An enhanced software tool to support better use of manure nutrients: MANNER-*NPK*

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Abstract

MANNER-*NPK* (MANure Nutrient Evaluation Routine) is a decision support tool for quantifying manure (and other organic material) crop available nutrient supply. The user-friendly design of an earlier version of MANNER was retained, but in response to user and stakeholder feedback, additional functionality was included to underpin new and revised nitrogen (N) transformation/loss modules (covering ammonia volatilization, nitrate leaching and nitrous oxide/di-nitrogen emissions, and organic N mineralization) and also to estimate manure phosphorus (as P_2O_5), potassium (as K_2O), sulphur (as SO_3) and magnesium (as MgO) supply. Notably, MANNER-*NPK* provides N availability estimates for following crops through the mineralization of organic N. Validation of the crop available N supply estimates was undertaken by comparing predicted values with data from more than 200 field experimental measurements. For cattle, pig and poultry manures, there was good agreement ($P < 0.001$) between predicted and measured fertilizer N replacement values, indicating that MANNER-*NPK* provides robust estimates of manure crop available N supply and N losses to the wider environment.

Keywords: Manures, nutrients, nitrogen, crop availability, losses, decision support tool
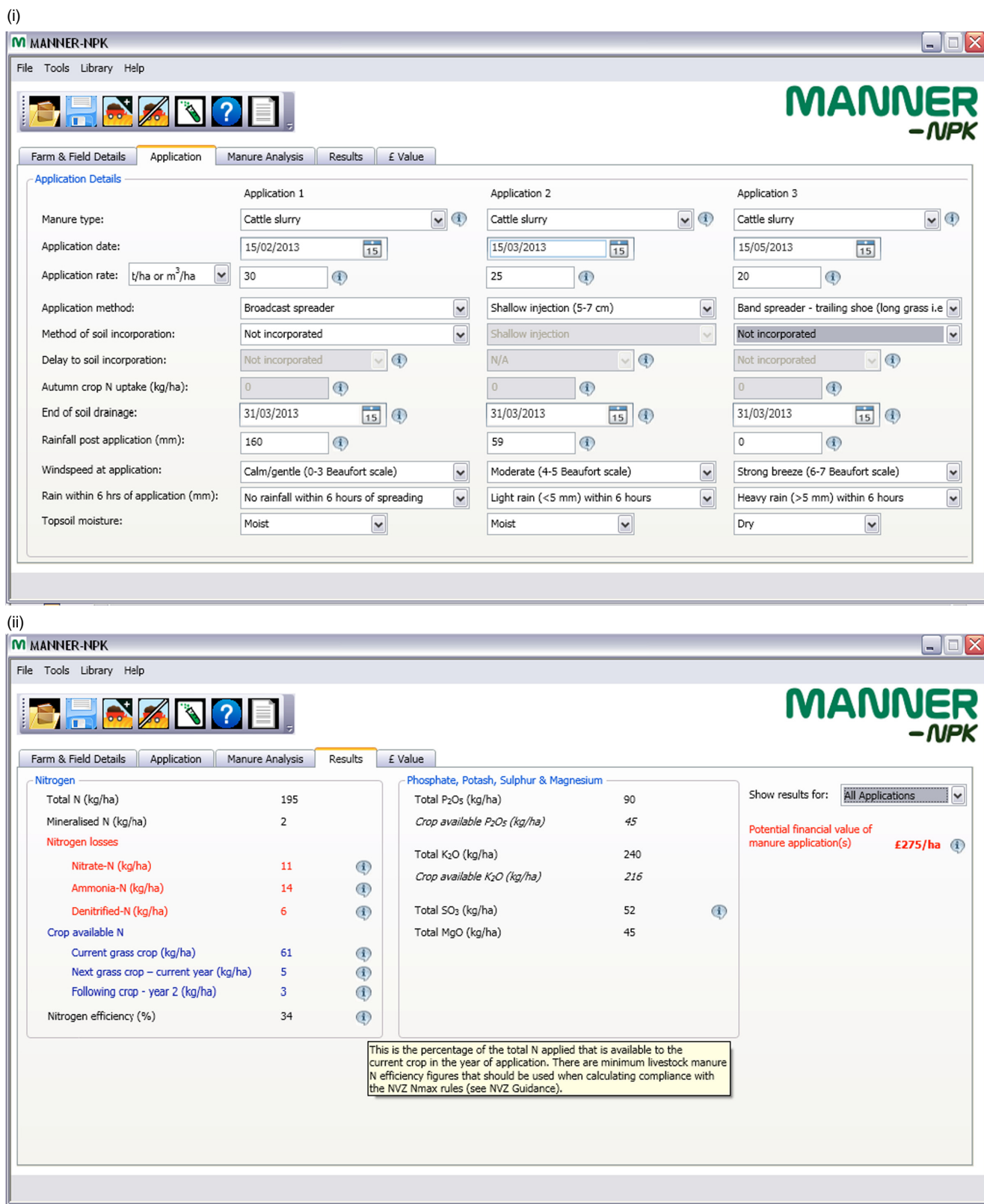
Introduction

Land application is the most cost-effective outlet for recycling farm manures and other organic materials (e.g. biosolids, composts, digestates), enabling plant available nutrients and organic matter to be utilized to contribute to crop nutrient demands and maintain soil fertility. However, in many countries, farmers do not always make adequate allowance for the contribution of organic materials to crop nutrient requirements, potentially resulting in nutrient oversupply and subsequent environmental pollution. Increasing the contribution of organic materials to crop nutrient requirements is essential in reducing nitrate (NO_3) and phosphorus (P) losses to water systems, and ammonia (NH_3) and nitrous oxide (N_2O) emissions to air from

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agriculture, to comply with existing and forthcoming EU Directives and International agreements (e.g. Nitrates Directive, Water Framework Directive, National Emission Ceilings Directive, Kyoto Protocol etc.).

The ADAS MANure Nitrogen Evaluation Routine (MANNER version 3.0) decision support system was originally developed to predict crop available N supply following farm manure (and other organic material) applications to land, taking into account manure N analysis, NH_3 volatilization and NO_3 leaching losses, and the mineralization of organic N (Chambers *et al.*, 1999). Over 10 000 copies have been distributed following its launch in August 2000. A new version of the software (MANNER-*NPK*; Figure 1) was developed to enhance the N loss and crop available N supply predictions by utilizing more recent scientific information. In response to user and stakeholder feedback, the software functionality was also extended to include predictions of phosphorus (as P_2O_5), potassium (as K_2O), sulphur (as SO_3) and magnesium (as MgO) supply to

(i)

(ii)

Figure 1 MANNER-*NPK* screenshot examples (i) Application tab, showing details for three cattle slurry applications to grassland in spring and (ii) Results tab, showing MANNER-*NPK* estimates of N losses and fertilizer nutrient replacement values of the three cattle slurry applications.

crops, and to enable users to view the results in terms of both the fertilizer replacement value (kg/ha) and the economic value (£/ha) of manure applications.

Methods

The MANNER conceptual model was enhanced to incorporate new modules to estimate N_2O (via nitrification and denitrification) and di-nitrogen (N_2) losses (via denitrification), and to take into account autumn crop N uptake (Figure 2). Some changes were also made to the inter-relationships between modules to better represent the N flow pathways and transformations that occur following manure application to land. In particular, MANNER-*NPK* now estimates the quantity of N available to following crops (i.e. in the cropping year after manure application) through the release of manure organic N.

The MANNER modules were updated as described in the following sections.

Manure nutrient analysis

The manure nutrient analysis database was revised on the basis of more recent analytical data. Manure P, K, S and Mg analyses can now also be entered to provide a prediction of the total and crop available supply of these nutrients. In addition, 'default' nutrient contents for 'new' manure types (e.g. green compost, digestates) have been included, together with nitrate-N analysis data, which can be an important source of readily available N from some manures.

MANNER-*NPK* adjusts the 'default' total and readily available N contents of slurry based on dry-matter content. Similarly, equations are embedded in the software relating slurry and poultry manure dry matter to P, K, S and Mg contents (Defra, 2010).

Ammonia volatilization

Standard ammonia volatilization curves. Ammonia volatilization is the first major loss pathway for manure N following land application. The 'standard' ammonia volatilization curves for different manures were updated using data from micrometeorological measurements of ammonia emissions from broadcast manures at a range of sites in England, under grassland and arable cropping. Michaelis–Menten type equations (Sommer & Ersboll, 1994) were fitted to each experimental dataset (equation 1) using GenStat:

$$\text{Ammonia lost at time}(t) = N_{max} * (t/(t + K_m)) \qquad (1)$$

where N_{max} is the maximum N loss as time (t) approaches infinity (expressed as a percentage of the manure readily available N - RAN - applied) and K_m is the time (in h) when half of N_{max} has been lost. Note: RAN is the sum of

the manure ammonium-N and, for poultry manures, uric acid-N contents. In total, four 'standard' emission curves were defined (Table 1). Experimental data on ammonia emissions from the other organic material types included in MANNER-*NPK* (e.g. biosolids, digestates, composts) were not available. Hence, it was assumed that emissions from these materials followed one of the four standard curves and any additional ammonia loss rules for that manure type, as described in Figure 3.

Factors influencing ammonia volatilization. Based on experimental data not previously taken into account (e.g. Smith *et al.*, 2000; Sogaard *et al.*, 2002; Misselbrook *et al.*, 2004), the ammonia loss algorithms were modified to take account of factors which had been shown to influence ammonia volatilization from field-applied manures (i.e. soil moisture content, land use, wind speed, rainfall after spreading, slurry dry-matter content, slurry application technique, soil incorporation technique and timing). Ammonia volatilization losses from each of the four broad manure types were adjusted according to decision support rules summarized in Figure 3.

For cattle slurry, an initial adjustment to the N_{max} is made based on the soil moisture status, as ammonia emissions from cattle slurry applied to 'dry' soils in summer (i.e. where soil moisture is below field capacity) were found to be greater than from 'moist' soils in the autumn-to-spring period (i.e. where soils are at field capacity), due to a combination of the hydrophobic effect of dry soil conditions on slurry infiltration and also higher temperature/lower humidity conditions in the summer (Smith *et al.*, 2000). A further adjustment to the N_{max} is made based on land use, as losses from grassland soils are typically higher than from arable soils (Smith *et al.*, 2000).

For both cattle and pig slurry, relationships between slurry dry-matter (DM) content and ammonia emissions have been observed where applications were made to grassland under 'moist' soil conditions (e.g. Sogaard *et al.*, 2002; Misselbrook *et al.*, 2004). Ammonia emission and DM relationships were included for slurries applied to moist soils in the autumn-to-spring period, based on data from Misselbrook *et al.* (2004). These relationships were used to derive an adjustment to N_{max} compared with emissions from cattle slurry at 6% DM and pig slurry at 4% DM.

An adjustment to the N_{max} for slurries is also made based on evidence that precision slurry application techniques (i.e. bandspreaders and shallow injectors) reduce ammonia emissions following land spreading (e.g. Smith *et al.*, 2000; Misselbrook *et al.*, 2002). As wind speed and rainfall at or around the time of slurry spreading also influence ammonia losses (Misselbrook *et al.*, 2004), further adjustments to N_{max} are made based on these factors (Figure 3).
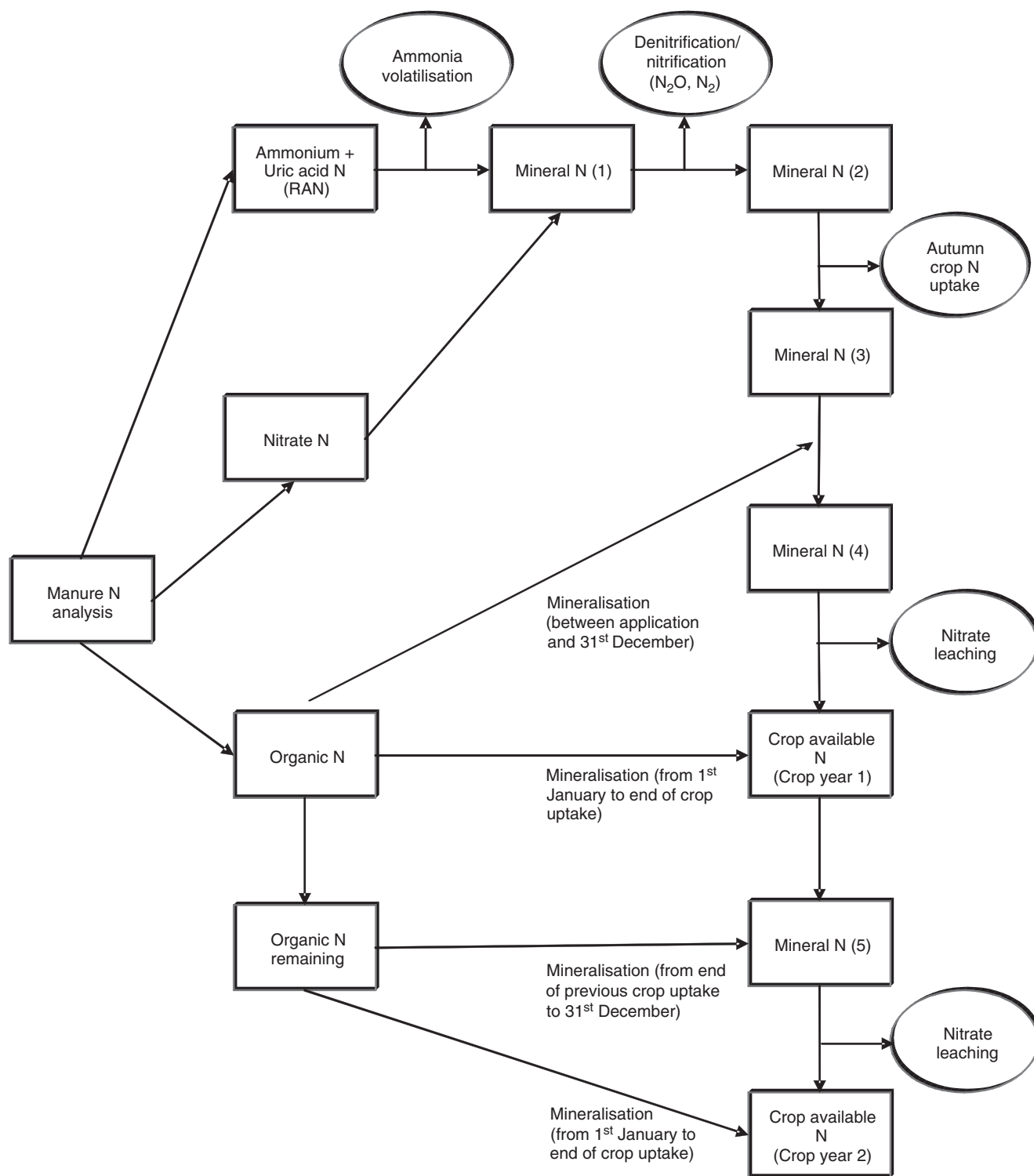
Figure 2 The MANNER-*NPK* conceptual model.

Soil incorporation technique affects ammonia emission mitigation efficiency and the subsequent emission rate, with the reduction in emission also dependent on manure type. Ammonia loss up to the time of soil incorporation (t) is calculated using the Michaelis–Menten equation (equation 1) with the K_m specified in Table 1, and an adjusted N_{max} value based on the manure type and soil incorporation technique (Table 2). Soil incorporation timings take into

Table 1 Michaelis–Menten equation parameters for the 4 'standard' ammonia loss curves

Standard curve	Measurements	N_{max} (%RAN applied)	K_m (h)
Cattle slurry[a]	42	32.4	7.5
Pig slurry[b]	5	25.5	11.6
FYM (cattle, pig and duck)[c]	8	68.3	14.9
Poultry manure[d]	11	52.3	40.4

[a]curve also used for dirty water, cattle slurry-based digestate and liquid-digested sludge, [b]curve also used for food and pig slurry-based digestate, and all categories of food 'waste', [c]curve also used for green and green/food compost, and paper crumble, [d]curve also used for digested sludge cake, thermally dried sludge, lime-stabilized sludge and composted sludge.

account the different shape of the standard emission curves (i.e. losses from poultry manure occur more slowly than from slurry and FYM). Ammonia emissions are assumed to continue after soil incorporation, albeit at a lower rate.

Nitrate leaching losses

The MANNER-*NPK* leaching module was enhanced to improve nitrate leaching loss predictions from freely drained sandy or silty soils where leaching occurs largely via matrix flow, and from poorly drained clay soils where leaching mainly occurs via bypass (crack) flow. These enhancements were based on data from field experiments quantifying nitrate leaching losses following a range of livestock manure applications to freely drained soils (e.g. Beckwith *et al.*, 1998; Chambers *et al.*, 2000) and poorly drained soils (e.g. Williams *et al.*, 2006).

Freely drained soils. Nitrate leaching algorithms were derived from the models of Burns (1974) and Addiscott (1977), which describe losses via matrix flow, with nitrate moving down with infiltrating water as it displaces soil water. The leaching curve for freely drained soils is bell-shaped, but 'stretches out' at higher hydrologically effective rainfall – HER values (Figure 4), where HER is defined as rainfall minus evapotranspiration. Approximately half of the nitrate placed at the soil surface will have leached beyond 90 cm depth when the volume of water (i.e. HER), which has passed through the overlying soil is equal to the water content of that soil (i.e. the volumetric moisture content - Vm) at field capacity (0.05 bar). Thus, leaching begins after about half of the soil Vm has been displaced and is largely complete after twice the Vm has been displaced. Due to differences in the soil Vm content, nitrate is lost more rapidly from sandy soils and (some) shallow soils over rock, compared with silty soils.

When manures are ploughed down or incorporated by discs or tines, the topsoil component of the Vm is reduced, to account for the reduced depth of soil through which the nitrate has to move. If there was a soil moisture deficit during the leaching calculation period, the HER is reduced by a factor of 0.7 of this deficit.

Poorly drained soils. In poorly drained (clay) soils, the infiltration capacity of the soil matrix is limited and much of the HER which subsequently reaches surface water systems will pass through the soil via cracks, mole channels and drains (i.e. via bypass flow), allowing incomplete equilibration with the soil matrix. MANNER-*NPK* simulates these losses using a simplified version of the EDEN model (Gooday *et al.*, 2008) using the HER and the volumetric moisture content as per the model for freely drained soils. The total nitrate lost from a poorly drained soil is predicted to be smaller than that lost from a freely drained soil, because a large part of the HER bypasses the soil matrix.

Nitrification. The rate at which manure ammonium-N is nitrified to nitrate-N is largely temperature driven and will affect the amount and timing of over-winter nitrate leaching losses. As a result, a 'nitrification delay' function has been incorporated into MANNER-*NPK* to account for delays in nitrate production (and therefore leaching). Using data from Bradbury *et al.* (1993), nitrification rates of manure ammonium-N were calculated on a monthly basis. The time taken for 50% of the ammonium-N to be nitrified was determined as this was assumed to be when leaching began (i.e. the majority of the ammonium-N had been nitrified into the 'mobile' nitrate form). For simplicity, MANNER-*NPK* 'adds' the time taken for 50% of the manure ammonium-N to be nitrified (depending on the month of application) to the manure application date.

Crop available N supply may also be influenced by immobilization of manure ammonium-N; for example, in laboratory experiments, Burger & Venterea (2008) found that 14–40% of applied manure ammonium-N was immobilized. However, there was not enough evidence from UK field experiments for immobilization processes to be included in this version of MANNER-*NPK*.

Hydrologically effective rainfall. Calculation of nitrate leaching requires an estimate of the amount of HER. A simple soil drainage model (as used in the PSYCHIC model; Davison *et al.*, 2008) calculates monthly values for rainfall, evapotranspiration and HER, and an end of drainage date for representative tillage land and permanent grassland situations under mean climate conditions at the selected site.
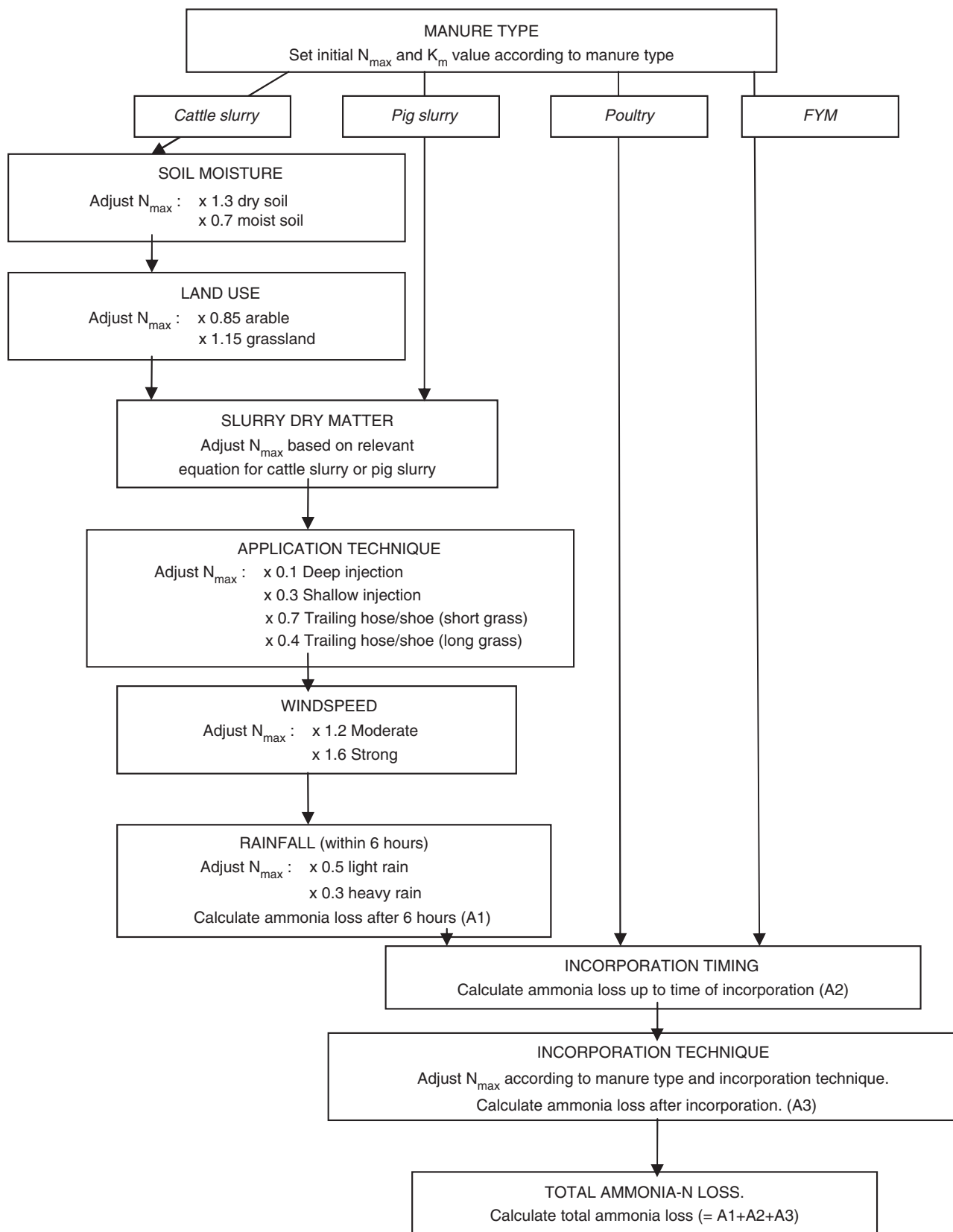
MANURE TYPE
Set initial N_{max} and K_m value according to manure type

Cattle slurry   *Pig slurry*   *Poultry*   *FYM*

SOIL MOISTURE
Adjust N_{max} :   x 1.3 dry soil
x 0.7 moist soil

LAND USE
Adjust N_{max} :   x 0.85 arable
x 1.15 grassland

SLURRY DRY MATTER
Adjust N_{max} based on relevant
equation for cattle slurry or pig slurry

APPLICATION TECHNIQUE
Adjust N_{max} :   x 0.1 Deep injection
x 0.3 Shallow injection
x 0.7 Trailing hose/shoe (short grass)
x 0.4 Trailing hose/shoe (long grass)

WINDSPEED
Adjust N_{max} :   x 1.2 Moderate
x 1.6 Strong

RAINFALL (within 6 hours)
Adjust N_{max} :   x 0.5 light rain
x 0.3 heavy rain
Calculate ammonia loss after 6 hours (A1)

INCORPORATION TIMING
Calculate ammonia loss up to time of incorporation (A2)

INCORPORATION TECHNIQUE
Adjust N_{max} according to manure type and incorporation technique.
Calculate ammonia loss after incorporation. (A3)

TOTAL AMMONIA-N LOSS.
Calculate total ammonia loss (= A1+A2+A3)

Figure 3 Decision support rules for the MANNER-*NPK* ammonia module.

Table 2 Soil incorporation technique and adjustment factor applied to N_{max}

Incorporation technique	Adjustment to N_{max}		
	FYM	Poultry	Slurry
Plough	0.1	0.05	0.1
Rotavator	0.2	0.1	0.15
Disc	0.3	0.2	0.2
Tine	0.7	0.3	0.3

The climate data were taken from a 5 × 5 km spatial resolution map for 1971–2000 (sourced from the Climate Research Unit, University of East Anglia) and interpolated to provide unique values for UK postcodes.

Manure organic N mineralization

Manure organic N mineralization is a microbially mediated process, with temperature an important driving factor (Swift *et al*., 1979). A number of workers have used temperature to predict organic N mineralization, where temperature was represented as thermal time, that is, cumulative day degrees (CDD) above 5 °C for soil temperatures at 10 cm depth (e.g. Douglas & Rickman, 1992; Clough *et al*., 1998).

In MANNER-*NPK*, field experimental data were used to derive relationships between net manure organic N mineralization and thermal time after application (Williams *et al*., 1998, 1999). Organic N mineralization curves, which have been shown to improve the accuracy of predicting manure organic N availability (e.g. Klausner *et al*., 1994), were produced for different manure types. Net organic N mineralization rates were found to be much greater up to 2300 CDD than after 2300 CDD; rates were linearly related to thermal time in both phases, but varied with manure type. The relationships fell into two broad groups, with pig slurry and poultry manure having a higher rate of organic N mineralization than cattle/pig FYM and cattle slurry.

Experimental data on organic N mineralization from other organic manure types (e.g. biosolids, digestates, composts) were not available. It was therefore assumed that N mineralization from these materials followed either the FYM/cattle slurry ('low' mineralization – compost, dirty water, cattle slurry-based digestate) or pig slurry/poultry manure ('high' mineralization – all biosolids types, food/pig slurry-based digestate, food 'waste') relationships.

Emissions of nitrous oxide and di-nitrogen

MANNER-*NPK* now includes estimates of N losses via denitrification and nitrification as N_2O and N_2. Although these losses are generally small in agronomic terms, N_2O is an important greenhouse gas with a global warming potential ca. 300 times greater than CO_2 (IPCC, 2007). The production of N_2O is predominantly carried out by nitrifying and denitrifying micro-organisms, with many management and soil factors influencing emissions following manure application to land (Granli & Bøckman, 1994).

Within the UK Greenhouse Gas Emissions Inventory, agricultural N_2O emissions are currently calculated using the Intergovernmental Panel on Climate Change (IPCC) methodology (IPCC, 1997). In the most recent IPPC methodology, direct manure N_2O emissions from soil following manure application, estimated using the Tier 1 IPCC default emission factor (EF), are based on total N applied (IPCC, 2006). However, Clemens & Ahlgrimm (2001) highlighted the importance of accounting for differing ammonia N losses following manure application.

The N_2O EF used in MANNER-*NPK* was derived from a database of field studies carried out between 1994 and 2003 on a range of grassland and arable sites in England (e.g. Misselbrook *et al*., 1998; Chadwick *et al*., 2000b; Thorman *et al*., 2003, 2006, 2007). Data were only included if the length of the measurement period was >21 days. However, the majority of EFs were generated from measurement periods of <90 days; so MANNER-*NPK* is likely to
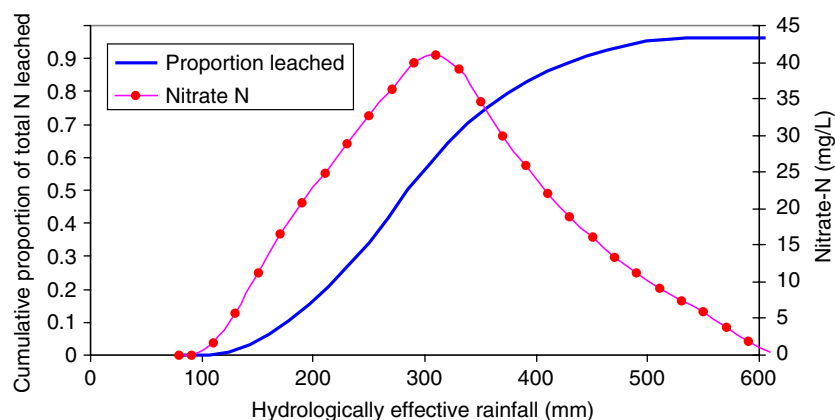
Figure 4 Nitrate leaching function for freely drained soils (assuming 100 kg/ha nitrate-N from applied manure).
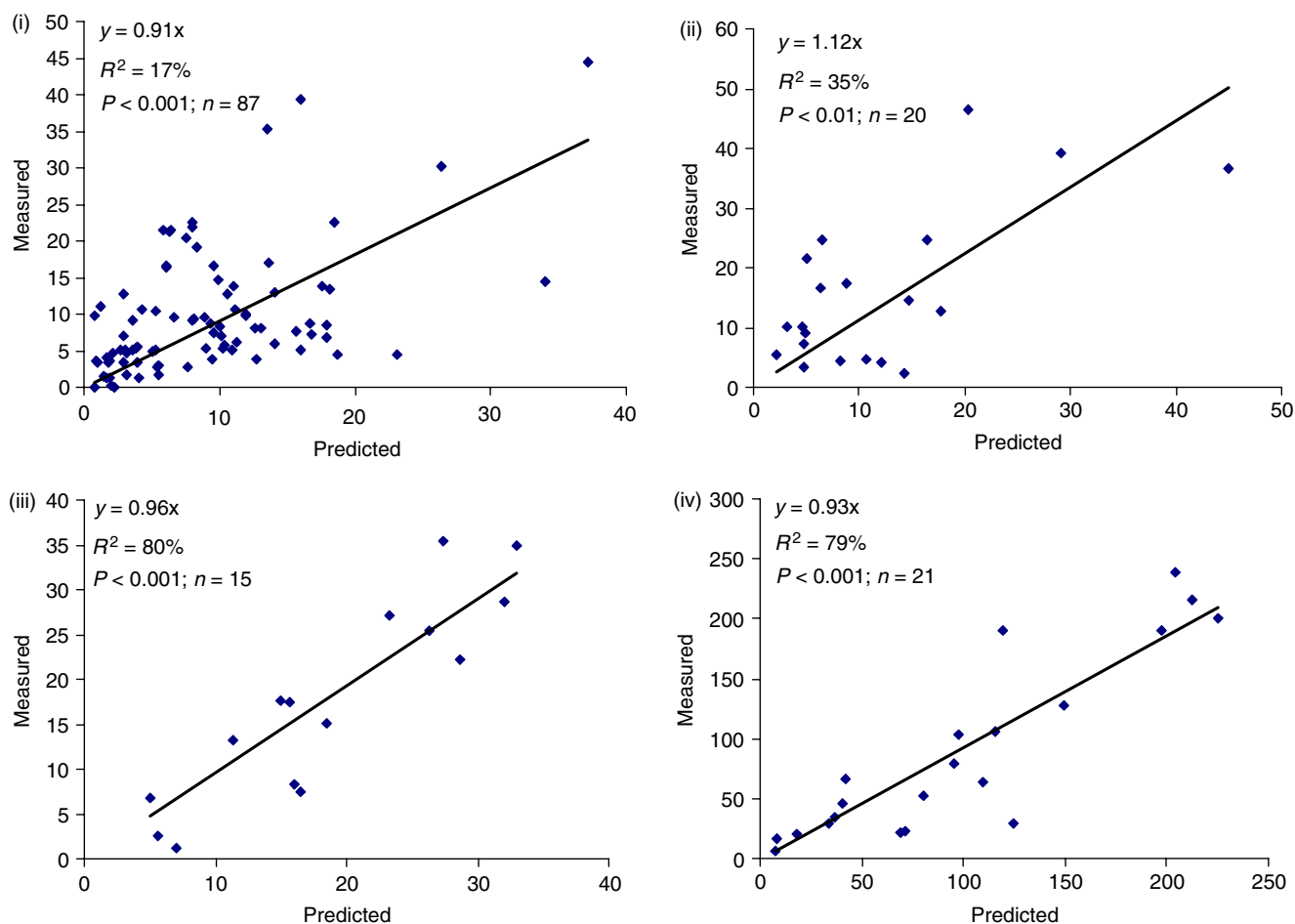
Figure 5 Predicted and measured ammonia emissions (kg N/ha) from (i) cattle slurry, (ii) pig slurry, (iii) farmyard manure and (iv) poultry manure.

underestimate N_2O emissions to some extent compared with whole-year emission measurements.

The EF following manure application was calculated from the amount of RAN remaining after NH_3 volatilization, assuming that N_2O emissions from organic N mineralization would be relatively small. There were no differences ($P > 0.05$) in EFs between manure types or between land uses, and no consistent effects of slurry application method or soil incorporation practice on N_2O emissions. Given the relative paucity of data and lack of consistency between studies, a single N_2O EF of ca. 2% of applied RAN remaining after ammonia volatilization loss was used. An $N_2:N_2O$-N loss ratio of ca. 3:1 (i.e. 3 times more N_2-N is lost than N_2O-N) was derived from a database containing results from 21 experimental studies where both N_2O and N_2 were measured following manure application (Ryden *et al.*, 1987). The N_2O-N and N_2-N EFs were applied to the RAN remaining after ammonia volatilization losses (Figure 2). Indirect N_2O losses (i.e. from nitrate leaching and redeposition of ammonia) were not considered as they do not affect the quantity of N available to a crop.

Autumn crop N uptake

Uptake of manure N by a crop established/growing after a late summer/autumn manure application will affect the amount of N potentially susceptible to over-winter loss by nitrate leaching. Generally, significant amounts of N will only be taken up by grassland, oilseed rape and early sown winter cereals, and autumn crop N uptake will effectively cease by the end of October. MANNER-*NPK* assumes that if manure was applied in late summer/autumn, then autumn crop N uptake, based on data published in Defra (2010), is subtracted from the amount of N potentially at risk from over-winter loss by nitrate leaching (Figure 2).

Crop N available in year 2

The release of manure organic N has been shown to continue at a low rate for a number of months/years after application (e.g. Williams *et al.*, 1998, 1999; Chadwick *et al.*, 2000a; Schröder *et al.*, 2007). MANNER-*NPK* estimates the N available to following crops by assuming that the N
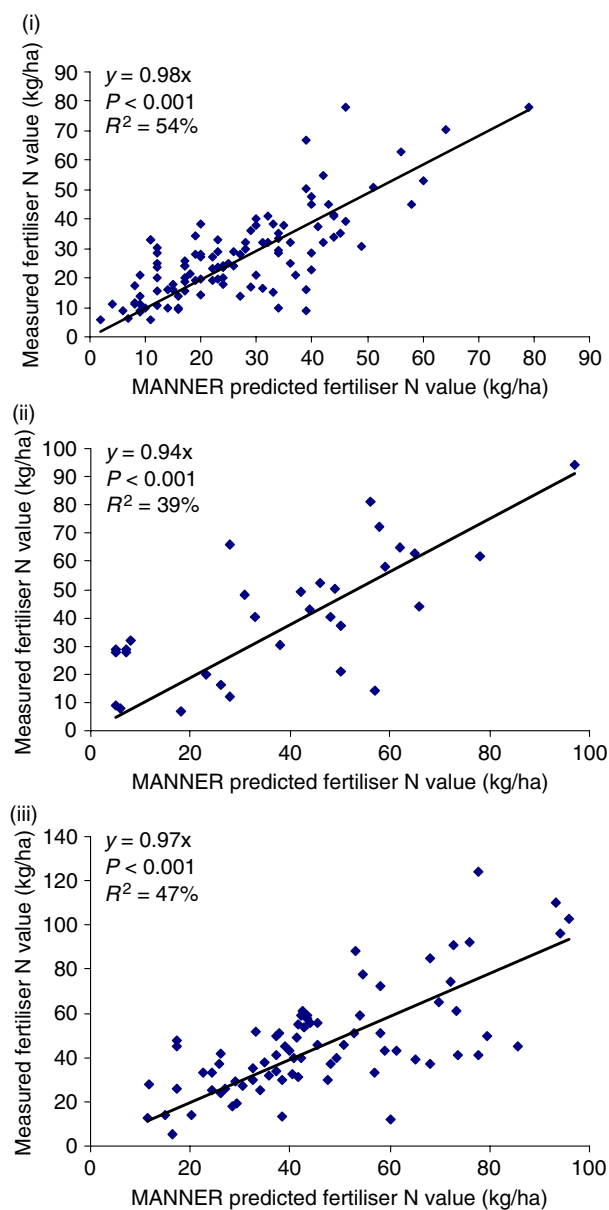
(i)

y = 0.91x
R² = 36%
P < 0.001

(ii)

y = 1.11x
R² = 39%
P < 0.001
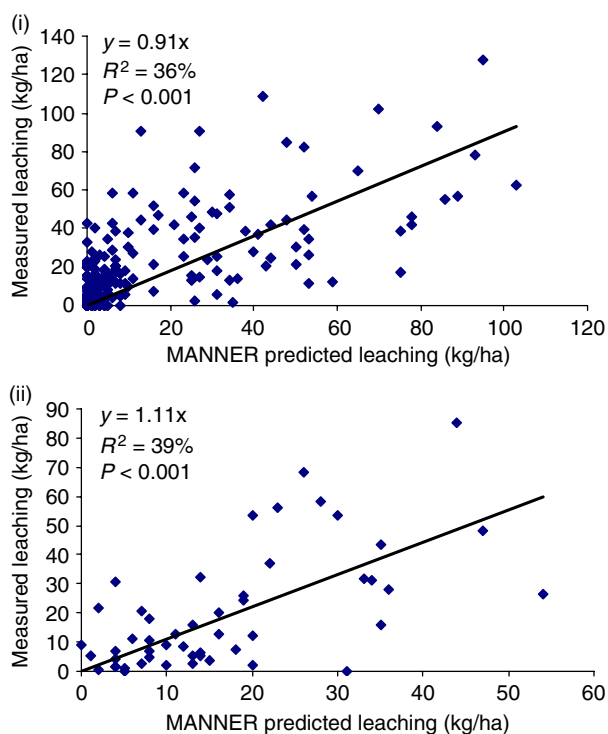
Figure 6 Predicted and measured nitrate leaching losses (kg N/ha from (i) freely drained soils and (ii) poorly drained soils.

(i)

y = 0.98x
P < 0.001
R² = 54%

(ii)

y = 0.94x
P < 0.001
R² = 39%

(iii)

y = 0.97x
P < 0.001
R² = 47%

Figure 7 Predicted and measured fertilizer N replacement values (kg/ha) for (i) cattle, (ii) pig and (iii) poultry manures.

released between the end of crop uptake in year 1 and the following 31st December is susceptible to loss by nitrate leaching, but that N released from 1st January onwards will not be leached. The N available to the following crop is the sum of these two components (assuming that there are no further losses from N_2O/N_2 emissions).

Model validation

Validation of the individual N modules was undertaken wherever suitable field experimental data were available to verify the accuracy of MANNER-*NPK* predictions. The data used covered a range of manure types, application and soil incorporation techniques/timings, soil types, crops and environmental conditions. Ammonia volatilization estimates were validated against data from >140 measurements undertaken between 1994 and 2001, where ammonia emissions had been measured using the micrometeorological mass balance technique (Misselbrook *et al.*, 2005). Estimates of nitrate leaching were validated against >250 measurements made between 1990 and 2006 (e.g. Beckwith *et al.*, 1998; Chambers *et al.*, 2000; Williams *et al.*, 2006), where nitrate leaching was measured using porous ceramic cups (freely drained soils) or from hydrologically isolated plots (poorly drained soils). Validation of crop available N predictions was undertaken using data from more than 200 field experimental studies (e.g. Chambers *et al.*, 1994, 1996;

Jackson & Smith, 1997) where manure fertilizer N replacement values had been quantified.

Enhancements to the user interface

Despite considerable modifications and improvements MANNER-*NPK* has retained the user-friendly design of earlier versions, whilst providing users with enhanced functionality. The requirements for extra data inputs are relatively minor and restricted to information that can be readily obtained (e.g. crop type, wind speed and soil moisture content).

Importantly, manure P, K, S and Mg analysis data can now be entered to provide a prediction of the total and crop available P (as P_2O_5), K (as K_2O), S (as SO_3) and Mg (as MgO) supply, based on figures published in the 'Fertiliser Manual (RB209)' (Defra, 2010), Figure 1.

Results and discussion

Ammonia emissions. Validation of MANNER-*NPK* ammonia volatilization predictions from each of the four manure type groups (i.e. cattle slurry, pig slurry, FYM and poultry manure) is shown in Figure 5. For each manure type group, the slope of the regression line was not significantly ($P > 0.05$) different from 1.0, indicating good agreement between predicted and measured ammonia emissions ($P < 0.01$).

Nitrate leaching. For both freely and poorly drained soils, the slope of the regression of MANNER-*NPK* predicted values against measured values was not significantly ($P > 0.05$) different from 1.0, indicating quantitative agreement between predicted and measured nitrate leaching losses (Figure 6). Furthermore, the relationship between the predicted and measured values was highly significant ($P < 0.001$).

Crop available N. Validation showed that for cattle, pig and poultry manures, relationships between predicted and measured fertilizer N replacement values were highly significant ($P < 0.001$), Figure 7. Also, the slope of the line was not significantly different from 1.0, indicating that MANNER-*NPK* predictions were robust ($R^2 = 54$, 39 and 47%, respectively).

To date, testing has been restricted to UK field situations; however, it should be possible to use the software in other temperate countries provided that suitable manure analysis and climate data (i.e. rainfall and evapotranspiration) are available.

Decision support tools such as MANNER-*NPK* are valuable in assisting farmers to assess the fertilizer value of their manures and the potential impact on the environment of different manure application practices. A recent review of decision support tools available in the EU (Cooper *et al.*, 2009) concluded that they must be easy to use and provide fertilizer recommendations that are reasonably accurate, with accuracy improved when they include actual measured values for certain parameters (e.g. manure total N). Furthermore, an effective decision support tool should allow farmers and advisors to investigate 'what if' scenarios, to see the impacts of changes in management on crop yields, profitability and the environment. MANNER-*NPK* has been designed to meet all these criteria.

Conclusion

An updated version of the MANNER decision support tool (MANNER-*NPK*) was developed incorporating improved research information on N losses and transformations following organic manure application to land. New modules were included to estimate N losses as nitrous oxide (via denitrification and nitrification) and di-nitrogen (via denitrification) and to estimate autumn crop N uptake that can decrease the amount of N at risk from nitrate leaching. Following user and stakeholder feedback, the software functionality was also extended to include predictions of crop P, K, S and Mg supply, and to present the results as both the fertilizer replacement (kg/ha) and economic (£/ha) value of manure applications.

Validation of the ammonia volatilization (cattle slurry, pig slurry, FYM and poultry manure) and nitrate leaching (freely drained and poorly drained soils) modules demonstrated good agreement ($P < 0.01$) between MANNER-*NPK* predicted and independently measured values. Similarly, MANNER-*NPK* predictions of crop available N supply from cattle, pig and poultry manures were in good agreement ($P < 0.001$) with measured values, indicating that MANNER-*NPK* provides a robust estimate of the fertilizer N replacement value of different types of farm manures spread under a range of conditions.

Acknowledgements

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