock types to Scotland.

Robustness:

The model was recently updated via $5M funding provided by the New Zealand Government in their May 2018 Budget. In addition, the subscription charge enables Overseer Ltd to continue developing OverseerFM to meet users' needs through improved user support, software and science development. OverseerFM use a 'product backlog' which is a list of everything that needs to be worked on to improve the software over the next few months, and which is available to view on their website (e.g. including the use of inhibitors, carbon sequestration etc. and model updates and edits to make it more user-friendly). This is based on feedback and suggestions from their help desk. In addition, known 'bugs' are listed online too. Once signed-in to Overseer Ltd, access to reports, publications and Q&A documentation is possible. Although the search did not find a document outlining the exact assumptions underlying OverseerFM nutrient flows, there was evidence of recent, up to date research being incorporated into the model and validation being conducted with raw on-farm measured data demonstrating strong correlation between measured and estimated values.

Practicality:

Within each block identified, the user can insert a wealth of information (using a simple, easy to use interface) such as, animals (type; birth/age; start/end weights; total numbers; time of year they are present; movement of animals on and off farm - sold/die/purchased animals; feed; can link all information to invoice transactions), crops/land cover (topography; 7 pasture types, area; yield; supplements used; cuts and amounts used by animals; cultivation within last 5 years; if animals are present; runoff characteristics; compaction; susceptibility to pugging; fodder crops; crops; tillage intensity; rotation across 'blocks' and over time). Other inputs include details on fertiliser application type and amount (drop down menus provided that link directly to company and fertiliser composition), lime applications, drainage description (mole or tile), irrigation and whether any supplements are applied. Includes whether feed (list of options provided) is bought in or taken from storage with an estimate of animal utilisation given, feed quality (good, average, poor) and default protein contents are used (not customisable). Within each block a comprehensive assessment of nutrient flows can be made and as the blocks are all connected nutrient flows across the whole farm can provide an overall farm budget. The tools has a lot of information embedded within it, such as soil type & characteristics, fertiliser name (manufacturer) and composition and dropdown menus to describe livestock movement between fields/blocks, feed and movement on and/or off the farm, which make it an easy to follow and

accessible tool (once subscription is paid). The tool also allows the user/farm manager to directly submit reports to consultants/advisors for advice or to local authorities for compliance reporting, which streamlines the process if multiple farms in a region use this method.

PLANET

PLANET (Planning Land Applications for Nutrients for Efficiency and the environment) is a nutrient management decision and support tool which can be used by farmers and consultants to produce nutrient budgets at both the farm-gate and field level. The NVZ Action Programme rules are built into PLANET and are used to assess compliance with NVZ requirements. It is capable of storing long-term records of field management and can produce printable reports. PLANET has MANNER-NPK built into it but MANNER-NPK as a module is not available in itself within PLANET. Nutrient excretion values from pigs and poultry can be imported from a model called ENCASH. Data can be downloaded from the Rural Payments Online system, including field Land Parcel Identification Number. Soil analysis can also be imported. The model is applicable to England, Wales and Scotland. The model also includes tools for understanding slurry, manure and dirty water generated on farm and can help determine storage requirements.

Accessibility & Ownership:

PLANET is a computer software which is available for download from the internet for free although registration is required to gain access. Originally developed by ADAS and SRUC with support from DEFRA and Scottish Government, there is however, no current support for ongoing development or maintenance of the software, ADAS currently manages the website. PLANET is capable of scenario testing and if a management activity actually occurred, the record can be confirmed in the software, or edited to reflect what actually happened before confirming the record. If the farm is in an NVZ and this is ticked in the model, then the user must confirm records before being allowed to proceed through the model, otherwise they can move more freely between tabs. While still applicable for NVZ compliance the fertiliser recommendation and default reference values for organic inputs are now out of date.

Coverage:

PLANET Scotland covers a range of farming scenarios, for arable, livestock and mixed farms.

Robustness:

Calculations in PLANET are based, in part, on NVZ rules and legislation. Fertiliser recommendations from RB209 and SAC Technical Notes are embedded in the model, and they are the recognised authority of crop nutrient requirements. Livestock Manure N Farm Limits are used to calculate the manure N capacity and loading of farms. Minimum manure and slurry N storage capacities are calculated for different livestock. The N_{max} limit tests compliance for individual crop types where land is in an NVZ.

Practicality:

The farm and land use systems for England, Wales and Scotland are captured very well in PLANET with the on-farm activities being appropriate to the UK. The model relies on farm data and records which should be held by a farmer and their adviser (if applicable). Topsoil type can be chosen from definitions of soil contained within the NVZ rules and legislation; soil type influences management practices in NVZ areas only. Crop and grass characteristics and area grown can be entered including legumes (clover, grass/clover, peas, beans and lucerne). Rotation characteristics and records are stored for as long as required. Livestock type, grazing intensity and category can be chosen from an extensive list and includes different types of cattle, as well as pigs, poultry, sheep, horse, lamb, goat and deer. Manure N production is calculated, and pigs and poultry N excretion can be imported from ENCASH, where there are legal limits for the nutrient content of pig and poultry manure. Animal feed N imports are expressed as crude protein (%) and harvested crop exports N content is calculated. Storage capacity and type can be recorded in great detail. Guideline values for manure NPK

composition are default in the model but can be edited along with amount and incorporation method. The mineral fertiliser NPK incorporation method cannot be selected but fertiliser formulations can be edited. The dates of sowing and fertiliser application provide an indication of potential ploughing frequency. Leaching losses are embedded in the software as part of the NVZ calculations for leaching and runoff risk. The model could benefit from N deposition being included and the tool has the potential to include messages for N mitigation out with the messages for potential breech of NVZ rules, but the production of records allows analysis of N pathways which can be used to inform management decisions.

Vogt

Accessibility & Ownership:

Vogt et al. (2013)[3] proposed a comprehensive nitrogen budget approach at a landscape/ catchment scale. The N budget was derived as a scientific research project and is not available as a stand-alone tool. It uses a number of methods to derive the different components of the N budget, for two rural catchments in Scotland. A high level scientific understanding and expertise is currently required to estimate the different components of the N budget and pull together a complete picture of N inputs and outputs at the catchment level (scientists). However, it would be possible to simplify the approach and make it more accessible for more generalist users.

Coverage & Practicality:

The approach covers N budget terms at the scale of individual fields and farming activities (livestock housing, manure storage, land spreading of mineral fertiliser and organic manures), atmospheric deposition input from the wider surrounding landscape (through detailed modelling) etc., and all land uses, including non-agricultural land. The approach has been developed and tested in catchments dominated by beef, sheep and poultry farming, with only forage crops representing the crop sector. Arable farming of cereals, vegetables, fruit & potatoes etc. has not been explicitly modelled, however the approach is flexible and can be expanded to cover all types of farming activities. Large amounts of data are required at the individual field/land parcel level, e.g. on N inputs (e.g. mineral and organic N, excreta from grazing animals), high-resolution N deposition, legume/clover content, harvested vegetation, fluvial export (measured).

Robustness:

The atmospheric N emission and deposition part of the approach uses different models that were developed by CEH and are not available publicly. The rest of the approach is based on data collection through farm surveys, field measurements and calculations based on the IPCC methodology (IPCC guidebook available online). All parts of the work are clearly documented, with references provided for calculations.

Evaluation of models

A full evaluation of all tools described in this report in relation to the criteria outlined in Table 2 are shown in Appendix 1. In order to be an effective tool for characterising nitrogen losses and gains from farming systems, the tools need to be able to describe the factors listed in Table 2, in particular factors that describe the farm types in relation to soil, climate and management characteristics. These are highlighted in Table 3a and 3b.

This project has identified that there are many models accounting for N in agricultural systems, which have been developed for different purposes, cover different scales and relate to different types of agricultural system types. The tools have differing strengths and weaknesses for the assessment of Scottish-based N budgets (see Section 3.1), however, key drawbacks include;

- PLANET: Focused on NVZs
- MANNER-NPK: Focus is on organic imports only and does not cover an extensive amount of detail of on-farm activities
- Farmscoper: Designed to evaluate pre-determined technologies, so representation of the farm management is not detailed at the level of input data

[3] Vogt E., Braban C.F., Dragosits U., Theobald M.R., Billett M.F., Dore A.J., Tang Y.S., van Dijk N., Rees R.M., McDonald C., Murray S., Skiba U.M. and Sutton M.A. (2013) Biogeosciences 10: 119-133 doi:10.5194/bg-10-119-2013. http://www.biogeosciences.net/10/119/2013/bg-10-119-2013.pdf

- Holos: Limited detail describing farm management and N pathways compared to other tools Canadian specific
- Overseer: Linked to New Zealand soil & climate data
- FarmAC: IPCC-based. Livestock are not included in the interface. Effect of P, K and pH on the soil processes is not included
- UK agricultural GHG/Ammonia Inventory: Model is mainly intended for the devolved authority scale. Based primarily on emission factors and not farm-scale processes
- IMAGE: Complex set of models. Lacks management details and the use of current statistical data. Not suitable for country level use
- Vogt et al 2013: Atmospheric N emission and deposition part of the approach uses different models that were developed by CEH and are not available publicly, however, this is the only model that calculates N deposition locally based on the farming activities present
- Ndicea Nitrogen Planner: Livestock systems not included

Overall the OverseerFM tool was highlighted as having the greatest potential to provide a reliable N budget tool that has the ability to be scaled up to national-level data. However, some adaptations would be needed to be applicable to Scottish agricultural systems.

Table 3a: Summary of results for farm/field scale tools. Green = Yes, Red = No, Yellow = Some or not applicable

	PLANET	MANNER-NPK	FarmAC	Overseer	Holos
Does the tool allow you to specify soil characteristics?					
Does the tool allow you to specify crop/grass characteristics (diversity/type)?					
Does the tool allow you to specify legume characteristics (diversity/type)?					
Does the tool provide an estimate of N-fixation & input based on legume coverage?					
Does the tool allow you to specify rotation characteristics?					
Does the tool allow you to specify some climatic characteristics?					
Does the tool allow you to specify N contribution from N deposition?					
Does the tool allow you to specify N contribution from mineral N-fertiliser type?					
Does the tool allow you to specify N contribution from mineral N-fertiliser intensity?					
Does the tool allow you to specify N contribution from mineral N-fertiliser application method?					
Does the tool allow you to specify livestock characteristics?					

	PLANET	MANNER-NPK	FarmAC	Overseer	Holos
Does the tool allow you to specify N contribution from manures (amount)?					
Does the tool allow you to provide an indication of manure composition (NPK)?					
Does the tool allow you to provide an indication of manure N application type (raw/slurry)?					
Does the tool allow you to provide an indication of manure storage?					
In the tool is N in excreta a function of animal diet?					
Does the tool allow you to provide an indication of N contribution from internal on-farm animal feed?					
Does the tool allow you to provide an indication of N contribution from external (bought in) animal feed?					
Does the tool allow you to provide an indication of grazing type (cows/sheep)?					
Does the tool allow you to provide an indication of grazing intensity?					
Does the tool allow you to provide an indication of ploughing type/depth?					
Does the tool allow you to provide an indication of ploughing frequency?					
Does the tool allow you to provide an indication of cutting frequency?					

	PLANET	MANNER-NPK	FarmAC	Overseer	Holos
Does the tool allow you to provide an indication of residue returns?					
Does the tool estimate gaseous N losses					
Does the tool estimate leached N losses					
Does the tool estimate yield & grain N					

Table 3b: Summary of results for landscape, national and inventory-scale tools. Green = Yes, Red = No, Yellow = Some or not applicable

	UK smart Inventory for GHG and ammonia	Farmscoper	Image	Ndicea	Vogt
Does the tool allow you to specify soil characteristics?					
Does the tool allow you to specify crop/grass characteristics (diversity/type)?					
Does the tool allow you to specify legume characteristics (diversity/type)?					
Does the tool provide an estimate of N-fixation & input based on legume coverage?					
Does the tool allow you to specify rotation characteristics?					
Does the tool allow you to specify some climatic characteristics?					
Does the tool allow you to specify N contribution from N deposition?					
Does the tool allow you to specify N contribution from mineral N-fertiliser type?					
Does the tool allow you to specify N contribution from mineral N-fertiliser intensity?					
Does the tool allow you to specify N contribution from mineral N-fertiliser application method?					

	UK smart Inventory for GHG and ammonia	Farmscoper	Image	Ndicea	Vogt
Does the tool allow you to specify livestock characteristics?					
Does the tool allow you to specify N contribution from manures (amount)?					
Does the tool allow you to provide an indication of manure composition (NPK)?					
Does the tool allow you to provide an indication of manure N application type (raw/slurry)?					
Does the tool allow you to provide an indication of manure storage?					
In the tool is N in excreta a function of animal diet?					
Does the tool allow you to provide an indication of N contribution from internal on-farm animal feed?					
Does the tool allow you to provide an indication of N contribution from external (bought in) animal feed?					
Does the tool allow you to provide an indication of grazing type (cows/sheep)?					
Does the tool allow you to provide an indication of grazing intensity?					
Does the tool allow you to provide an indication of ploughing type/depth?					

	UK smart Inventory for GHG and ammonia	Farmscoper	Image	Ndicea	Vogt
Does the tool allow you to provide an indication of ploughing frequency?					
Does the tool allow you to provide an indication of cutting frequency?					
Does the tool allow you to provide an indication of residue returns?					
Does the tool estimate gaseous N losses					
Does the tool estimate leached N losses					
Does the tool estimate yield & grain N					

Gaps identified

The assessment of tools identified gaps that are highlighted in Tables 3a and 3b, however, across all tools there were areas of the nitrogen-flow and overall GHG budgets that seemed lacking, these included;

- N deposition (except for Vogt et al.)
- N content in feed
- The inclusion of machinery and fuel use and the implications on potential N losses and overall N/GHG budget
- Description and inclusion of legumes were limited. In particular the proportion of legume incorporation during any given season. This will have implications on N fixation and amount of fertiliser-N required. In addition, the legacy effect of fertility building through the use of legumes is lacking in the tools identified. The limited inclusion of N input from the proportion of legumes and fixation is likely to be due to a lack of robust scientific evidence across legume types, climates and management.
- Novel management techniques that may affect nitrogen transfers, N use efficiency and productivity
- At present the majority of tools account for livestock as a simple input-output of nitrogen depending on animal type, such as cows, sheep etc. However, with livestock improvements through genetic breeding, the efficiency of N use across animals can lead to a variation in N loss from the animal. This is likely to be due to a lack of consistent, robust evidence at this stage to include in N budget tools.

- How the outputs from these tools link to the wider sectors, such as industry and transport, human consumption, food production, waste etc.

Conclusions and recommendations

- Further validation required to determine robustness of these tools in relation to changing climates and new management initiatives.
- Use the OverseerFM tool as a template to either develop a new or existing tool that will apply to Scottish-based farm budgeting for nitrogen.

References

Climate Change Act (Scotland) 2009. http://www.legislation.gov.uk/asp/2009/12/pdfs/asp_20090012_en.pdf Accessed August 2019.

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Appendix 1 - Methodology

2.1 Pre-selection of nitrogen accounting tools

This step included the compilation of a comprehensive list of tools and models that are capable of providing nitrogen accounting. This was conducted via academic knowledge and a semi-systematic internet (Google) and Web of Science search for tools.

- Web of Science (5,235): TS=((*farm* OR agriculture*) AND (NITROGEN OR greenhouse gas OR GHG) AND (tool OR calculator OR accounting OR footprint* OR benchmark*))
- Google: ' farm nitrogen calculator' and Farm nutrient calculator'

A list of 47 tools was compiled. This was shortlisted to a maximum of 10 tools using pre-defined criteria that consisted of

I. Model/tool type: Is the tool a farm-based calculator, national inventory or a process-based model?

II. Targeted scale/agro-ecosystem: Does the tool/model appear to include agricultural landscapes similar to Scotland such as crop, grasslands and livestock systems?

III. Suitable for Scottish agriculture: Does the model appear to be suitable for application to Scottish agriculture based on soil, climate and management factors included in the tool?

IV. Documentation available: Does the tool/model have documentation available to allow further assessment?

V. Model/tool available for evaluation: Can the tool/model be easily accessed for the purpose of assessing its ability to be applied to Scottish agriculture?

Following the initial screening of models and tools a final shortlist was determined that included 6 whole farm-budget tools (PLANET, MANNER-NPK, FarmAC, Holos, Ndicea and OverseerFM) and 4 landscape, national or inventory scale tools (Farmscoper, Image, Vogt et al 2013, UK GHG and Ammonia Inventory) listed in Table 1.

2.2 Evaluation of shortlisted tools.

The shortlisted models were evaluated further using pre-defined criteria (Table 2) to allow for an unbiased audit of models based on a robust scientific methodology and validation. Criteria encompasses model composition, applicability and implementation that are of importance to land managers, policy makers and wider stakeholders in Scotland. The selected tools were evaluated further using more comprehensive criteria to allow for an unbiased audit of the tools. The criteria for evaluation were developed on the following main topics:

- *General purpose and Function:* Purpose and target audience of the tool.
- *Accessibility & legalities:* Who is the developer, whether the tool has a cost to purchase, ease of accessing the tool, specific license/software requirements.
- *Practicalities & ease of use:* Establish whether there is an user-friendly interface, the extent of input data required, availability of input data, compatibility of inputs and outputs with official statistics data (where available).
- *Transparency:* Assess the availability and accessibility of model descriptions and information. Assess documentation available to evaluate the framework of calculations and track data sources to determine the underlying assumptions, the robustness of concepts outlined in the model and the comprehensiveness of nutrient pathways described.

- *Scientific Robustness:* Evaluate the scientific relevance and source of calculations included and the validity of flows throughout the model framework and identify any gaps in the model framework.
- *Scale & Comprehensiveness:* Evaluate the spatial (farm-gate to national) and temporal (point source to annual N budgets) scales at which the model can be applied.
- *Application diversity:* Specificity of model to particular farm types and land uses or whether the model can be applied to a wide range of farm and land use types relevant to Scotland.
- *Data Outputs:* Type & format of outputs, information supplied by outputs, visualization available, conversions available, scale, interpretation, ownership.
- *Evidence of Implementation:* Compile evidence where model has been applied and if possible where field data collection as validated model outputs. Identify pros and cons experienced during model application.

The evaluation process comprised answering a series of questions (Table 2) based on the accessibility; function, scale, practicality and application; composition (inclusion/exclusion of parameters that are included in nitrogen cycling and pathways in agricultural budgets) and finally what outputs are provided, as described above.

Table A1: Tools shortlisted for analysis

Model / Tool	Developer / Owner	Model / tool type	Targeted scale / agro-ecosystem	Suitable for Scottish agriculture	Documentation available	Model / tool available for evaluation	Source
PLANET	ADAS/SRUC	Whole-farm nutrient budget	Crop & livestock	Yes	Yes	Yes	http://www.PLANET4farmers.co.uk/Content.aspx?name=PLANET
MANNER-NPK	ADAS/SRUC	Whole-farm nutrient budget	Crop & livestock	Yes	Yes	Yes	http://www.PLANET4farmers.co.uk/MANNER.aspx
Farmscoper	ADAS	Whole-farm nutrient budget	Crop & livestock	Yes	Yes	Yes	http://www.adas.uk/Service/farmscoper
Holos	Agriculture and Agri-Food Canada	Whole farm GHG	Crop & livestock	Some/ Majority	Yes	Yes	http://www.agr.gc.ca/eng/science-and-innovation/agricultural-research-results/holos-software-program/?id=1349181297838
OverseerFM	Overseer Ltd New Zealand	Farm nutrient cycling & GHG	Crop & livestock	Yes	Yes	$200	https://www.overseer.org.nz/overseerfm

Model / Tool	Developer / Owner	Model / tool type	Targeted scale / agro-ecosystem	Suitable for Scottish agriculture	Documentation available	Model / tool available for evaluation	Source
FarmAC	Aarhus University. EU Animal Change project	Tier 2 livestock & manure management	Crop and Livestock	Yes	Yes	Yes	https://www.farmac.dk/
UK GHG / Ammonia Inventory	Defra (developed by UK research consortium)	Emission Factors	Crop and Livestock	Yes	Yes	Yes	https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html
IMAGE	Bouwman et al 2006	Emission factor approach with consideration of mitigation technologies	Crop and Livestock	Yes	Yes	Yes	https://www.pbl.nl/en/publications/2006/Integratedmodellingofglobalenvironmentalchange.AnoverviewofIMAGE2.4
Vogt et al 2012	CEH	nitrogen budgets for catchments / landscape scale	Crop & livestock	Yes	Yes	Yes	https://www.researchgate.net/publication/232808389_Estimation_of_nitrogen_budgets_for_contrasting_catchments_at_the_landscape_scale

Model / Tool	Developer / Owner	Model / tool type	Targeted scale / agro-ecosystem	Suitable for Scottish agriculture	Documentation available	Model / tool available for evaluation	Source
Ndicea Nitrogen Planner	Louis Bolk Institute, Netherlands	Nitrogen availability vs crop demand	Crop	Yes	Yes	Yes	http://www.ndicea.nl/indexen.php

Table A2. List of criteria used to evaluate selected N-accounting tools.

Accessibility	Who is the model developer?
	How much does the tool cost to purchase?
	Does the tool require a license agreement?
	Does the tool require specialised software?

Function, Scale, Practicality & Application	Who is the target user?
	Indicate the level of expertise required
	Does the tool appear to be user friendly? E.g. does it have an easy to follow interface
	What spatial scale is the tool designed for?
	Does the tool rely on raw field data or can survey data be used?
	How much data is required?
	What are the land use/farm types that the tool can be applied to?
	What temporal scale is the tool designed for?

Outputs and other information	To what scale (spatial/temporal) are N budget outputs provided?
	Is the tool capable of future predictions / scenario testing
	Is the tool capable of providing management suggestions and/or mitigation options
	Are there any obvious gaps in the tool in generating an N budget?
	Are there any obvious sections of the tool that need to be updated/edited based on new understanding?
	Indication of comprehensiveness of N pathway described

Tool composition & comprehensiveness	Does the tool allow you to specify soil characteristics?
	Does the tool allow you to specify crop/grass characteristics (diversity/type)?
	Does the tool allow you to specify legume characteristics (diversity/type)?
	Does the tool provide an estimate of N-fixation & input based on legume coverage?
	Does the tool allow you to specify rotation characteristics?
	Does the tool allow you to specify some climatic characteristics?
	Does the tool allow you to specify N contribution from N deposition?
	Does the tool allow you to specify N contribution from mineral N-fertiliser type, intensity & application method?
	Does the tool allow you to specify livestock characteristics?
	Does the tool allow you to specify N contribution from manures (amount) and composition (N, P, K)?
	Does the tool allow you to provide an indication of manure N application type (raw/slurry) and storage?
	In the tool is N in excreta a function of animal diet?
	Does the tool allow you to provide an indication of N contribution from internal on-farm animal feed?
	Does the tool allow you to provide an indication of N contribution from external (bought in) animal feed?
	Does the tool allow you to provide an indication of grazing type (cows/sheep) and intensity?
	Does the tool allow you to provide an indication of ploughing type, depth and frequency?
	Does the tool allow you to provide an indication of cutting frequency and residue returns?
	Does the tool estimate gaseous N losses
	Does the tool estimate leached N losses
	Does the tool estimate yield & grain N

Appendix 2. Tool evaluations

Table A3 - Accessibility

Tool	Who is the model developer?	Cost	License agreement required?	Specialised software required?	Additional notes
PLANET	Originally ADAS and SRUC with support from DEFRA and Scottish Government. No current support for ongoing development or maintenance.	£0	No but requires registration to get access. Lack of funding means that the download site may not be available soon.	Download software from internet	ADAS supports England & Wales users, SRUC supports Scotland users but not specifically supported across the UK at this time. PLANET has MANNER built in but it is not obvious.
MANNER-NPK	Developed by ADAS with support from multiple agencies; maintained and supported by ADAS	£0	No but requires registration to get access	Download software from internet	Designed for use throughout UK including Scotland and Northern Ireland but no support throughout UK at the moment.
Farmscoper	Developed by ADAS with support from multiple agencies; maintained and supported by ADAS	£0	No	No (MS Excel and MS Access)	Designed for England and Wales (underlying data only included for these countries). It is designed to estimate mitigation options for multiple environmental impacts (nitrate, phosphorus, sediment, nitrous oxide, methane, ammonia, plant protection products, biodiversity, energy use and water use)
Overseer	Overseer Ltd	$200 (NZD)	No	No	Designed for use in New Zealand. Used by many farmers as decision making tool and local authorities for reporting compliance
Holos	Agriculture and Agri-Food Canada	£0	Not that I can see. It is free to download	Download software from the website	Available in French also. Once downloaded you can choose from Holos Classic and Holos Research. Holos classic has a simple, easy to use interface where defaults are shown. Holos Research allows the user to dig deeper behind the scenarios/processes to input more specific data (although default will be present and used if nothing else is inputted)
UK smart Inventory for GHG and ammonia	Consortium of Rothamsted Research, ADAS, Cranfield University, SRUC & CEH	n/a	currently only useable by the consortium; database contains high-resolution data that are only available under license	yes	The UK agricultural emission inventory is not a tool for N accounting as such, but specifically for estimating atmospheric nitrogen (N2O, ammonia) emissions, and the input/output data provide quantitative information on many of the parameters of an N budget for the agriculture sector (e.g. mineral fertiliser & manure input to crops & grass, N excretion, etc.)
FarmAC	Aarhus University, Denmark; additional development was part funded by EU Animal Change project	£0	No	Online - Internet browser	Languages (Danish, English, French)
Image	The IMAGE modelling framework has been developed by the IMAGE team under the authority of PBL Netherlands Environmental Assessment Agency	n/a	n/a (not available for other users)	yes, it is a bespoke set of models	All scenario data (>200 indicators) for major projects are available for download. The model represents both the agricultural and the wastewater system (and the hydrosphere and atmosphere).
Ndicea	Lois Bolk Institute	£0	No	Download tool	Developed for the organic sector. Language Dutch, UK, Denmark, Spain

Tool	Who is the model developer?	Cost	License agreement required?	Specialised software required?	Additional notes
Vogt	PhD student Esther Vogt & team of supervisors at CEH/SRUC	n/a	No	The atmospheric N deposition part of the approach uses different models that were developed by CEH and are not available publicly. The rest of the approach is based on data collection through farm surveys, field measurements and calculations based on the IPCC methodology (guidebook online)	The N budget approach described in the paper (Vogt et al. 2013, Biogeosciences 10:1190133) is not available as a stand-alone tool. It uses a number of methods to derive the different components of the N budget at a landscape scale, for two catchments in Scotland

Table A4 - Function, Scale, practicality & Application

Tool	Target user	Expertise required	Does the tool appear to be user friendly?	Spatial scale the tool is designed for	Does the tool rely on raw field data or can survey data be used?	How much data is required?	Land use/farm types coverage	Temporal scale the tool is designed for	Additional notes
PLANET	Farmers or consultants	Farmer (recommended to consult adviser if unsure)	Yes, if in NVZ must confirm records before moving through parts of model otherwise, easy to move between sections	Individual fields/ farm level/ farmgate nutrient balance	Farm records and raw data	Records of farm management - cropping sequences/management/fertiliser-manure use and storage, imports and exports	Arable, livestock, mixed	Annual, records can be kept for years in PLANET	Data can be downloaded from Rural Payments Online system, and field Land Parcel Identification Number. Soil analysis can be imported or manually edited.
MANNER-NPK	Farmers or consultants	Farmer (recommended to consult adviser if unsure)	Yes - very flexible as 5 tabs which can be moved between in any order	Individual fields/ farm level farmgate nutrient balance	Farm records and raw data	Farm/field details, records of manure/slurry or organic material type, application date/rate, incorporation, wind speed, topsoil moisture content and manure nutrient analysis, laboratory analysis of manures	Any	Immediate estimations	Practical software tool, meant to provide quick estimates of crop nutrients from organic manures
Farmscoper	Researchers (potentially consultants and farmers too)	Farmers (with good computer literacy)	Not self-explanatory, but detailed help is provided	Farm and catchment scale	By default it uses survey data (June Census), but raw field data can be entered	The tool can be run with the default data, but farm data can also be provided about basic activities and the use of mitigation options.	17 farm types (June Census Robust Farm Types)	Annual	Farmscoper is a calculator tool using the spatially explicit (1 km^2) results from process based models, which were aggregated to 3 soil types and 6 climate regions
Overseer	Farmers. But will also be used by consultants and local authorities	You will need to know the management operations on your farm in order to use the tool effectively.	Yes. The tool is very easy to follow and use. The tool uses tabs and drop down menus and prompts when cells are missing (if required) and easy to view visuals of whole-farm and blocks within farms	Farm scale	Some- for example fertiliser application rate/type, animal numbers/type/movement etc. Data for farm operations. Soil characteristics can be put in if soil testing has been done or soil map can be used	Farm operation information - fertiliser, crop type, pasture type, supplements, feed, yields, what is removed, stored or used on farm, irrigation & drainage. If data not known defaults are available	Arable, pasture, livestock, mixed, trees	Annual records provided. Model has legacy software so previous years can be used in next year's data input	Outputs can be downloaded to excel or alternatively shared directly with other model users (by allowing permission to view or edit the account)

Tool	Target user	Expertise required	Does the tool appear to be user friendly?	Spatial scale the tool is designed for	Does the tool rely on raw field data or can survey data be used?	How much data is required?	Land use/farm types coverage	Temporal scale the tool is designed for	Additional notes
Holos	Farmers and farm advisors	Holos classic: expertise of a working farm is needed, otherwise Canadian defaults will be used. Holos research allows for more technical applications and therefore would require more specialised knowledge and more data	Yes, there are tabs and drop down menus and input boxes, making it clear to follow and easy to see what inputs you can and can't use	Farm level	Field data required. For Holos classic - this should be data that a farmer would typically know and not necessarily need to collect in addition to routine analysis/monitoring. If using Holos-Research more in depth data would be required/useful	Depends. As defaults (based on IPCC emission factors) are provided, this allows the user to make estimates based on small data inputs/changes, but the model is capable of more if data is available	Arable & livestock & mixed	Model runs on an annual time step, but annual and monthly data outputs can be provided.	
UK smart Inventory for GHG and ammonia	expert users only (i.e. current consortium who developed and are running the annual agricultural emission inventory for the UK)	very high level of expertise required (currently only UK inventory team led by RothRes)	No	spatially variable data used at 10 km grid square resolution; modelling at the holding level aggregated to non-disclosure output at DA level	No field data required; high resolution agricultural statistics	annual June Census/Survey and Cattle Tracing System at the holding level; British Survey of Fertiliser Practice, Farm Practice & Farm Business surveys, yield data, soil & agri-climatic datasets, etc.	all agricultural crops & grassland; all robust farm types (RFT) across the UK	annual (with some monthly data used, e.g. on cattle populations)	

Tool	Target user	Expertise required	Does the tool appear to be user friendly?	Spatial scale the tool is designed for	Does the tool rely on raw field data or can survey data be used?	How much data is required?	Land use/farm types coverage	Temporal scale the tool is designed for	Additional notes
FarmAC	Farmers and farm advisers	educated, competent farmers or farm advisers"	Yes - tabs between sections; drop down and input boxes. A caveat is the creation of a 'baseline' scenario which is required for the model to function. There are two modes that are available for selection before the user can go through the model; adaptation mode allows the model to perform a long-term (more than 50 years) adjustment to the farm details and soil management entered whereas the projection mode allows the model to look at a shorter period of a few years, to give an average result of the management on farm.	Field/ Farm-scale	Raw field data, climate data, survey (of the correct type) can be used	Field/crop sequences, livestock, manure management	Arable, livestock, mixed	Annual	
Image	scientists (substantial training needed for scientists)	high level of expertise both in N flows and in model use	n/a (not a tool for generic use)	Land use, land cover, and associated biophysical processes are treated at a grid level of 5x5 arcminutes (corresponding to 10x10 km at the equator)	Not for the present year. The model is calibrated - by exogenous data (e.g. FAO) - to reproduce the state-of-the-world in 2005 (calculates the state in 2005 over the period starting in 1970). From 2005 onwards, a range of model drivers rooted in more generic narratives and scenarios drive the two main modules (agricultural production and energy use).	The model uses various external datasets for calibration, and then agricultural production etc. are calculated internally	All land use systems	Annual or five-year steps up to 2050 or 2100	Plant growth and carbon modelling is carried out by the LPJmL model which is coupled to IMAGE
Ndicea	Farmers and farm advisers	educated, competent farmers or farm advisers"	Yes	Field	Field data	Field/crop sequences/management of the crop	Arable and grassland	Daily	

Tool	Target user	Expertise required	Does the tool appear to be user friendly?	Spatial scale the tool is designed for	Does the tool rely on raw field data or can survey data be used?	How much data is required?	Land use/farm types coverage	Temporal scale the tool is designed for	Additional notes
Vogt	scientists/expert users	high level of expertise required to estimate the different components of the N budget (scientists)	n/a (not a tool)	field scale (individual land parcels) - bringing together data to assess at the catchment/ landscape scale	some field data required, but estimates from survey, expert knowledge and model output can be used	field level N inputs (e.g. mineral and organic N, excreta from grazing animals), high-resolution N deposition, legume/clover content, harvested vegetation, fluvial export (measured)	all agricultural crops, grassland, all semi-natural vegetation types, all farm types	annual (but sub-annual possible)	

Table A5 - Documentation & Transparency & Validation

Tool	User guide available?	Underlying assumptions available?	Underlying calculations available?	N budget calculations: IPCC, Publications, Grey Literature, Unpublished studies etc.	Is a list of tool versions/updates available?	Are data sources used within the tool available	Are publications/evidence of implementation provided?	Information on how to interpret outputs provided	Evidence of validation provided?	notes
PLANET	Yes, including in tool (some parts of help not functioning correctly, see notes at end), and includes video tutorials	No but it says it follows industry recommendations from RB209 and SAC TN's. Also driven by NVZ legislations.	No but recommendations literature is pointed to which will contain calculations; software driven by NVZ legislation	Based on recommendations from RB209 and SAC Technical notes - software driven by NVZ legislation	Current version is 3.3.3, some info available to say what was included in v3 update, but history of updates not apparent	Yes	Yes publications are referred to and the model is based on NVZ rules and legislations	Yes including video tutorials	No but is based on recommendations from RB209 and SAC TN's - software driven by NVZ legislation which is hardwired in to model	
MANNER-NPK	Yes user and technical guides - included in the software	Yes	No the raw formula is not available but throughout technical doc it states what is calculated	Yes	No but it is only version 1.01 (Feb 2013)	Yes	Yes publications are referred to and the model is based on NVZ rules and legislations	Yes	No but it is based on recommendations	
Farmscoper	Yes	Yes, in project reports	Not directly, as the emission values are imported from process based models (PSYCHIC, N-CYCLE, MANNER, NITCAT, EDEN, FIO-Farm, NARSES, NT26AE) - descriptions of these models are available in scientific papers cited in the documentation	The N budget is not calculated, N losses are derived from N inputs (livestock N excretion and synthetic and organic N application)	Yes	No, the database file is not accessible	Some publications are listed on the website	No	Underlying nutrient and sediment models have been validated. Farmscoper is not expected to accurately predict the pollutant losses for any specific catchment, but the outputs should correlate with observed data across a number of catchments and at national scale.	
Overseer	Yes there is a lot of documentation, reports, Q&A and YouTube demonstrations	Not that I could find	Not that I could find	Based on scientific research and IPCC global warming potentials	Yes there is transparency of model versions and model development	No	Yes	There is some documentation providing advice. There is also a helpline	Some validation provided in the documentation and publications	

Tool	User guide available?	Underlying assumptions available?	Underlying calculations available?	N budget calculations: IPCC, Publications, Grey Literature, Unpublished studies etc.	Is a list of tool versions/updates available?	Are data sources used within the tool available	Are publications/evidence of implementation provided?	Information on how to interpret outputs provided	Evidence of validation provided?	notes
Holos	Two training manuals for the Holos version 3. One is for the standard (simplified) interface and the other one for the research interface. They both focus on a beef system (which includes land use), but unfortunately they don't have any materials for the other livestock groups at this time (although it is something they are working on)	No	No	Canadian IPCC default values used. 'Eco-districts' are used to determine climate - based on Canadian climatic zones	"Holos is continually being updated with new data and improved features. Holos Version 3.0, released in May 2017, includes the addition of a basic economics cost/benefit analysis sub-component as well as the ability to input farm details in Imperial units of measure. It is available in both English and French"	Unclear	Yes, the website lists a number of publications where Holos has been used in research	Not specifically. Guide states that Holos outputs are estimates and not exact values and that the model was intended to demonstrate to users whether or not the changes to their farm will increase or decrease their farm emissions.	Not specifically, but publications are provided	
UK smart Inventory for GHG and ammonia	No - as the inventory model is not publicly available	Not a tool for wider use, but the model and all underlying datasets and assumptions are documented in detail	Not a tool for wider use, but the model and all underlying datasets and assumptions are documented in detail	The model only derives emissions of ammonia and GHGs, not wider N budget calculations, however the outputs are available on request for extracting quantitative information for inclusion in N budgets	The model (and all input data and assumptions) are carefully documented, including updates/improvements	Most datasets are available (some under license, e.g. livestock and crop/grass statistics)	Yes, annual emission inventory reporting, including at the devolved administration level (see naei.beis.gov.uk)	some interpretation is provided in the annual emission inventory reporting (Defra)	The inventory modelling is carefully checked and uncertainties are reported.	
FarmAC	Yes	Yes - assumptions stated throughout guidance document; factors available in the Parameterising tab; values are in code and source is described e.g. emission factors for NH2 and NOx from IPCC	Yes - available on request - see model v 1.4 document sent to Kairsty & Vera from Nick Hutchings (nick.hutchings@agro.au.dk) - guidance also available in the user interface	Yes - modelled; uses Tier 2 (emissions) and Tier 3. Academic literature is also referred to in the guidance.	No - version list and what updates were applied is not apparent	Yes	Yes	No	Yes (models runs tests to see if calculations can work and if results are achievable e.g. dry matter yield in section 7 crop model)	

Tool	User guide available?	Underlying assumptions available?	Underlying calculations available?	N budget calculations: IPCC, Publications, Grey Literature, Unpublished studies etc.	Is a list of tool versions/updates available?	Are data sources used within the tool available	Are publications/evidence of implementation provided?	Information on how to interpret outputs provided	Evidence of validation provided?	notes
Image	n/a (the tool is not available)	Yes: a book and website describing the details of the model and numerous peer-reviewed papers.	Yes	N inputs and N outputs in products: internally calculated based on demand for agricultural products, N emissions: a mix of process based (e.g. IPCC 2006) and regression models. The soil nutrient budget sub-module calculates N and P inputs and outputs	Yes	The underlying data sources are a mixture of public data (e.g. FAO) and own assumptions (e.g. livestock feed composition) - most of the latter is available in scientific papers.	Yes	Yes; the outputs always need to be considered in the context of the driving future scenario	The model is calibrated, but no evidence on validation can be found in the description (the individual components might be validated)	
Ndicea	Yes - inbuilt to tool	Yes - paper published van der Burgt, G.J.H.M., Oomen, G.J.M., Habets, A.S.J. et al. Nutr Cycl Agroecosyst (2006) 74: 275. https://doi.org/10.1007/s10705-006-9004-3	Yes	Modelled	Yes - http://www.ndicea.nl/indexen.php	No	Yes	Yes	No - but available in the publications	
Vogt	No	Yes - paper published: Vogt E., Braban C.F., Dragosits U., Theobald M.R., Billett M.F., Dore A.J., Tang Y.S., van Dijk N., Rees R.M., McDonald C., Murray S., Skiba U.M. and Sutton M.A. (2013) Biogeosciences 10: 119-133 doi:10.5194/bg-10-119-2013. http://www.biogeosciences.net/10/119/2013/bg-10-119-2013.pdf	yes, for some parts of the calculations; see published paper	Yes	No - only initial version of approach, as published	Some can be made available on request; some have been made available by farmers for use in this study and details cannot be shared	Yes	Yes	Yes	

Table A6 – Does the Tool allow you to specify …? (farming practice)

	Does the tool allow you to specify soil characteristics?	Does the tool allow you to specify crop/grass characteristics (diversity/type)?	Does the tool allow you to specify legume characteristics (diversity/type)?	Does the tool provide an estimate of N-fixation & input based on legume coverage?	Does the tool allow you to specify rotation characteristics?	Does the tool allow you to specify some climatic characteristics?
PLANET	Drop down box of 6 soil types when creating individual fields - these are legal definitions of soil type relevant to NVZ legislation and can affect management suggestions. Soil type has an effect on outputs and NVZ guidance e.g. closed periods, and shallow soils have legal restrictions	Yes crop group, type - variety can be manually entered - for potatoes, varieties are listed if variety group is unknown	Clover, grass/clover, peas (dried or vining), field beans, Lucerne	Yes; crop type selection in farm gate balance tab allows tool to calculate N fixed by legumes by area cropped	Yes one crop at a time and field records are kept for as long as required, so can produce report with rotation characteristics	Rainfall amount at beginning of farm creation based on standard code; can be altered for actual amount of rainfall and "excess winter" rainfall can selected as an option, if in NVZ the model allows for the top up of N that can be applied when there is excess rainfall
MANNER-NPK	Topsoil (15 options) and subsoil textures (17 options) can be specified; soil drainage end date; chose whether topsoil is moist or dry. Certain topsoil and subsoil combinations change the nitrogen results tab for N efficiency (%) and availability to next crop plus potential financial value of manure applications	Yes	No	No	No	Yes Rainfall amount based on postcode; rainfall amount post application, wind speed at application, rain within 6 hrs application; end of soil drainage period (date)
Farmscoper	No only 'free-draining' and 'other' categories can be chosen (3 built-in soil types are considered in the tool)	No (3 grass and 15 crop types are pre-defined)	No, only clover use can be chosen as a mitigation option	No (for the clover-grass mix the estimates from the underlying model consider that)	No	Yes (annual average rainfall)
Overseer	Tool is linked to Landcare IS soil maps and will provide up to 3 soil types in each block/field selected (if more are detected and comprise a substantial contribution to the overall land unit, it is advised to break up the area into smaller blocks), however this data can be overridden if necessary (E.g. if you have Soil Test data).	Yes - topography; 7x pasture types, area; yield; supplements used; cuts and amounts used by animals; cultivation within last 5 years; if animals are present; runoff characteristics; compaction; susceptibility to pugging; fodder crops; crops; tillage intensity; rotation across ‘blocks’ and over time	Included in 'pasture type' tab but limited (ryegrass & white clover mix)	Not that I can see	Yes. An easy to use visual graphic of all fields within the farm show where crops and animals are rotated	You can add latitude-longitude, which links do s-maps to provide climate data

	Does the tool allow you to specify soil characteristics?	Does the tool allow you to specify crop/grass characteristics (diversity/type)?	Does the tool allow you to specify legume characteristics (diversity/type)?	Does the tool provide an estimate of N-fixation & input based on legume coverage?	Does the tool allow you to specify rotation characteristics?	Does the tool allow you to specify some climatic characteristics?
Holos	Not really. In Holos classic you can only select from 4 soil types (Black/grey chernozem, Brown chernozem, Dark brown chernozem and 'Eastern Canada') and 3 soil textures (fine, medium, coarse)	Yes there are a range of annuals (25 types, majority of which are common to Scotland), perennials (Hay-grass, Hay-legume, hay-mixed, hay & forage seed) fallow and tree species/types to choose from. For 'grasslands' there is a choice between seeded grassland (pasture, improved pasture, rangeland, permanent cover) and broken grassland. You can specify type, year seeded, length, irrigated, herbicide/ N/ P applications and Yield. In Holos Research you can also include moisture content, AGR-N, BGR-N, yield ratio, AGR ratio, BGR ratio, fuel energy and herbicide.	Limited - options include dried peas, lentil, soybean	Not that I can see	No it is a single year calculator	You have to specify province and eco-district of Canada. Eco-districts have been predetermined that use 30 year climate data in each area. Holos Classic will use 30-yr data but in Holos-Research you can edit annual precipitation and potential evapotranspiration and monthly average temperature
UK smart Inventory for GHG and ammonia	Soil data are used as part of the emission calculations (summarised at a 10 km grid resolution)	Yes, all livestock, crop and grassland types reported in the annual agricultural survey/census data across Scotland (and the wider UK); for grass, this includes improved grass (over & under 5 yrs old) and rough grazing	legumes as part of grass wards not specified (only grass over and under 5 yrs old & rough grazing), legume crops (e.g. peas) from agricultural census/survey statistics	No. The presence of clover is accounted for in N content of herbage and used to in leaching calculations; but no explicit output of N fixation	No	the model uses agri-climatic characteristics (temperature, rainfall) in the emission calculations, mainly for N2O, and for mineral fertiliser emissions of ammonia
FarmAC	Yes, limited - drop down box of 17 soil texture types - need to know beforehand what type of soil it is from testing or soil maps/databases - different soil types can be selected in each crop sequence to indicate differences in soil type across a field (See section 9.2 of The FarmAC model user guide)	Yes	only peas, lucerne, clover, permanent grass-clover, rotational clover grass	No - modelled based on crop specific parameters; Crop parameterisation has an N-fixation Factor "Rate of reduction in N fixation with increasing mineral N availability"	Yes	Yes

	Does the tool allow you to specify soil characteristics?	Does the tool allow you to specify crop/grass characteristics (diversity/type)?	Does the tool allow you to specify legume characteristics (diversity/type)?	Does the tool provide an estimate of N-fixation & input based on legume coverage?	Does the tool allow you to specify rotation characteristics?	Does the tool allow you to specify some climatic characteristics?
Image	No, it is from external data source (FAO Harmonized World Soil Database)	No, internally calculated in the model in the computable general equilibrium agro-economic model MAGNET (based on land availability and demand for agricultural products); 12 crops (wheat, maize, rice, millet, field peas, sugar beet, cassava, sunflower, soybean, groundnut, rapeseed, sugarcane; irrigated and rain fed separated within groups), intensive grassland, extensive grassland	No, internally calculated in the model (based on land availability and demand for agricultural products)	Yes	No	No, it is derived internally from a climatic model (MAGICC 6.0) which is linked to the core modules
Ndicea	Yes	Yes	Type	Yes	Yes	Yes
Vogt	Yes	Yes	Yes	Yes	Yes	Yes

Table A7 – Does the tool allow you to specify……. (issues around nitrogen)

	N contribution from N deposition?	N contribution from mineral N-fertiliser type?	N contribution from mineral N-fertiliser intensity?	N contribution from mineral N-fertiliser application method?	Livestock characteristics?	N contribution from manures (amount)?	Manure composition (NPK)?	Manure N application type (raw/slurry)?	Manure storage?
PLANET	No	Yes, can alter mineral fertiliser composition and later chose inorganic fertiliser imports type and composition	Yes	No (can't specify method, only date of application)	Yes in farmgate nutrient balance tab	Yes	Yes (pre-populates with guideline values but can be changed)	Yes - extensive indication of manure types	Yes can, in detail, specify store types and capacities along with rainfall collection areas and capacities
MANNER-NPK	No	No	No (there is an option to look at nutrient price data only for AN and CAN to compare to price/ estimate potential financial value of N from manures)	No	No	Yes, default numbers set for manure/slurry/organic material but can be edited if lab analysis available	Yes, default numbers set for manure/slurry/organic material but can be edited if lab analysis available	Yes - application method, soil incorporation and delay between application and incorporation	No
Farmscoper	No	No (only total mineral N)	Yes	Yes, included as mitigation options	Yes, to some extent (manure management, grazing time)	No, it uses default manure N content (based on underlying modelling of manure storage)	No	Yes	Yes
Overseer	No	Yes - the model has a drop down menu of fertiliser manufactures and their products (with specific NPK contents)	yes	yes you can specify between surface applied and incorporation	Yes, animal type, months in field/block, can remove animals between fields, can include age, weights, starting numbers, year born, and grazing days stock change number. Events can be linked to farmer's invoices	Yes manures are included in calculations	N (P, K. S, Mg, Ca, and Na) content of dairy factory manure, compost and mulches can be specified.	Yes	No

	N contribution from N deposition?	N contribution from mineral N-fertiliser type?	N contribution from mineral N-fertiliser intensity?	N contribution from mineral N-fertiliser application method?	Livestock characteristics?	N contribution from manures (amount)?	Manure composition (NPK)?	Manure N application type (raw/slurry)?	Manure storage?
Holos	no	Quantity of N can be applied but fertiliser type is not included	Yes	No	Yes - Beef (Cows and calves, Sockers and grassers), Dairy (lactating groups, calves, young heifers, bred heifers, drycows, bulls), Swine (lactating, starters, growers, finishers, dry sows, boars); Sheep (ewes, rams); Poultry (layers, broilers, turkeys, ducks, geese). Input parameters include weights, milk production, milk fat content, number of animals housing, diet, manure system	In Holos-Research you can specify manure system - Compost, deep bedding, liquid (no crust), liquid (crust), pasture, solid storage, daily spread	No	Yes	yes
UK smart Inventory for GHG and ammonia	Yes, re-emission from N deposited is calculated for agricultural land (indirect emissions)	Yes - N input data from the British Survey of Fertiliser Practice are used in the calculations	Yes - N input data from the British Survey of Fertiliser Practice are used in the calculations	Yes - N input data from the British Survey of Fertiliser Practice are used in the calculations	Livestock characteristics are used to calculate N excretion and emissions by livestock type and intensity (e.g. high yielding dairy cows vs. less intensive systems); using e.g. cattle breed information from the Cattle Tracing System	Yes - manure amounts are used in the model calculations	No - typical manure types are used in the model calculations; P and K not included	Yes, different application types are used within the model	Yes, the model uses data on average storage types for manure across the DAs
FarmAC	Yes	Yes	Yes; you can edit the N intensity (as well as P and K) in the "fertMan" html files which also contain mineral fertilisers	Yes	Yes but only cows/sheep - pigs are in the model but the tab (non-ruminants) is not currently functioning	Yes	Specified in the parameter files which can be manually edited	Yes	Yes
Image	No, internally calculated in the model	No, internally calculated in the model	No, internally calculated in the model based on crop yield estimations and nitrogen use efficiency assumptions	No, internally calculated in the model	No, internally calculated in the model in the computable general equilibrium agro-economic model MAGNET (based on production possibilities land demand for agricultural products); 5 livestock categories: beef, dairy, small ruminants, pigs, poultry	No, it is calculated internally	No, it is calculated internally	No	No
Ndicea	No	Yes	Yes	No	No - doesn't deal with livestock	Yes	Yes	Yes	No
Vogt	Yes	Yes	Yes	Yes	YEs	Yes	Yes	yes	yes

Table A8 – Does the Tool allow you to specify …

	N in excreta a function of animal diet?	N contribution from internal on-farm animal feed?	N contribution from external (bought in) animal feed?	Grazing type (cows/sheep)?	Grazing intensity?	Ploughing type/depth?	Ploughing frequency?	Cutting frequency?	Residue returns?
PLANET	No - some flexibility for Pigs and Poultry as there is a 'legal' N limit for feed for these livestock units but you can only change values not calculate them. Depending on cattle type selected, N is also considered in their diet e.g. if a milking cow or a follower, diet will change depending on function. PLANET can import values for pigs and poultry from a software called encash which does consider N excretion values	Yes in the farmgate nutrient balance report the harvested crops exported N is shown	Yes as crude protein %	Yes, cattle, pigs, poultry, sheep, others (horse, lamb, goat, deer). Livestock type selection for main categories is extensive.	Yes in livestock manure N limit grazing intensity for area farmed in an NVZ for a whole year	Not specifically. Only manure incorporation method can be specified as can delay between spreading and incorporation	Yes/no sowing date can be entered; fertiliser app date can be entered to indicate freq. Manure application method can be specified with date to indicate ploughing	Yes by entering start/end dates	Yes; straw can be incorporated or baled
MANNER-NPK	No	No	No	No	No	Yes and No - only method of manure/slurry/organic material incorporation method and date	Yes and No - can be indicated in that 3 manure/slurry/OM application with incorporations can be entered in the calculator	No	No
Farmscoper	No	No	No	Yes	No	No	No	No	Yes, as a mitigation measure
Overseer	No - not clear that these are linked via the interface	You can specify whether harvested N (or animals) remain on farm or off. Also whether inputs are from on-farm	Yes	Yes, you can specify animal type and grazing months on each block/field listed on the farm	No just quantity of animals per plot per month	Yes, minimum, direct and conventional	Yes. Cultivation can be added/included in any month	Yes. Harvest/cuts can be added/included in any month	Yes; straw can be incorporated or baled

	N in excreta a function of animal diet?	N contribution from internal on-farm animal feed?	N contribution from external (bought in) animal feed?	Grazing type (cows/sheep)?	Grazing intensity?	Ploughing type/depth?	Ploughing frequency?	Cutting frequency?	Residue returns?
Holos	Modifying diet parameters does not appear to affect manure details (but options for the 'manure system' does)	Diet options include High, medium and low energy & diet additives (2% or 4% fat)	No	You can choose between housed or ranging animals and flat or hilly pasture	No	Yes (No-till, reduced and intensive)	No	No	Not that I can see
UK smart Inventory for GHG and ammonia	yes	yes - system-specific forage is taken into account at a national (DA) average level (e.g. 3 dairy systems)	yes - system-specific bought-in feed is taken into account at a national (DA) average level (e.g. 3 dairy systems)	Yes, the model takes account of the livestock type grazing and calculates specific grazing emissions by animal category	No	No	No	No	yes - estimated at national level by crop type
FarmAC	Yes	Yes	Yes	Yes	Yes	Not explicitly in the field management selection as with other models but can indicate how fertilisers are incorporated	No - but you specify the date on which harvest, planting etc. occur which will capture some of the ploughing data, and you can indicate how fertilisers are applied, giving another indication of ploughing frequency.	Yes - you specify the quality of the herbage cut for each period; you enter start and end dates for cropping sequences and it can be captured in this way but it must be end date+1 to start a new sequence to get the next cut, rather than indicate that that, from the original start date, the grass is cut several times throughout its growing season	Yes in the crop sequence tab under product selection
Image	Yes	n/a (the model doesn't have representation of farms)	No, it is calculated internally	No, it is calculated internally	No, it is calculated internally			No	No, it is calculated internally
Ndicea	No	No	Yes - but doesn't model livestock	No - but specify grazing / cutting of sward	No	No	Not directly - but specify dates for rotation	Yes	Yes - specify if straw removed for cereals
Vogt	No	Yes	Yes	Yes	Yes	No	No	yes	yes

Table A9 - Does the tool allow you to provide an indication of…..

	Gaseous N losses	Leached N losses	Yield & grain N
PLANET	No	Not directly but it is taken into account to some degree for organic sources and for mineral in some instances as part of the NVZ legal limits working in the background. Regardless of whether a farm is ticked as in an NVZ or not they are taken into consideration in the model.	Yes
MANNER-NPK	Yes	Yes	No
Farmscoper	Yes	Yes	No
Overseer	Yes	Not directly	Yes
Holos	Yes	No	Yes
UK smart Inventory for GHG and ammonia	Yes	Yes	Above and below ground N is used as input data, not estimated by the model
FarmAC	Yes	Yes	Yes
Image	Yes (NH_3, N_2O, NO_x), and deposition too; N_2O calculation is based in IPCC 2006 guidelines	Yes	Yield: yes, grain N: it certainly estimates it in the model but might not be an output
Ndicea	Ammonia - not N2O	Yes - but doesn't model livestock	No - entered
Vogt	yes	Yes	yes

Table A10 - Outputs and Other Info

	To what scale (spatial/temporal) are N budget outputs provided?	Is the tool capable of future predictions / scenario testing	Is the tool capable of providing management suggestions and/or mitigation options	Are there any obvious gaps in the tool in generating an N budget?	Are there any obvious sections of the tool that need to be updated/edited based on new understanding?	Indication of comprehensiveness of N pathway described	Additional Notes
PLANET	Field	Yes and records can then be confirmed if they actually happened	Yes can provide management suggestions, no suggestions for mitigation options	Mineral fertiliser incorporation method, gaseous N losses and N deposition are not fully accounted for	Update to reflect new technical notes and rb209 as based on older versions	No	If box for NVZ is ticked, plant requires users to confirm records (by clicking a button in the software) before proceeding through the model; when NVZ is not ticked, users can proceed through model without as many restrictions and warning signs for potential breeches of NVZ rules are disabled. PLANET allows users to import pigs and poultry values from a model called encash which takes in to consideration NVZ legal limits. Help function doesn't seem to work; it won't let two applications of PLANET run at the same time, forcing help to close. Other organic materials such as bio solids, paper crumble etc. cam also be selected in the organic manures tabs. Can enter costs of mineral fertilisers to allow for cost analysis to be done.
MANNER-NPK	Field	Yes you can use it to predict N efficiency, N losses, and £ value of manures compared to mineral fertilisers	Not really - indicates if non-compliance with NVZ Action Programme rules and indicates potential crop available N and N efficiency for current and upcoming crop	No mineral N fertiliser usage although it was designed to look at OM sources of N	T	Yes in appendices of technical guide	Also estimates total and available P2O5, K2O applied, total SO3 and MgO applied
Farmscoper	No N budget is provided	Yes, it can optimise mitigation options based on reduction targets and costs	Yes, it has over 100 mitigation options	Yes, including N deposition, animal feed, type of synthetic N	No	Sorry, I don't understand the question	
Overseer	Annuals for field/block and total farm	Yes. You can save your 'actual' field and copy to Scenario model to adjust parameters and assess outcomes	You can input a range of management scenarios. There are management advice within the model (such as mining pugging). No particular 'menu' for mitigation or adaptation	Mineral fertiliser application method, leached N	The model is continuously being updated via feedback and research developments and uses IPCC global warming potentials	User videos are good at explaining the linkages and some of the N flows within the model	

	To what scale (spatial/temporal) are N budget outputs provided?	Is the tool capable of future predictions / scenario testing	Is the tool capable of providing management suggestions and/or mitigation options	Are there any obvious gaps in the tool in generating an N budget?	Are there any obvious sections of the tool that need to be updated/edited based on new understanding?	Indication of comprehensiveness of N pathway described	Additional Notes
Holos	N2O and CO2e monthly or annually	yes	No direct suggestions or options but the output data can indicate where the main losses or gains of N are, which can inform management or mitigation decisions and practics	Limited soils types (Chernozems). Based on specific areas of Canada. Results are N2O emissions and CO2 equivalent so it lacks NH3 gas loss, N leached losses and N storage in soils. Manure composition	The model is based on IPCC and national climate data so can be updated alongside inventory data. As details of underlying assumptions are not available, judgement cannot be made as to whether pathways are described as best they can be with recent knowledge	Without documentation of all assumptions and connections is it difficult to judge	
UK smart Inventory for GHG and ammonia	annual; all key input/output data provided at the DA level; emissions to air at a 1 km grid resolution (published via naei.beis.gov.uk) other more spatially detailed information can be extracted on request (likely subject to costs for staff time)	yes	No direct suggestions or options but the output data can indicate where the main losses or gains of N are, which can inform management or mitigation decisions and practices	The model is designed to create NH3 and N2O emissions to the atmosphere, and some of the input/output data can be used for national/regional scale N budgets; N deposition data, run-off, import/export of materials is not included in the system, but these data are available from elsewhere for piecing together Scottish N budget estimates (e.g. recent SEPA project: Scottish N budget led by CEH; Carnell et al. 2019)	The model is updated annually with the latest statistics and datasets, and undergoes annual improvement cycles more generally	N Emissions to the air are calculated comprehensively; N leaching pathways also estimated	

	To what scale (spatial/temporal) are N budget outputs provided?	Is the tool capable of future predictions / scenario testing	Is the tool capable of providing management suggestions and/or mitigation options	Are there any obvious gaps in the tool in generating an N budget?	Are there any obvious sections of the tool that need to be updated/edited based on new understanding?	Indication of comprehensiveness of N pathway described	Additional Notes
FarmAC	Temporal (annual / per year)	Yes	No direct suggestions or options but the balance sheet at the end can indicate where the main losses or gains of N are, which can inform management or mitigation decisions and practices	Other organic material sources of N could be included in the model.	Could include existing soil testing factors/results (pH, current PK, PMN or SNS Index), pesticide use not included but may not be relevant; only cow/sheep livestock can be selected, missing chickens, etc. pigs are there but doesn't function; number of soil layers is fixed in code but does not function. Other organic material sources of N could be included in the model	Yes	Tool html code and input files and parameters are available for download; the numbers can be edited is an advanced user. When navigating, if there is an action which was not complete an error messages comes up with details about code and is not user friendly in this sense as it doesn't explain what the issue is or how to resolve to proceed
Image	5x5 arcminutes (corresponding to 10x10 km at the equator); annual	Yes, it is designed for that	No, but the scenarios can include some mitigation (e.g. efficiency improvements)	The soil N budget doesn't consider changes in the soil N pool; animal excreta storage and application methods are not considered; synthetic fertiliser types and application method is not considered	Nothing of crucial importance, but it is constantly improved, with a development plan for 2015-2020	Sorry, I don't understand the question	The model is designed for global assessment of future economic-ecological pathways. As such it is no suitable for deriving a detailed and robust annual N budget for Scotland, but can provide a guide of how N flows would evolve in the region given certain future pathways.
Ndicea	Daily	Yes - based on entered weather	No	N2O emissions	Livestock and manure management prior to application to the field. Ploughing depth.	Yes	Regions are English based - but weather and soils can be entered for Scotland. The evapotranspiration rates need to be calculated in a specific way. Experience of using the model revealed that the high OM of Scottish soils may cause an issue. This was corrected by assuming that the soil only contained 1/2 the actual SOC.
Vogt	field and catchment/ landscape scale, annual	partly	No direct suggestions or options but the output data can indicate where the main losses or gains of N are, which can inform management or mitigation decisions and practices	No	the overall approach is sound, but individual equations and emission factors etc. should be reviewed and amended with more recent publications;	Yes	the approach is not currently a tool as such, but could be reviewed and developed towards a more user-friendly system needing less expert input