The nitrate leaching tool - technical reference

Chief Scientist's Group report

Date: May 2021

SC160010

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Professor Doug Wilson
Chief Scientist

Executive summary

This document provides the technical background to the Environment Agency's Nitrate Leaching Tool (NLT). The NLT is a spreadsheet-based tool that calculates the risk of nitrate leaching from agricultural land: arable crops and permanent pasture. The GIS database available to Environment Agency staff and contractors includes details of fields in England that are registered with the Rural Payments Agency, such as soil properties, land use and registered field areas. From this, data can be exported to a spreadsheet and additional field-scale data entered. Where the tool is being used by external users this information must be entered manually. The spreadsheet contains macros that use the input data to estimate the risk of nitrate leaching.

This document provides details of the data and calculations that underpin the tool. An accompanying document provides instructions on how to enter data and carry out calculations.

The NLT calculations operate in different ways for arable crops and grassland. Calculation of nitrate risk from arable land is built around the concept of a soil nitrogen balance: the difference between the sum of all sources of nitrogen applied to the soil such as fertiliser, soil nitrogen supply and atmospheric deposition, and the sum of all nitrogen removed from the soil, principally in crop offtake. Any surplus nitrogen is considered at risk of leaching. An estimate is then made of the proportion of this 'at-risk' nitrogen that leaches from the soil, as a function of soil properties and excess rainfall.

For grassland, estimates of nitrogen leaching are based on the N-CYCLE model, which predicts nitrate leaching as a function of soil type and drainage, fertiliser inputs and livestock type.

The tool can also simulate the application of a number of mitigation methods to reduce nitrate leaching.

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1 Introduction

The Nitrate Leaching Tool (NLT) is an Excel application that uses spatial data at a field-scale to predict the leached concentration of nitrate (NO3-) from agricultural land each year. The NLT is designed to be used on farms and fields, to identify fields and practices that present a high risk, and to engage with farmers and growers to reduce nitrate leaching. The tool is not appropriate for using as the basis of fertiliser recommendations.

The calculation methods in the tool are simple, and do not simulate every detail of nutrient management. The tool provides a rapid assessment of the risk of nitrate leaching under typical management conditions, rather than a detailed, mechanistic calculation of soil nitrogen cycling.

The simple basis of the calculations means that the tool can easily and quickly calculate results in the field or on the go. The assumptions underpinning the various calculations and choice of parameter values are presented in this document, together with implications for the applicability of the tool.

The output from the NLT of average annual concentrations of leached nitrate does not capture the typical peaks and troughs of concentrations observed in field data taken from the base of the soil zone throughout the year. However, in most groundwater systems the recharge processes naturally result in some degree of mixing of water. Therefore, the average concentrations adequately represent those concentrations reaching the groundwater table in all but the most rapid responding catchments.

1.1 Purpose of this document

This document sets out the technical background to the Nitrate Leaching Tool (version 9 or later), which is an Excel workbook for predicting nitrate loadings and concentrations in drainage waters from agricultural land. It is not intended as a user guide, which is the subject of a separate document.

The following sections of the report describe the technical basis of the calculations underpinning the Nitrate Leaching Tool (NLT).

2 Calculation of nitrogen leached for arable and vegetable crops

The calculation of nitrate leaching for arable and vegetable crops broadly follows the method developed by Anthony and others (1996) in the NEAP-N model. The conceptual framework has two parts:

- estimation of the residual soil mineral nitrogen (residual N) at risk of leaching in a sufficiently wet winter (after crop harvest in the autumn but before winter)1,
- calculation of the fraction of residual N that is leached subsequently through soil drainage over the winter period. The fraction of residual N leached is estimated as a function of soil field capacity and the hydrologically effective rainfall (HER)

2.1 Calculation of residual N for arable and vegetable crops

The NLT calculates residual N for arable and vegetable crops using a soil nitrogen budget approach, which is the balance of additions (fertiliser, manure, atmospheric deposition, biologically fixed by leguminous crops) and losses (offtake from the immediately preceding crop). The simplified balance of inputs and outputs is shown in Equation 1.

The main calculations are carried out within the NLT in VBA Procedure (‘ArableSMNsub’) in Module (‘ArableSMN’). Losses other than offtake, such as by microbial mineralisation and volatilisation, are not explicitly considered, but may be implicitly accounted for in some of the annual additions such as from manure application, for example by a reduction in the assumed N content of manure to account for losses during storage and spreading.

Equation 1: Residual N for arable and vegetable crops

$$N_{res} = I_f + I_m + I_{atm} + I_{bio} + I_s - L_{crop}$$

Where

N_{res}	Residual N after harvest (kg N ha^{-1})
I_f	Annual addition of manufactured fertiliser, including autumn and spring applications (kg N ha^{-1}) [See section 2.1.1]
I_m	Annual addition of organic manure including up to two separate applications (kg N ha^{-1}) [See section 2.1.2]

[1] In southern and western England, this is typically in October, but it can be later in other parts of the country. For example, in eastern England the onset of winter drainage is typically in mid-November.

I_{atm}	Annual addition from atmospheric deposition (kg N ha^{-1}) [See section 2.1.3]
I_{bio}	Biological nitrogen fixation by legume crops (kg N ha^{-1}) [45, See section 2.1.4]
I_s	Soil nitrogen supply based on previous cropping (kg N ha^{-1}) [80, See section 2.1.5]
L_{crop}	Offtake of nitrogen by previous crop (kg N ha^{-1}) [See section 2.1.6]

2.1.1 Addition of manufactured fertiliser (I_f)

The default values in the NLT for annual fertiliser additions are presented in Table 2.1. They can be reviewed and changed in column C in worksheet ('Templates'). Default values for the different land-uses (according to crop type) are taken from the British Survey of Fertiliser Practice 2017 (Defra 2018) unless otherwise noted. The range of fertiliser applications, based on minimum and maximum recommended requirements from the Fertiliser Manual RB209 (AHDB 2019), are used to sense-check user input.

Table 2.1: Default values for manufactured fertiliser application (I_f) according to land-use (mainly crop-type) and range of recommended values (Defra 2018 and AHDB 2019)

Land Use	Nitrogen application rate (kg N ha^{-1})	
	Default	Range (min – max)
Arable: Asparagus	120 [1]	0 – 150
Arable: Brussels sprouts and cabbage	94	0 – 330
Arable: Cauliflower	94	0 – 290
Arable: Forage maize	72	0 – 150
Arable: Onions	110 [4]	0 – 160
Arable: Potatoes	136	0 – 270
Arable: Fodder beet	110 [4]	0 – 130
Arable: Spring rye or triticale	128	0 – 140
Arable: Ryegrass (seed)	85 [2]	0 – 160
Arable: Spring barley	103	0 – 160
Arable: Spring oats	101	0 – 140
Arable: Spring oilseed rape or linseed	85	0 – 150
Arable: Spring sown grass	128 [5]	0 – 370
Arable: Spring wheat	132	0 – 210
Arable: Sugar beet	96	0 – 120
Arable: Winter barley	152	0 – 220
Arable: Winter oats	101	0 – 190
Arable: Winter oilseed rape	181	0 – 220
Arable: Winter wheat	188	0 – 280
Veg: Beans [3]	0	0
Veg: Brussels sprouts	94	0 – 330
Veg: Bulb onions overwintered	85	0 – 160
Veg: Bulb onions spring	85	0 – 130
Veg: Calabrese	94	0 – 235
Veg: Carrots	85	0 – 100
Veg: Cauliflower (over winter)	94	0 – 190
Veg: Cauliflower summer	94	0 – 290
Veg: Collards post Dec 31	94	0 – 310
Veg: Collards pre Dec 31	94	0 – 210
Veg: Head cabbage post Dec 31	94	0 – 240
Veg: Head cabbage pre Dec 31	94	0 – 325
Veg: Leeks	85	40 – 200
Veg: Lettuce (crisp)	85	30 – 200

Land Use	Nitrogen application rate (kg N ha^{-1})	
	Default	Range (min – max)
Veg: Peas [3]	0	0
Veg: Radish	85	0 – 100
Veg: Swede	85	0 – 135
Veg: White cabbage storage	94	0 – 340

Notes

1. Based on the requirement for subsequent years after establishment (AHDB 2019).
2. Based on the average requirement for the crop type at a Soil Nitrogen Supply (SNS) Index of 1 or 2 (light sand soil) or SNS index 2 or 3 (other mineral soils) (AHDB 2019).
3. Leguminous arable crops that do not require manufactured fertiliser (AHDB 2019).
4. RB209 recommended rate for SNS Index of 2 (AHDB, 2019).
5. Rate for grass established <5 years.

2.1.2 Addition of organic manure (I_m)

Organic manure applied to agricultural land adds useful amounts of organic matter and nutrients to soils, including nitrogen (AHDB 2019). Nitrogen in manure is present as readily available nitrogen (ammonium, nitrate and uric acid) and organic nitrogen. The latter is broken down slowly and becomes potentially available for crop uptake over a period of months to years. For the purposes of the nitrogen balance assessment, only the readily available nitrogen in applied manure is included in the annual addition (Im).

Equation 2: Annual addition of manure

$$I_m = \sum A \times N_t$$

Where

I_m Annual addition of manure (kg N ha^{-1})

A Annual application rate for each type of manure (t ha^{-1} FW or m^3 ha^{-1})

N_t Readily available nitrogen content for each type of manure (kg N t^{-1} FW or kg N m^{-3}) [See Table 2.2]

Table 2.2: Range of organic manure types and readily available nitrogen content (Nt) according to the Fertiliser Manual RB209 (Defra 2011), and, for reference, crop available N (RB209, AHDB 2019)

Manure type	Readily available N (kg N t^{-1} FW or kg N m^{-3})	Crop available N (kg N t^{-1} FW or kg N m^{-3})
Fresh cattle FYM	1.2	0.6
Old cattle FYM	0.6	0.6
Fresh pig FYM	1.8	0.7
Old pig FYM	1.0	0.7
Fresh sheep FYM	1.4	0.7
Old sheep FYM	0.7	0.7
Fresh duck FYM	1.6	0.65
Old duck FYM	1.0	0.65
Poultry litter	9.5	4.75
Broiler/turkey litter	10.5	4.75
Cattle slurry (2% DM)	0.9	0.48
Cattle slurry (6% DM)	1.2	0.65

Manure type	Readily available N (kg N t^{-1} FW or kg N m^{-3})	Crop available N (kg N t^{-1} FW or kg N m^{-3})
Cattle slurry (10% DM)	1.3	0.72
Cattle slurry liquid only (1.5% DM)	0.8	0.45
Cattle slurry liquid only (3% DM)	1.0	0.6
Cattle slurry liquid only (4% DM)	1.5	0.9
Cattle slurry solid only (20% DM)	1.0	0.4
Pig slurry (2% DM)	2.2	1.2
Pig slurry (4% DM)	2.5	1.26
Pig slurry (6% DM)	2.8	1.32
Pig slurry liquid only (3% DM)	2.2	1.368[1]
Pig slurry solid only (20% DM)	1.3	0.5
Biosolids (digested liquid)	0.8	0.825[2]
Biosolids (digested cake)	1.6	1.65
Biosolids (thermally dried)	2.0	6
Biosolids (lime stabilised)	0.9	1.275
Biosolids (composted)	0.6	1.65

1. Value estimated by interpolation between the figures for 2% DM and 4% DM pig slurry

2. Assumed equal to half the value for digested cake, as per RB209 (Defra, 2011)

Note that Table 2.2 shows both readily available nitrogen and crop available nitrogen contents of manure. The NLT uses the readily available nitrogen (RAN) figures from RB209 (Defra, 2011) rather than revised figures from RB209 (AHDB, 2019), which are expressed in terms of crop available nitrogen. This is because crop available nitrogen is a measure of the nitrogen content of manure after accounting for any losses, for example through volatilisation or leaching. Using crop available nitrogen will underestimate the nitrogen at risk of leaching. Instead, the NLT estimates the nitrogen content of manure on the basis of RAN. This produces a maximum estimate of the nitrogen at risk from leaching since losses of nitrogen from the manure due to volatilisation of ammonia are not accounted for[2].

2.1.3 Addition from atmospheric deposition (I_{atm})

Atmospheric dry and wet nitrogen deposition rate (Iatm) in kg N ha^{-1} varies across the country according to a number of factors, including the presence of local point sources such as power plants and other heavy industry. The NLT uses a rate taken from maps of total nitrogen deposition (dry and wet) developed by CEH (2016). From the 5km resolution CEH maps, average values have been estimated for each 100km OS grid square.

The default value determined from the farm's grid reference can be found in cell G2 on worksheet ('Actual Land Use') and after the data has loaded the user can change it. A typical total deposition rate for England is 12kg N ha^{-1} (Defra 2012).

[2] Losses from volatilisation are highly variable and depend on the manure type, method of application, whether the manure is incorporated into the soil, soil type and other factors.

2.1.4 Addition by biological nitrogen fixation (I_{bio})

Leguminous arable crops such as combining peas (*Pisium sativum*) and field beans (*Vicia faba*) are able to fix nitrogen in the soil directly from the atmosphere (Baddeley and others 2013). Crop residues of legumes contain some of the nitrogen that they have fixed, and this becomes available to subsequent crops. These residues are just as likely to contribute to leaching or nitrous oxide release as any other crop residue. The amount of biologically fixed nitrogen varies widely depending on crop type and growing conditions, especially the amount of biomass and available soil nitrogen.

Baddeley and others (2013) estimated the amount of nitrogen fixed by these two crops to be 62.4kg N t^{-1} for beans and 40.2kg N t^{-1} for peas. Using the default yields for each arable crop (see Table 2.4 in section 2.1.6), this corresponds to an annual addition by biological nitrogen fixation (I_{bio}) of 224.6kg N ha^{-1} for beans and 140.7kg N ha^{-1} for peas.

The default I_{bio} values for beans and peas used in the NLT are, therefore, 224.6kg N ha^{-1} and 140.7kg N ha^{-1} respectively. It can be found in column P in worksheet ('Templates') and can be overwritten by a user specified value.

2.1.5 Soil nitrogen supply (I_s)

The soil nitrogen supply (SNS) is determined from the SNS Index for each field as shown in Table 2.3. Further information on the definition and use of SNS Index can be found in the Fertiliser Manual RB209 (AHDB 2019).

The default value for the SNS Index for each field is 1 for all land-uses (see column K in worksheet ('Templates'). The SNS value in kg N ha^{-1} is calculated from the SNS Index for each field in the VBA Procedure ('ArableSMNsub') in Module ('ArableSMNsub').

Table 2.3: Predicted soil nitrogen supply (kg N ha^{-1}) based on SNS Index (AHDB 2019)

SNS Index	Range (AHDB 2019)	Default (kg N ha^{-1})
0	0 – 60	0[1]
1	61 – 80	60
2	81 – 100	80
3	101 – 120	100
4	121 – 160	120
5	161 – 240	160
6	>240	240

[1] Introduced as an option (Nov 2015) to accommodate very low leaching land uses. It is not based on a specific reference.

2.1.6 Nitrogen crop offtake (I_{crop})

In the nitrogen balance (see Equation 1), the only explicit losses from the soil-plant system are from crop offtake. This is the nitrogen stored in fruits, shoots, grains, and roots that are harvested and removed from the soil. Offtake depends on two factors: the amount of nitrogen stored in harvested plants and the crop yield.

The NLT uses a different approach for arable crops, including cereals, oilseed rape, potatoes, fodder, and leguminous vegetables, and vegetable crops.

2.1.7 Arable crops

Equation 3 sets out the calculation of nitrogen offtake (L_{crop}) for arable crops. In the NLT, this is done within VBA Procedure ('ArableSMNsub') in Module ('ArableSMN'). There are two required parameters: crop yield (Y) and the nitrogen coefficient (Cp). The default values by crop type are set out in Table 2.4 and are discussed below.

The fresh weight (FW) crop yield in t FW ha^{-1} is taken primarily from Nix (2015). The default values can be found in column AA of the worksheet ('Templates') and can be overwritten by the user.

Nitrogen coefficients (kg N t^{-1} FW) [3] are used to represent the nitrogen content of harvested crops (Eurostat 2011). Nitrogen budget data is submitted by member states and collated at a European level. These coefficients are widely recognised as a significant area of uncertainty in our understanding of the soil nitrogen balance (Eurostat 2013). The nitrogen coefficients are the ten-year average (2000 to 2009) for data submitted by the UK, with some values approximated by crop type as noted in the table (Eurostat 2011). The default values by crop type can be found in column B in worksheet ('List Options').

Equation 3: Nitrogen losses via crop offtake for arable crops

$$L_{crop} = \sum C_p \times Y$$

Where

L_{crop}	Offtake of nitrogen by previous crop (kg N ha^{-1})
C_p	Nitrogen coefficient for the content in edible crop (kg N t^{-1} FW) [see Table 2.4]
Y	Crop yield (t FW ha^{-1}) [See Table 2.4]

Table 2.4: Crop yields and nitrogen coefficients used to calculation arable crop offtake (Nix 2015, Eurostat 2011)

Land use	Crop yield t FW ha^{-1}	Nitrogen coefficient kg N t^{-1} FW
Arable: Asparagus	n/a	2 [1]
Arable: Brussels sprouts and Cabbage	n/a	5 [2]
Arable: Cauliflower	12	5 [2]
Arable: Forage maize	40	3 [3]
Arable: Onions	41	4 [4]
Arable: Potatoes	45	3
Arable: Fodder beet	85	2 [4]
Arable: Rye or triticale	5.6	16
Arable: Ryegrass (seed)	1.3	26 [5]
Arable: Spring barley	5.45	15
Arable: Spring oats	5.5	16
Arable: Spring oilseed rape or linseed	2	38 [6]
Arable: Spring sown grass	38 [7]	26 [5]
Arable: Spring wheat	5.75	21
Arable: Sugar beet	70	2

[3] It has been assumed that the Eurostat 2011 figures are as fresh weight (FW) since the report does not specify.

Arable: Winter barley	6.9	15
Arable: Winter oats	6.3	16
Arable: Winter oilseed rape	3.4	30
Arable: Winter wheat	8.3	21
Veg: Beans	3.6	42
Veg: Peas	3.5	35

Notes
1. Value for leafy and stalked vegetables excluding brassicas (Eurostat 2011).
2. Value for brassicas (Eurostat 2011).
3. Value for green maize (Eurostat 2011).
4. N coefficient is a typical value for fodder beet (Eurostat 2011).
5. Value for temporary and permanent pasture consumption (Eurostat 2011).
6. Value for linseed. Oil seed rape is 30kg N t^{-1} FW (Eurostat 2011).7. Source: The Anderson Centre (2015): https://www.jic.ac.uk/media/cms_page_media/ 2015/7/27 /Potential%20of%20UK%20Pulses_Andersons-FINAL_240615.pdf
7. Based on a typical DM yield of 9.5 t/ha and 25%DM content of silage (after RB209, AHDB 2019).

2.1.8 Vegetable crops

Equation 4 sets out the calculation of nitrogen offtake (Lcrop) for arable crops. In the NLT, this is done within the VBA Function (‘Vegetable Offtake’) in Module (‘Functions’). The key difference with the arable offtake calculation is that the nitrogen coefficient (%N DW) is calculated by an empirical relationship, which also requires that crop yields are corrected from fresh weight to a dry matter basis. The approach is described in section 6 of the Fertiliser Manual RB209 (AHDB 2019). It is important to note that this is not necessarily the crop nitrogen offtake as it is nitrogen uptake by the whole plant.

Equation 4: Nitrogen losses via crop offtake for vegetable crops

$$L_{crop} = \sum \frac{a \times (1 + b \times e^{-0.26 \times \frac{Y}{F_y}})}{100} \times \frac{Y}{F_y} \times 1000\ kgt^{-1}$$

Where

L_{crop}	Offtake of nitrogen by previous crop (kg N ha^{-1})
a	Empirical parameter controlling shape of the curve (unitless) [See Table 2.5]
b	Empirical parameter controlling shape of the curve (unitless) [See Table 2.5]
Y	Crop yield (t ha^{-1} FW) [See Table 2.5]
F_y	Conversion factor for fresh weight crop yield to dry matter crop yield (t FW t^{-1} DM) [See Table 2.5]

The default parameters for estimating the nitrogen content of the vegetable crops (a, b and the F_y) are set out in columns C to E in worksheet (‘List Options’) and are taken from Appendix 10 in the Fertiliser Manual RB209 (AHDB 2019). F_y is calculated as the ratio of the fresh market yield (t FW ha^{-1}) divided by total dry matter (t DM ha^{-1}). Fresh weight crop yields (Y) in t FW ha^{-1} are primarily based on the fresh market yields reported in section 6 of the Fertiliser Manual RB209 (AHDB 2019), with any exceptions noted in the table. The default values are stored in column O in worksheet (‘Templates’) and can be overwritten by the user.

Table 2.5: Parameters for estimating nitrogen offtake by vegetable crops (Defra 2011)

Land use	a	b	FW to DM t FW t^{-1} DM	Yield t FW ha^{-1}
Vegetable (Brussels sprouts)	2.50	3.50	1.53	20.3
Vegetable (White cabbage storage)	2.55	0.80	7.53	110.0
Vegetable (Head cabbage pre Dec 31)	2.55	0.80	5.56	60.0
Vegetable (Head cabbage post Dec 31)	2.55	0.80	5.30	53.0
Vegetable (Collards pre Dec 31)	3.45	0.60	3.92	20.0
Vegetable (Collards post Dec 31)	3.45	0.60	4.41	30.0
Vegetable (Cauliflower over winter)	3.45	0.60	1.48	12 [1]
Vegetable (Calabrese)	1.80	3.50	1.63	16.3
Vegetable (Cauliflower summer)	3.45	0.60	4.50	30.6
Vegetable (Lettuce crisp)	2.60	1.10	9.48	45.5
Vegetable (Radish)[2]	0.81	7.00	17.9	50.0
Vegetable (Bulb onions spring)	1.20	3.50	6.44	60.5
Vegetable (Bulb onions over winter)	1.20	3.50	6.44	60.5
Vegetable (Leeks)	2.00	4.00	3.98	47.0
Vegetable (Swede)	1.35	1.87	5.30	84.8
Vegetable (Carrots)	0.82	7.00	2.98	63.1

Notes

1. Value from Nix (2015).
2. Data for radish are inferred from data in Nendel and others (2009). 'a' and 'b' coefficients are based on those for carrots, and, therefore, there is less confidence in the data

2.1.9 Annual loss to denitrification

To account for the fact that nitrate can be denitrified and lost to the atmosphere, the NLT includes a term for denitrification of inorganic fertiliser. This term has a default value of 0% and is open for the user to view and edit, at the top of the 'Actual Land Use' tab, similar to the atmospheric deposition value. Ideally, the importance of this term should be a function of soil properties (how freely the soil drains) as denitrification is most significant in wet and heavy soils (Dunn and others, 2004). However, the NLT base data currently only contains limited soils data to make well-founded estimations that could be used on a field scale in the NLT. The denitrification value (%) will be applied to all fields. It is conservative, in the absence of strong evidence to the contrary, to assume that no denitrification will occur (that is, to retain the default value of 0%).

Environment Agency (2005) presents a literature survey of denitrification in the unsaturated zones of principal UK aquifers, and found that rates were typically low in the Cretaceous Chalk (1.5%-2%) and Permo-Triassic Sandstone (0.3%-2%).

2.2 Mitigation methods

For arable and vegetable crops, mitigation measures to reduce the residual N can be applied pre-harvest and post-harvest to individual fields. More than one measure can be applied to each field. Data on the effectiveness of each mitigation method is obtained from Newell Price and others (2011). The NLT includes 23 measures for arable and vegetable crops (pre- and post-harvest) as summarised in Table 2.6. These are stored in columns I, J, and K in worksheet ('List Options').

Table 2.6: Mitigation measures for arable and vegetable crops

Mitigation measure	Notes	Mitigation effectiveness (%)	
		Arable and vegetable crops (pre-harvest)	Arable and vegetable crops (post-harvest)
4: Plant autumn cover crops		100	50
5: Early harvest and establishment		100	70
6: Spring not autumn cultivation		65	100
7: Reduced cultivation		80	100
12: Maintain SOM levels		120	100
16: Allow drainage to deteriorate		80	100
17: Improve drainage		130	100
18: Maintain ditches		120	100
20: Plant N-efficient crops		90	100
21: Calibrate fertiliser spreader	f	95	100
22: Use fertiliser recommendations	f	95	100
23: Integrate fertiliser and manure	f, m	90	100
25: Avoid high risk areas (fertiliser)	f	98	100
26: Avoid high risk times (fertiliser)	f	95	100
27: Use fertiliser placement	f	98	100
28: Use nitrification inhibitors	f	65	100
29: Replace urea with ammonium nitrate	f	95	100
67: Calibrate manure spreader	m	95	100
69: Avoid high risk times (slurry)	m	80	100
72: Avoid high risk times (FYM)	m	95	100
Undersowing of maize		85[1]	100[1]

<u>Notes</u>
f – applies only to fields applying manufactured fertiliser
m – applies only to fields applying manure
1 – Value from Whitmore and Schroeder (2007)

Each mitigation measure in Table 2.6 is assigned an efficiency value as a percentage based on Newell Price and others (2011). Values greater than 100% indicate an increase in the autumn soil mineral nitrogen content of the soil, and values less than 100% indicate a reduction.

The efficiency of multiple measures is treated as multiplicative. For example, the combined effect of measure A (70% efficiency) and measure B (50% efficiency) is 35% efficiency (70 x 50 / 100 = 35%). Barraclough (2014) noted that "... while there is some empirical evidence for the effect of single mitigation options, at present there is no evidence to support the approach adopted [in the NLT] for multiple options."

The adjusted residual N for arable and vegetable crops is undertaken in VBA Procedure ('ArableSMNsub') in Module ('ArableSMN') as described by Equation 5.

There are a number of additional rules applied to the outcome of Equation 5. These are:

- the adjusted residual N (kg N ha^{-1}) after the use of **<u>pre-harvest</u>** mitigation measures cannot be less than 20kg N ha^{-1} (section 2.2.1)

- post-harvest mitigation methods are applied after the effect of pre-harvest measures has been calculated and these may reduce the residual N to zero

Equation 5: Adjusted residual N to take account of mitigation measures

$$N_{res,adj} = N_{res} \times \sum \frac{M_1 \times M_2 \ldots M_n}{100}$$

Where

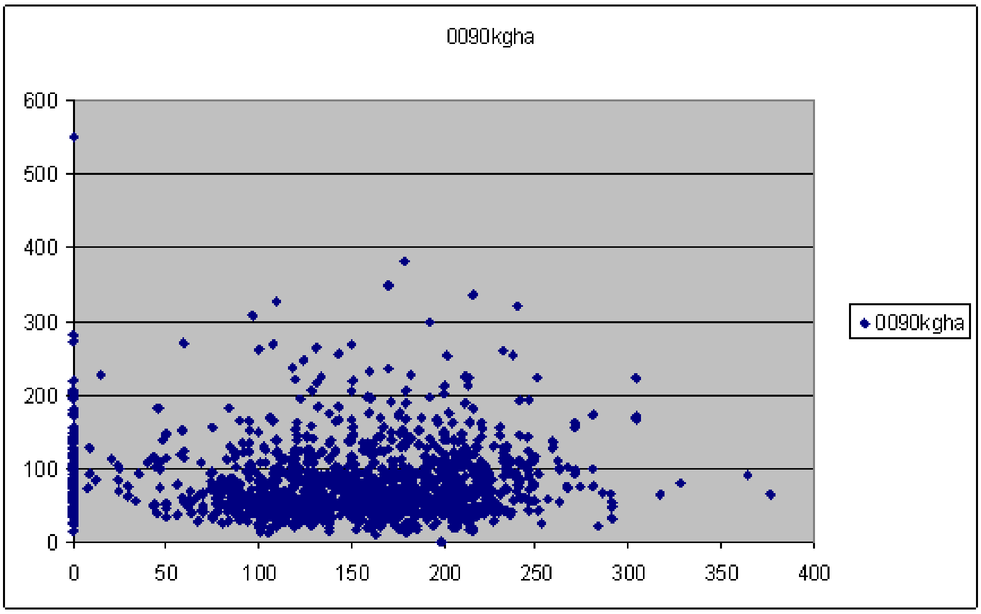
$N_{res,adj}$	Residual N after accounting for mitigation measures (kg N ha^{-1})
N_{res}	Residual N based on nitrogen balance (kg N ha^{-1}) [See Equation 1]
M_n	One or more mitigation efficiencies (%) for pre- and post-harvest [See Table 2.6]

2.2.1 Minimum residual N levels under arable cultivation

The NLT sets a minimum limit on the residual N achievable by applying multiple pre-harvest mitigation options. At present, this is set as 20kg N/ha based on ADAS data of residual nitrogen under arable cultivation, which rarely drops below this value as shown in Figure 2.1. It should be noted that the Environment Agency does not have access to the original data; only a picture of the resulting graph, which is shown below.

This minimum residual N limit for pre harvest mitigation options is hardcoded into the NLT as the constant ‘MinArResidualN’ in the Macro ArableSMNSub.

Figure 2.1: Residual N under arable cultivation



While pre-harvest mitigation options cannot reduce residual N below 20kg N/ha, post-harvest options such as the planting of autumn cover crops may reduce the adjusted soil mineral nitrogen content to zero. There is no such minimum residual level for grasslands.

2.3 Area adjusted residual N

After the effect of pre- and post-harvest mitigation methods have been taken into account, the NLT adjusts the residual N for each field for the amount of uncultivated headland. It estimates a weighted area average by assuming that the headland has a residual N of 10kg N ha^{-1} (Barraclough, personal communication) regardless of land-use (the variable 'BackgroundN').

Equation 6 is used to derive an area adjusted residual N for each field in VBA Procedure ('ArableSMNsub') in Module ('ArableSMN'). Headland area for each field is estimated using the empirical relationship in Equation 7, which according to Barraclough (2014) is derived from data for 117,000 fields in southern England (Barraclough, personal communication.). The default headland width of 6m is used for all arable and vegetable crops. It is found in column D of worksheet ('Templates') and can be overwritten by the user.

Equation 6: Area adjusted residual N

$$N_{res,area} = \frac{\left((A_f - A_h) \times N_{res,adj}\right) + (A_h \times N_{res,hd})}{A_f}$$

Where

$N_{res,area}$	Area adjusted residual N after harvest (kg N ha^{-1})
A_f	Total area of field (ha) [GIS data for each field]
A_h	Area of headland (ha) [See Equation 7]
$N_{res,adj}$	Residual N after accounting for mitigation measures (kg N ha^{-1}) [see Equation 5]
$N_{res,hd}$	Residual N for headlands (kg N ha^{-1}) [10, after Barraclough (personal communication)]

Equation 7: Area of headland

$$A_h = \frac{W_h}{6} \times 0.2521 \times A_f^{\,0.5426}$$

Where

A_h	Area of headland (ha)
W_h	Width of the uncultivated headland (m) [6]
A_f	Total area of field (ha) [GIS data for each field]

2.4 Proportion of residual N leached

For arable and vegetable crops, the proportion of residual N leached from soil is calculated in the NLT using the approach from NEAP-N (Anthony and others 1996, Lord and Anthony 2000, Addiscott 1991). Lord and Anthony (2000) proposed that the quantity of nitrate potentially leached from soil was a function of the ratio between excess rainfall and soil water content at field capacity to a depth of 90cm. These calculations are presented in VBA Function ('NLeach') in Module ('Functions').

Anthony and others (1996) described the approach in more detail. They used the Solute Leaching Intermediate Model (SLIM) developed by Addiscott (1991) to simulate nitrate leaching losses from field drains at 90cm depth for a range of soil textures and soil nitrate contents. The nitrate content at the onset of drainage was distributed between three 30cm layers in the ratio 2:1:1 as depth increased. The proportion of the soil nitrate leached during each model run was plotted on a graph as a function of increasing drainage efficiency (ε), defined as the ratio of cumulative drainage to the soil water content at field capacity. Anthony and others (1996) found that the proportion of soil nitrate lost was approximately the same for all soil textures for any value of ε and for any initial soil nitrate content. Nitrate leaching losses calculated by SLIM could, therefore, be predicted by Equation 8 and 9. Lord and Anthony (2000) termed this the SLIMMER algorithm.

Equation 8: Proportion of residual N leached Anthony and others **(1996)**

$$P = 1.111 \times \varepsilon - 0.203\varepsilon^3 \qquad where\ \varepsilon \leq 1.35$$

$$P = 1.0 \qquad where\ \varepsilon > 1.35$$

Where

P	Proportion of residual N leached
ε	Soil drainage efficiency (-) [See Equation 9]

Equation 9: Drainage efficiency

$$\epsilon = \frac{h}{\varphi}$$

Where

ε	Soil drainage efficiency (-)
h	Cumulative soil drainage (mm) [NLT uses the hydrologically effective rainfall (HER) from GIS data for each field]
φ	Soil field capacity (mm) [GIS data for each field]

Note that Anthony and others (1996) concluded that the long-term mean annual hydrologically effective rainfall (HER) was equivalent to drainage, and this has been used in the NLT. Barraclough (2014) stated that the proportion of residual N leached was calculated directly by the NLT using the NEAP-N algorithm. However, the empirical parameters (see Equation 10) are different from the original equation (see Equation 8) as they are reportedly derived from analysis of Figure 2 in Lord and Anthony (2000).

Equation 10: Proportion of residual N leached as implemented (after Lord and Anthony 2000)

$$P = 0.01 \times (121.03 \times \varepsilon - 34.516\varepsilon^2) \qquad where\ \varepsilon \leq 1.35$$

$$P = 1.0 \qquad where\ \varepsilon > 1.35$$

Where

P	Proportion of residual N leached (fraction)
ε	Soil drainage efficiency (-) [See Equation 6]

The amount of nitrogen lost from soil is calculated in Equation 11.

Equation 11: Amount of nitrogen lost from soil

$$L_{n,area} = P \times N_{res,area}$$

Where

$L_{n,area}$	Nitrogen leached from field (kg N ha^{-1})
P	Proportion of residual N leached (fraction) [See Equation 7]
$N_{res,area}$	Area adjusted residual N after harvest (kg N ha^{-1}) [See Equation 6]

Note that hydrologically effective rainfall includes soil drainage that will ultimately become recharge to groundwater, drainage that moves laterally in the subsurface ('interflow') and will ultimately contribute to flow in streams or rivers and surface run-off. The NLT does not attempt to predict the proportion of HER that follows each of these possible pathways.

3 Calculation of nitrogen leached for grassland

Crop yields and nitrogen offtake are rarely known in grassland cropping, so the NLT tool uses the approach from the Nitrogen Cycle (N-Cycle) model developed by David Scholefield at North Wyke Experimental Station (Scholefield and others 1991). N-Cycle simulates the cycling of nitrogen in grassland systems grazed by livestock and is constructed from empirical data from ten field systems grazed by beef cattle. The Environment Agency has reproduced the original model as an Excel workbook for internal use with the kind permission of North Wyke.

3.1 N-CYCLE overview

The N-Cycle model is shown in Figure 2.1. It predicts the annual amount of nitrogen in livestock liveweight gain, and the amounts lost through ammonia volatilisation, denitrification, and leaching, on the basis of fertiliser application and soil and site characteristics.

Scholefield and others (1991) considered the following inputs and outputs:

- inputs to soil-nitrogen (annual flux) included fertiliser nitrogen, atmospheric nitrogen, net mineralisation from soil and dead plant material, livestock urine nitrogen, and a quarter of the dung nitrogen

- outputs from soil-nitrogen (annual flux) included plant uptake nitrogen, ammonia volatilisation, denitrification and leaching

Note that N-Cycle provides direct predictions of nitrate leaching, not residual nitrogen at risk of leaching, and, therefore, the leaching algorithm used in arable scenarios (see section 2.4) is not applied to the output from the N-Cycle model.

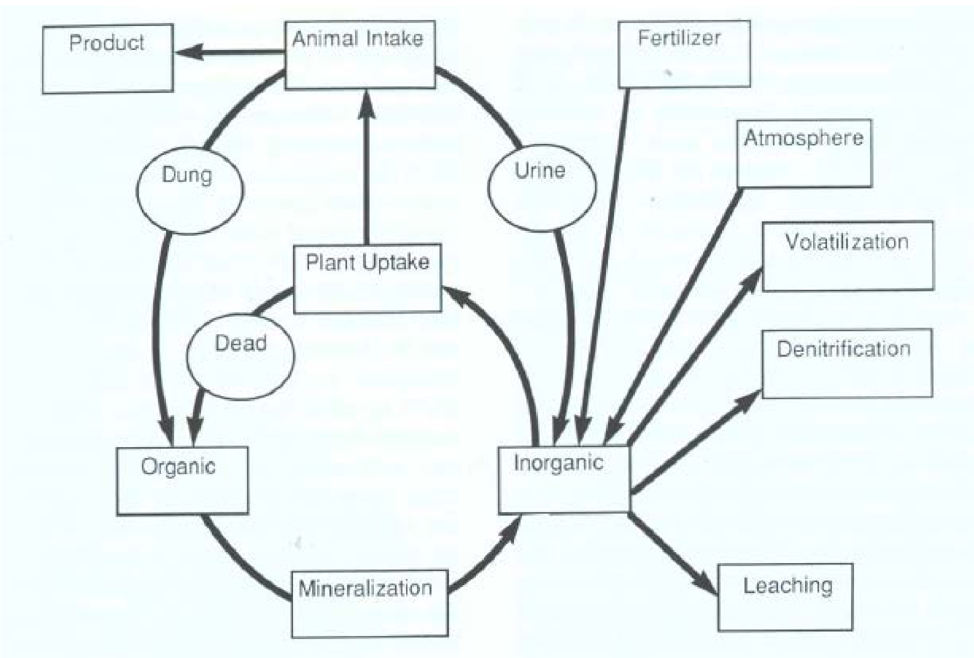


Figure 2.1: Schematic of the transformations and flows in N-Cycle (Scholefield and others 1991)

The model inputs included a wide range of factors that affect soil mineralisation of organic nitrogen including (Scholefield and others 1991):

- previous cropping history and sward age
- soil texture and drainage characteristics
- climatic conditions

Users could also specify important human-influenced (anthropogenic) inputs, including the application rate of manufactured fertilisers and the atmospheric deposition of nitrogen.

Outputs from the model indicated that fertiliser inputs had a strong influence on ammonia volatilisation, denitrification and leaching at a given site but that, over a range of sites with a given fertiliser rate, total nitrogen loss and the proportions lost by the three processes were greatly influenced by the amount of nitrogen mineralised by the soil (Scholefield and others 1991).

3.1.1 Baseline scenario (no grazing)

Barraclough (2014) proposed using N-Cycle to develop a baseline relationship between applied fertiliser (kg N ha^{-1}) and leached nitrogen (kg N ha^{-1}) for a grassland scenario without animal grazing (where there are no losses from grazing or returns from dung/urine). The N-Cycle model was run in batch mode for varying fertiliser application rates between 0 and 400kg N ha^{-1} for each climate zone (1, 2, and 3), soil-type (sand, loam and clay) and drainage class (good, moderate and poor). An example output is shown in Figure 2.2.

The following conditions were fixed for all baseline scenarios:

1. an atmospheric deposition rate of 25kg N ha^{-1}
2. long-term grassland cropping history
3. sward age over 20 years

Baseline scenario outputs were summarised as a series of polynomial regression curves as illustrated in Equation 12. Table 2.7 presents the parameters for each scenario included in the NLT. The combinations of soil type and drainage class were simplified from 9 to 3: sandy soil with good drainage, loam soil with moderate drainage, and clay soil with poor drainage. These polynomials are stored on worksheet (‘NCycle’).

Equation 12: Leached nitrogen from applied fertiliser for baseline scenario

$$L_{n,b} = \left(A \times {I_f}^2\right) + \left(B \times I_f\right) + C$$

Where

$L_{n,b}$	Amount of nitrogen leached in baseline scenario (kg N ha^{-1})
A	Empirical fitted coefficient (see Table 2.7)
B	Empirical fitted coefficient (see Table 2.7)
C	Empirical fitted coefficient (see Table 2.7)
I_f	Annual addition of manufactured fertiliser in kg N ha^{-1} **(see section 3.1.7)**

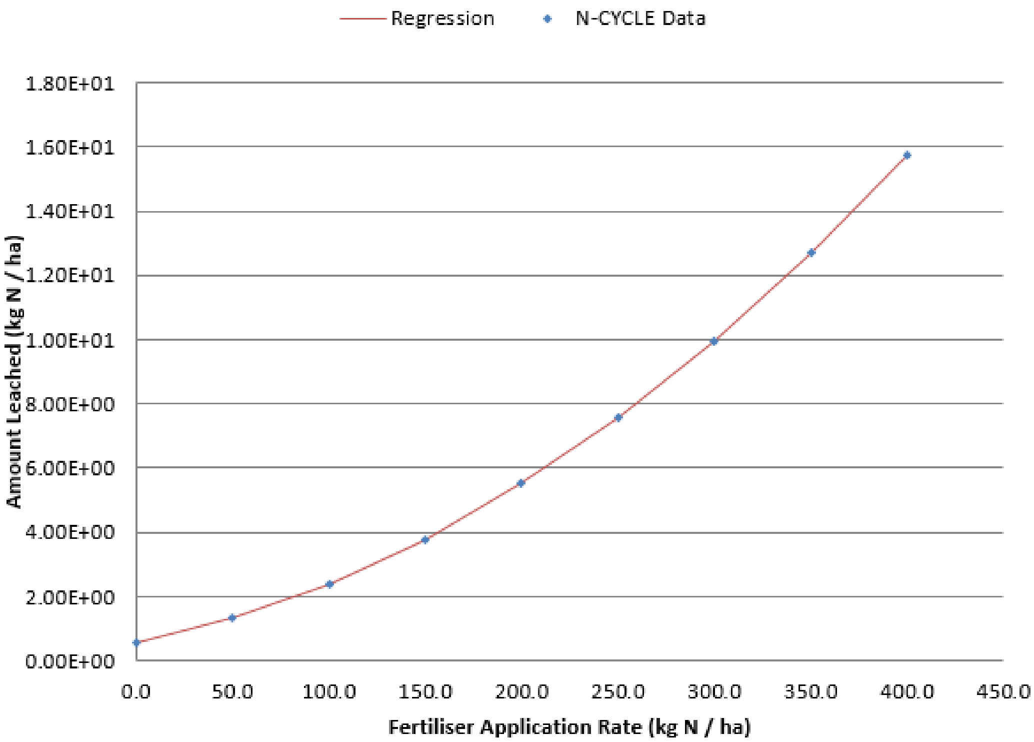


Figure 2.2: Example baseline scenario showing the relationship between fertiliser application rate and the amount of nitrogen leached from soil (kg N ha^{-1})

Table 2.1: Polynomial parameters for predicting nitrogen leaching (kg N ha^{-1}) from a grassland system (no grazing) for different climate zones and soil/drainage classes by varying fertiliser application rate

	Climate zone								
	1			**2**			**3**		
	A	B	C	A	B	C	A	B	C
Sand-Good	0.000310	0.0764	5.41	0.000304	0.0635	3.87	0.000298	0.0512	2.61
Loam-Moderate	0.000192	0.0518	3.98	0.000188	0.0427	2.81	0.000184	0.0341	1.87
Clay-Poor	0.0000675	0.0135	0.786	0.0000661	0.0114	0.581	0.0000652	0.0094	0.412

3.1.2 Scenarios for beef and dairy cattle grazing

In the original N-Cycle model (Scholefield and others 1991), livestock grazing was assumed to be a closed system (that is, all excreta from animals, including dung and urine were assumed to be returned to the field soil). For the purposes of the NLT, the model was further interrogated to distinguish between the baseline condition (no grazing) and the additional contribution made to the amount of nitrogen leached through returned excreta. The advantage of this is being able to take into account different farming practices such as directly applying stored manure on the nitrogen leached.

Running the model in batch mode as before (see section 3.1.1), the amount of nitrogen leached for a given fertiliser application was determined for both a dairy and beef grazing system. The difference between the amounts leached for these livestock systems and the baseline no grazing scenario was determined by subtraction for each fertiliser application, assuming that the additional amounts leached were due livestock excreta returning to the soil. By also recording the amount of nitrogen returned to the soil by excreta for each fertiliser application, the ratio of the difference in amounts leached to excreted nitrogen was calculated. This ratio was determined to be the fraction of excreta at risk from leaching (F_{risk}), and was found to vary with fertiliser application rate and scenario (that is, it differed between beef and dairy systems, by climate zone, and by soil type and drainage class). See Figure 2.3 for an example.

Baseline scenario outputs were summarised as a series of polynomial regression curves as illustrated in Equation 13. Tables 2.8 and 2.9 present the parameters for beef and dairy systems respectively for each scenario included in the NLT. The combinations of soil type and drainage class were simplified from 9 to 3: sandy soil with good drainage, loam soil with moderate drainage, and clay soil with poor drainage. These polynomials are stored on worksheet ('NCycle').

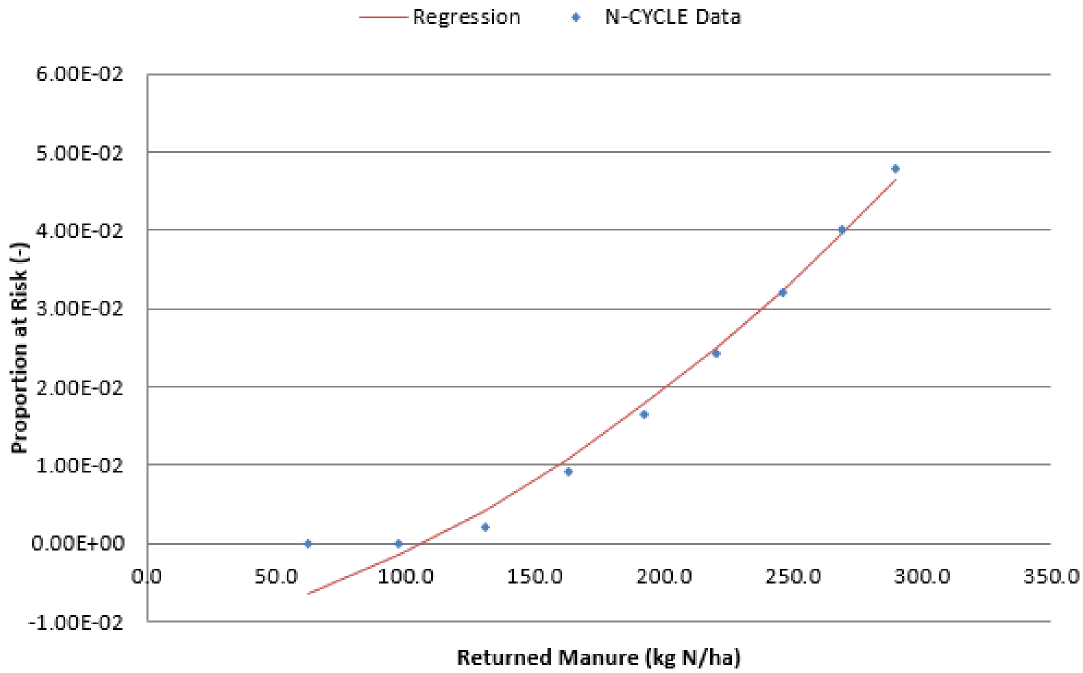


Figure 2.3: Example scenario showing the relationship between excreta rate calculated by N-Cycle (kg N ha^{-1}) and the fraction of animal excreta at risk of leaching (-)

Equation 13: Fraction of livestock excreta at risk of leaching for a given scenario

$$F_{risk} = \left(A \times {I_e}^2\right) + (B \times I_e) + C$$

Where

F_{risk}	Fraction of excreta at risk from leaching (-)
A	Empirical fitted coefficient (see Tables 2.8 and 2.9)
B	Empirical fitted coefficient (see Tables 2.8 and 2.9)

C Empirical fitted coefficient (see Tables 2.8 and 2.9)

I_e Annual return of livestock excreta from outdoor grazing cattle in kg N ha^{-1} **(see Section 3.1.8)**

Table 2.2: Polynomial parameters for predicting the fraction of animal excreta at risk of leaching (-) for a beef cattle grazed grassland system for different climate zones and soil/drainage classes (Sandy – Good, S-G; Loam-Moderate, L-M; and Clay-Poor, C-P) by varying excreta rate

	Climate zone								
	1			**2**			**3**		
	A	B	C	A	B	C	A	B	C
S-G	2.05×10^{-6}	-7.47×10^{-5}	-8.53×10^{-3}	1.65×10^{-6}	5.40×10^{-5}	-1.22×10^{-2}	1.57×10^{-6}	6.25×10^{-5}	-1.22×10^{-2}
L-M	1.38×10^{-6}	-7.39×10^{-5}	-8.53×10^{-3}	1.00×10^{-6}	5.40×10^{-5}	-1.22×10^{-2}	9.44×10^{-7}	6.25×10^{-5}	-1.22×10^{-2}
C-P	4.20×10^{-7}	1.31×10^{-5}	-8.53×10^{-3}	3.22×10^{-7}	5.40×10^{-5}	-1.22×10^{-2}	2.28×10^{-7}	6.24×10^{-5}	-1.22×10^{-2}

Table 2.3: Polynomial parameters for predicting the fraction of animal excreta at risk of leaching (-) for a dairy cattle grazed grassland system for different climate zones and soil/drainage classes (Sandy – Good, S-G; Loam-Moderate, L-M; and Clay-Poor, C-P) by varying excreta rate

	Climate zone								
	1			**2**			**3**		
	A	B	C	A	B	C	A	B	C
S-G	3.64×10^{-6}	-2.43×10^{-4}	-1.22×10^{-2}	3.60×10^{-6}	-2.42×10^{-4}	-1.22×10^{-2}	3.49×10^{-6}	-2.25×10^{-4}	-1.22×10^{-2}
L-M	1.98×10^{-6}	-5.88×10^{-5}	-1.22×10^{-2}	1.91×10^{-6}	-4.97×10^{-5}	-1.22×10^{-2}	1.83×10^{-6}	-4.04×10^{-5}	-1.22×10^{-2}
C-P	5.26×10^{-7}	5.40×10^{-5}	-1.22×10^{-2}	4.83×10^{-7}	6.24×10^{-5}	-1.22×10^{-2}	4.42×10^{-7}	6.96×10^{-5}	-1.22×10^{-2}

3.1.3 Outdoor pigs and lowland sheep

The N-CYCLE model that forms the basis of the NLT calculations of nitrate leaching from cut and grazed grassland systems does not include calculations of losses from land under outdoor pigs or lowland sheep. The Farmscoper model does, however, include a parameterisation of leaching from outdoor pigs and lowland sheep, from which levels of residual N have been calculated and used in the NLT to predict residual N at risk of leaching (pre soil calculation).

Outdoor pigs and lowland sheep were introduced into the NLT following as closely as possible the calculations and assumptions of the Farmscoper model[4]. The approach used in Farmscoper is not available in published literature, therefore, a range of scenarios were run to derive a set of empirical coefficients from the Farmscoper algorithm.

Farmscoper estimates the leaching from outdoor pigs and lowland sheep as the sum of a baseline rate of leaching from ungrazed pasture, and additional leaching from inorganic fertiliser applications, as well as from dung and urine from grazing animals. The proportion of nitrogen in inorganic fertiliser and the amount produced by grazing animals that is assumed to leach is constant.

Nitrogen production by grazing animals is calculated according to the stocking density (that is, the number of livestock per hectare of grassland) and the annual nitrogen production per head of livestock. Default values are given in columns S to V of worksheet ‘Templates’ in the NLT. Nitrogen production is then reduced pro rata, according to the duration of the livestock grazing period. For example, if the livestock graze for seven months of the year, annual nitrogen production is calculated as seven twelfths of total production.

As with N-Cycle, Farmscoper provides predictions of nitrate leached, not residual N at risk of leaching. However, Farmscoper predictions of nitrate leached do vary with rainfall. Leaching in Farmscoper will reach its maximum not within the wettest rainfall band but in the moderate (900-1200mm) rainfall band, since Farmscoper assumes that farms in the wettest areas will be less intensive and denitrification may be more likely.

In the NLT, the coefficients of the worst-case scenario have been used, that is the highest amount of nitrogen that can leach from a given quantity of residual N at risk. It is assumed that in this worst-case scenario, all residual N that is at risk will leach (that is, the fraction leached is 1) and, therefore, the residual N is equal to the predicted leached N.

In the NLT, to simulate the reduction in leaching in lower rainfall areas, the NEAP-N leaching algorithm has been applied to this ‘worst-case’ output from Farmscoper, in the same way as for arable scenarios (see section 2.4). Note that this is not the same approach as was used with the N-Cycle model for dairy and beef scenarios, in which the leaching algorithm is not applied to the output from the N-Cycle model.

Box 1 shows an illustration of the calculation of coefficients for baseline (soil) leaching and leaching from dung and urine from outdoor pigs. The actual field set-up is clearly not realistic, but variables have been chosen to illustrate the method and for clarity.

Box 1: Illustration of calculation of coefficients for outdoor pigs.

Calculations are based on Farmscoper predictions for:

- a field of 1ha under permanent pasture
- free draining soil
- 10 sows in pig and other sows
- 900-1200mm annual rainfall

[4] http://www.adas.uk/Service/farmscoper

From this scenario, Farmscoper predicts nitrate leaching from soil of 4.07kg/ha. This is the baseline rate of leaching from ungrazed pasture. This baseline rate varies with rainfall, and is highest for the 900-1200mm rainfall rate used here.

Farmscoper predicts leaching losses from pigs (voided) of 40.8kg/ha (medium term) and 20.4kg/ha (long term), giving a total leaching loss from pigs of 61.2kg/ha. The total N produced by a sow is assumed to be 21.5kg N/year, and so the total N stocking density for 10 pigs is 215kg N/ha/year (note that Farmscoper uses slightly different coefficients for N production by livestock from the NLT). The proportion of N produced by pigs that is leached is, therefore, 61.2/215, or 28.5%. This proportion does not significantly vary between rainfall bands.

Table 2.10 shows all coefficients used in the NLT (not visible in the user interface), based on Farmscoper 3.0 (ADAS, 2015) using the worst-case rainfall zone (900 – 1200mm). How these coefficients are used to predict the amount of leached nitrate is described in detail in section 3.1.9.

Table 2.4: Coefficients derived from Farmscoper for estimating nitrate leaching from outdoor pigs and lowland sheep

Land use	N production (kg N/ animal/ yr)	Baseline Leaching from Permanent Pasture (kg N/ha)	Proportion of applied fertiliser N assumed to leach	Proportion of applied N in dung and urine from animals assumed to leach	Proportion of applied manure N assumed to leach
Outdoor pigs	18[1]	4.05	7.94%	28.5%	35%
Lowland sheep	12.3	4.05	7.94%	6.1%	35%

1. Average value from range of pig types

3.1.4 Grassland (dairy and beef) leaching of nitrogen within NLT

Previous sections described the theoretical background to calculating nitrogen leaching from dairy and beef system grasslands. The aim of this section is to describe how this is used within the NLT.

In the NLT, the leaching of nitrogen from grassland is assumed to be the sum of the baseline (no grazing scenario) plus additional contributions from applied manures (determined from the fraction of excreta at risk). See Equation 14.

Equation 14: Leached nitrogen from grassland scenario

$$L_n = L_{n,b} + \{F_{risk} \times (I_e + I_m)\}$$

Where

L_n Amount of nitrogen leached (kg N ha^{-1})

$L_{n,b}$ Amount of nitrogen leached from soil in baseline scenario in kg N ha^{-1} (**see Equation 12**)

F_{risk} Fraction of excreta at risk from leaching (**see Equation 13**)

I_e Annual return of livestock excreta from outdoor grazing animals in kg N ha^{-1} (**see section 3.1.8**)

I_m Annual addition of manure in kg N ha^{-1} (**see section 2.1.2**)

Note that the assumed additional contribution from animal excreta and organic manure cannot be less than zero (although the polynomial regressions behind F_{risk} may generate a negative value). Where F_{risk} is negative, the NLT sets the additional contribution to zero. The grasslands calculations are undertaken in VBA Procedure ('NCycleLeaching') in Module ('NCycle').

The choice of polynomial curves from Tables 2.7, 2.8, and 2.9 depend on soil-type/drainage class and climate zone for the fields assessed as set out in sections 3.1.5 and 3.1.6. Other required parameters, including fertiliser application rate and animal excreta returned are also described in sections 3.1.7 and 3.1.8 respectively.

3.1.5 Soil type and drainage class

Three combinations of soil type and drainage class are available in the NLT. Which one is used in the grassland calculations depends on the Standard Percentage Runoff (SPR) for each field as shown in Table 2.11. SPR is included in the NLT BaseData geodataset and is derived from the National Soil Map NATMAP dataset (LandIS, 2013). NATMAP data is the flagship soil data product from the National Soil Research Institute.

Table 2.5: Relationship between standard percentage run-off (SPR) and combination of soil type and drainage class for use in grassland scenarios

SPR (%)	Soil type – drainage class
< 30	Sand – Good (S-G)
30 < SPR > 60	Loam – Moderate (L-M)
> 60	Clay – Poor (C-P)

In most cases, it is expected that the user will have some additional information on soil type and drainage. In these circumstances, the user can replace the default SPR values in the BaseData worksheet (column H).

3.1.6 Climate zone

N-Cycle used three climate zones mapped on to the UK to define the parameters for soil mineralisation of nitrogen (Scholefield and others 1991). Zone 1 covers southern England and coastal Wales, and represents relatively warm and dry areas. Zone 2 covers the remainder of lowland England and Wales. Zone 3 represents cooler and wetter upland areas including the Pennines and Welsh mountains.

The appropriate zone for estimating nitrogen leaching from grasslands is selected in the NLT based on the grid reference of the first field in worksheet ('Base Data'). The data for this estimate is stored in worksheet ('NCycle'). The selected value is displayed in cell L2 in worksheet ('Actual Land Use') and can be overwritten by the user.

3.1.7 Annual addition of manufactured fertiliser (I_f)

The annual addition of manufactured fertiliser to grassland is required to estimate the baseline level of nitrogen leached (see Equation 12). The default values in the NLT for annual fertiliser additions are presented in Table 2.12. They can be reviewed and changed in column X in worksheet (‘Templates’). Default values for the different grassland uses are taken from the British Survey of Fertiliser Practice 2014 (Defra 2015). The range of fertiliser applications, based on minimum and maximum recommended requirements from the Fertiliser Manual RB209 (Defra 2011), are used to sense-check user input.

Table 2.6: Default values for manufactured fertiliser application (I_f) according to different grassland scenarios and range of recommended values (Defra 2011 and 2015)

Land use	Nitrogen application rate (kg N ha^{-1})	
	Default	Range (min – max) [1]
Grass: Beef	91	0 – 370
Grass: Dairy cut and grazed	156	0 – 370
Grass: Dairy grazed	156	0 – 340
Grass: Silage	164	0 – 370

Notes

1. Based on the requirement for a good or very good Grass Growth Class (Defra 2011).

3.1.8 Annual return of livestock excreta from outdoor grazing animals (Ie)

The annual return of livestock excreta (kg N ha^{-1}) is required to calculate the fraction of excreta at risk (F_{risk}) in Equation 13 and to estimate the total amount of nitrogen leached from a cattle grazed grassland system (see Equation 14). The annual return is a function of livestock type, stocking rate and grazing period and is modelled using Equation 15. The calculation is undertaken in VBA Procedures (‘NProduction’) and (‘NCycleLeaching’) in Module (‘NCycleLeaching’).

Equation 15: Addition of livestock excreta from outdoor grazing animals

$$I_e = 0.9 \times n \times R_e \times T \times \frac{1}{12} year\ month^{-1}$$

Where

I_e	Annual return of livestock excreta from outdoor grazing animals (kg N ha^{-1})
n	Livestock density (number of animals ha^{-1}) **[See Table 2.12]**
R_e	Amount of nitrogen excreted per animal (kg N per animal per year) **[See Table 2.12]**
T	Outdoor grazing period (months) **[See Table 2.12]**

Equation 15 assumes that during the grazing period, 10% of excreted nitrogen is lost by volatilisation of urea (therefore, the factor of 0.9). This figure is based on the assumption by Scholefield and others (1991) that volatilisation reduces the nitrogen content of cattle urine by 15% and that urine contributes around 70% of the nitrogen excreted.

The default values for beef and dairy grassland systems are presented in Table 2.13 and are found in columns R to V in worksheet (‘Templates’) and in columns O and Q in worksheet (‘List Options’). The amount of nitrogen excreted per animal is based on estimates for a large dairy cow and a large suckler provided by ADAS in supporting paper F2 for the consultation on implementing the Nitrate Directive (Defra 2007). Livestock density is based on the upper bound estimates of stocking level for beef and dairy systems as described in the Fertiliser Manual RB209 (Defra 2011).

Table 2.7: Default values for the amount of nitrogen excreted per animal (Re), livestock density (n), and outdoor grazing period (T) for different grassland scenarios

Land use	R_e kg N yr^{-1} $animal^{-1}$	n animals ha^{-1}			T months
		Low	Medium	High	
Grass: Beef	92	0.83	2.00	3.17	7 (grazed) 5 (1 cut) 4 (2 or 3 cuts)
Grass: Dairy cut and grazed	117	2.00	2.60	3.10	5 (1 cut) 4 (2 or 3 cuts)
Grass: Dairy grazed	117	2.00	2.60	3.10	7

3.1.9 Outdoor pigs and lowland sheep nitrogen leaching in the NLT

This section describes the implementation of the coefficients, whose development is described in section 3.1.3, to estimate nitrate leaching from outdoor pigs and lowland sheep systems.
In the NLT, leaching from outdoor pigs and lowland sheep is estimated according to equation 16.

Equation 16: Calculation of nitrate leaching from outdoor pigs and lowland sheep

$$N_{res} = L_{n,b} + \left(F_{risk,m} \times I_m\right) + \left(F_{risk,f} \times I_f\right) + \left(F_{risk,e} \times I_e\right)$$

Where
N_{res} Amount of residual N at risk of leaching (kg N ha^{-1})
$L_{n,b}$ Amount of nitrogen leached from soil in baseline scenario in kg N ha^{-1}
$F_{risk,m}$ (**see Table 2.10**)
I_m Fraction of manure at risk from leaching (**see Table 2.10**)
Annual addition of manure in kg N ha^{-1} (see section 2.1.2)
$F_{risk,f}$ Fraction of inorganic fertiliser at risk from leaching (**see Table 2.10**)
I_f Annual application of inorganic fertiliser in kg N ha^{-1}
$F_{risk,e}$ Fraction of livestock excreta at risk from leaching (**see Table 2.10**)
I_e Annual return of livestock excreta from outdoor grazing animals (kg N ha^{-1})

The annual return of livestock excreta, I_e, is calculated from the stocking density (head/ha) and the annual N production (kg N/head). Default values are as shown in Table 2.14.

Table 2.8: Default values for the amount of nitrogen excreted per animal (R_e), livestock density (n), and outdoor grazing period (T) for outdoor pigs and lowland sheep

Livestock type / stocking density	Length of grazing season (months)	Stocking density (head/ha)[4]	Annual N production (kg N/head)[5]
Sheep-High[1]	12 (All Year)	10	12.3[2,3]
Sheep-Medium	12 (All Year)	4.12	12.3
Sheep-Low	12 (All Year)	0.59	12.3
Outdoor Pigs-High	12 (All Year)	25[4]	18[5]
Outdoor Pigs-Medium	12 (All Year)	16[6]	18
Outdoor Pigs- Low	12 (All Year)	7[6]	18

1. 1 Sheep = 0.17 LU
2. Stocking Density for good conditions as upper bound. Source: RB209 (Tables 8.1 to 8.8)
3. Source: Nitrates Consultation Supporting Paper F2 (Tables 26 - 28)
4. Recommendation for ideal sites, from: The Defra Code of Recommendations for the Welfare of Livestock
5. Value derived from Farmscoper
6. Estimated value

Finally, the N leached (kg N ha^{-1}) is calculated from the residual N at risk (N_{res}) using Equations 10 and 11, as for arable scenarios (see section 2.4). In the NLT, the worst-case scenario has been used, that is the highest amount of nitrogen that can leach from a given quantity of residual N at risk. It is assumed that in this worst-case scenario, all residual N that is at risk will leach (that is, the fraction leached is 1).

3.2 Mitigation methods

For grasslands, mitigation measures act to reduce the amount of leached N (L_n) calculated by the N-Cycle model (see Equation 14). Unlike for arable and vegetable crops where some measures can be applied pre- and post-harvest, these measures are applied only once. This is a limitation of the NLT, in that because leached N is calculated directly for grassland with no intermediate calculation of residual N at risk, it is not possible to apply mitigation coefficients to the calculated residual N before calculating leaching.

The NLT includes 16 measures for grasslands as summarised in Table 2.15. These values are stored in columns L and M in worksheet (‘ListOptions’). The adjusted leached N for grasslands is calculated in VBA Procedure (‘CalculateN’) in Module (‘CalcN’) as described by Equation 16.

Equation 17: Adjusted leached nitrogen to take account of mitigation measures

$$L_{n,adj} = L_n \times \sum \frac{M_1 \times M_2 \ldots M_n}{100}$$

Where

$L_{n,adj}$	Amount of nitrogen leached after accounting for mitigation measures (kg N ha^{-1})
L_n	Amount of nitrogen leached from N-Cycle (kg N ha^{-1}) **[See Equation 14]**
M_n	One or more mitigation efficiencies (%) for pre- and post-harvest **[See Table 2.14]**

Table 2.9: Mitigation measures for grasslands (Newell Price and others 2011)

Mitigation measure	Notes	Mitigation effectiveness (%)
16: Allow drainage to deteriorate		80
17: Improve drainage		130
18: Maintain ditches		120
20: Plant N-efficient crops		90
21: Calibrate fertiliser spreader	f	95
22: Use fertiliser recommendations	f	95
23: Integrate fertiliser and manure	f, m	90
25: Avoid high risk areas (fertiliser)	f	98
26: Avoid high risk times (fertiliser)	f	95
27: Use fertiliser placement	f	98
28: Use nitrification inhibitors	f	65
29: Replace urea with ammonium nitrate	f	95
31: Use clover	f	80
67: Calibrate manure spreader	m	95
69: Avoid high risk times (slurry)	m	80
72: Avoid high risk times (FYM)	m	95

Notes

f – applies only to fields applying manufactured fertiliser
m – applies only to fields applying manure

3.3 Area adjusted nitrogen leached

After the effect of mitigation methods have been taken into account, the NLT adjusts the nitrogen leached for each field for the amount of uncultivated headland. It estimates a weighted area average by assuming that the headland leaches a background N of 10kg N ha^{-1} (Barraclough, personal communication) regardless of land-use (the variable ‘BackgroundN’).

Equation 18 is used to derive an area adjusted amount of nitrogen leached from each field in VBA Procedure (‘CalculateN’) in Module (‘CalcN’). Headland area for each field is estimated using the empirical relationship in Equation 7, which according to Barraclough (2014) is derived from data for 117,000 fields in southern England. The default headland width of 6m is used for all grassland scenarios. It is found in column D of worksheet (‘Templates’) and can be overwritten by the user.

Equation 18: Area adjusted amount of nitrogen leached

$$L_{n,area} = \frac{\left(\left(A_f - A_h\right) \times L_{n,adj}\right) + \left(A_h \times N_{res,hd}\right)}{A_f}$$

Where

$L_{n,area}$	Nitrogen leached from field (kg N ha^{-1})
A_f	Total area of field (ha) [GIS data for each field]

A_h Area of headland (ha) [See Equation 7]

$L_{n,adj}$ Amount of nitrogen leached after accounting for mitigation measures (kg N ha^{-1}) [see Equation 17]

$N_{res,hd}$ Residual N for headlands (kg N ha^{-1}) [10]

4 Concentration of nitrogen leached

The concentration of nitrogen leached from soil (mg N per litre) is calculated by Equation 19 and the overall nitrogen load from each field (kg N) by Equation 20. It applies to the outputs from both the arable and grassland calculations.

The arable crop calculations are found in VBA Procedure ('ArableSMNsub') in Module ('ArableSMN'), while the grassland calculations are found in VBA Procedure ('CalculateN') in Module ('CalcN').

Equation 19: Nitrogen concentration in field drainage

$$C_n = \frac{L_{n,area}}{h \times 0.001 m.mm^{-1} \times 10000 m^2.ha^{-1}} \times 1000000\, mg.kg^{-1} \times 0.001\, m^3.L^{-1}$$

Where

C_n	Concentration of nitrogen in field drainage (mg L^{-1})
$L_{n,area}$	Nitrogen leached from field (kg N ha^{-1}) [See either Equation 11 or 17]
h	Cumulative soil drainage (mm) [NLT uses the hydrologically effective rainfall (HER) from GIS data for each field]

Equation 20: Nitrogen load from an individual field

$$T_n = L_{n,area} \times A_f$$

Where

T_n	Amount of nitrogen leached from an individual field (kg N)
$L_{n,area}$	Nitrogen leached from field (kg N ha^{-1}) [See either Equation 11 or 17]
A_f	Total area of field (ha) [GIS data for each field]

5 Limitations of the NLT

The NLT uses a simple soil N balance calculation to estimate nitrate at risk of leaching. This section describes some of the farm management practices that are not captured within the NLT and, where possible, provides suggestions on how to address them.

5.1 Timing of manure and fertiliser application

The tool assumes that manure and inorganic fertiliser are applied at the ‘correct’ times of the year to maximise the availability of nutrients to the crop and minimise leaching. In practice, this typically means spring applications.

Late summer or autumn applications are at risk of leaching during the winter, and this will need to be considered when assessing output from the NLT. The ADAS MANNER[5] tool can provide guidance on the likely leaching of nitrogen from autumn applications of manure. Of course, there may be other factors to consider when planning manure applications, such as the requirements of the Nitrate Vulnerable Zones (NVZ) Action Plan.

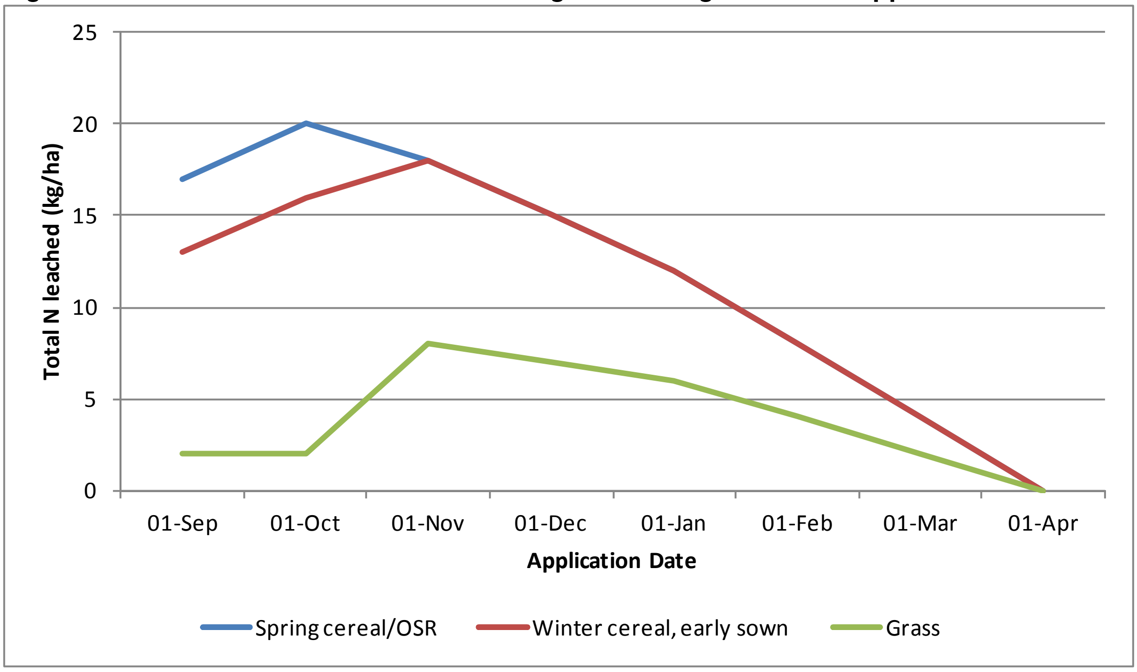
Figure 5.1 shows nitrate leaching from an application of cattle slurry at 50m^3/ha as predicted by the MANNER tool, as a function of application date, for autumn crops, spring crops and grass. In general, and all else being equal:

- spring crops will allow more leaching than autumn crops or grass. This is because autumn sown crops will take up some nitrogen in the autumn, reducing the amount of nitrate at risk
- the risk of nitrate leaching decreases for later applications as the total winter soil drainage post-application is reduced
- Applications in April or later are predicted, in this case, to result in no leaching and maximum availability of nutrients to the crop, as soil drainage has ceased before the application date

There are other factors that can influence nitrate leaching from applications of manure, such as the method of spreading and the weather conditions during and after spreading. The MANNER tool can provide further guidance on these factors.

[5] http://www.planet4farmers.co.uk/manner

Figure 5.1: Predicted variation in N leaching with timing of manure application



5.2 Utilisation of nutrients by a following crop

The NLT soil N balance calculations span a period of one agricultural year, from (typically) September to August. The tool estimates the soil mineral nitrogen (SMN) at risk of leaching in the autumn, post-harvest, as the excess N above that taken up by the crop.

However, depending on how the land is managed following crop-harvest, much of this SMN may not end up being leached. For example, a following autumn-sown arable crop may take up a significant quantity of nitrate that would result in the residual nitrate at risk of leaching being significantly reduced.

In particular, this must be accounted for when assessing potential leaching from fields where the soil nitrogen supply has been deliberately built up, for example outdoor pigs in an arable rotation, or the use of legumes in rotational grass. In these cases, the NLT will predict a very high risk of nitrate leaching because the excess nitrogen applied during the crop year for which calculations are carried out will be substantial.

The user must consider whether the subsequent management of the field will utilise this soil nitrogen and reduce the risk of leaching. Subsequent sections deal with these specific examples in more detail.

5.3 Outdoor poultry, horses and other livestock

Current Defra guidance[6] provides figures for the quantity of nitrogen produced by grazing livestock such as deer, goats and horses. These figures are reproduced in Table 4.1 of the user guide, and can be used to estimate the approximate equivalent nitrogen loading to land from each type of grazing livestock, recognising that this will represent a major simplification of nitrogen cycling processes on grassland.

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6 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/261371/pb14050-nvz-guidance.pdf

It is notable that a horse produces approximately one fifth of the nitrogen produced by a dairy cow. The nitrogen loading to soil from horses at typical stocking densities will, therefore, be well below that of dairy cattle.

5.4 Clover in grassland systems

The NLT cannot represent the fixing of nitrogen by clover (or other legumes) in grass swards. Clover will increase the pool of organic nitrogen available to mineralise, therefore potentially increasing the risk of nitrate leaching if the sward is ploughed out. The user will need to account for this when considering predictions of nitrate leaching from rotational grass. Further guidance on the potential soil nitrogen supply from clover is provided in RB209 (Defra, 2010). In terms of a soil nitrogen budget on arable land, soil nitrogen supply from clover can be represented in the NLT as an elevated SNS index or as a fertiliser input.

5.5 Estimation of grazing deposits

The rate of nitrogen deposition by grazing livestock is calculated according to the livestock type and stocking density entered by the user, the estimated length of the grazing season and annual rates of N production by livestock (Defra NVZ guidance). The figures for annual N production by livestock and stocking density are provided in the 'Templates' tab (Blue section: 'Livestock') and may be overtyped if required.

Grazing deposits (kg N/ha/yr) are calculated as:

Annual N production per head of livestock x No. of livestock per ha (stocking density) x Length of grazing season (fraction of year)

Parameter values are as shown in Table 3.3.

Table 3.1: Default grassland parameters

Livestock type / stocking density	Length of grazing season (months)	Stocking density (head/ha)[4]	Annual N production (kg N/head)[5]
Dairy-High	7, 5 or 4[1]	3.1	117
Dairy-Medium	7, 5 or 4[1]	2.6	117
Dairy-Low	7, 5 or 4[1]	2.0	117
Beef-High[2]	7, 5 or 4[1]	3.17	92
Beef-Medium	7, 5 or 4[1]	2.0	92
Beef-Low	7, 5 or 4[1]	0.83	92
Sheep-High[3]	12 (All Year)	10	12.3[6]
Sheep-Medium	12 (All Year)	4.12	12.3
Sheep-Low	12 (All Year)	0.59	12.3

Outdoor pigs-High	12 (All Year)	25[7]	18[6]
Outdoor pigs-Medium	12 (All Year)	16[8]	18
Outdoor pigs- Low	12 (All Year)	7[8]	18

1. 7 months for grazed fields, 5 months for 1 cut then grazed, 4 months for 2 or 3 cut then grazed
2. 1 Beef cow = 0.6 LU
3. 1 Sheep = 0.17 LU
4. Stocking Density for good conditions as upper bound. Source: RB209 (Tables 8.1 to 8.8)
5. Source: Nitrates Consultation Supporting Paper F2 (Tables 26 - 28)
6. Value derived from Farmscoper
7. Recommendation for ideal sites, from: The Defra Code of Recommendations for the Welfare of Livestock
8. Estimated value

The figures above will result in an estimate of, for example, 211kg N/ha/yr in dung and urine from dairy cattle with high stocking density, on a grazed field (7 months grazing season). It is assumed that dung and urine produced during the remainder of the year is managed as manure or slurry and, by default, the NLT assumes that this manure is spread elsewhere or exported off the farm. If the manure is spread to the grazed field, it must then be included in the NLT as a manure (or fertiliser) application.

Note that the onus is on the user to make sure that the fertiliser rate and stocking density selected for each field are consistent (that is, that the selected fertiliser rate is sufficient to produce enough herbage to feed the selected stocking rate).

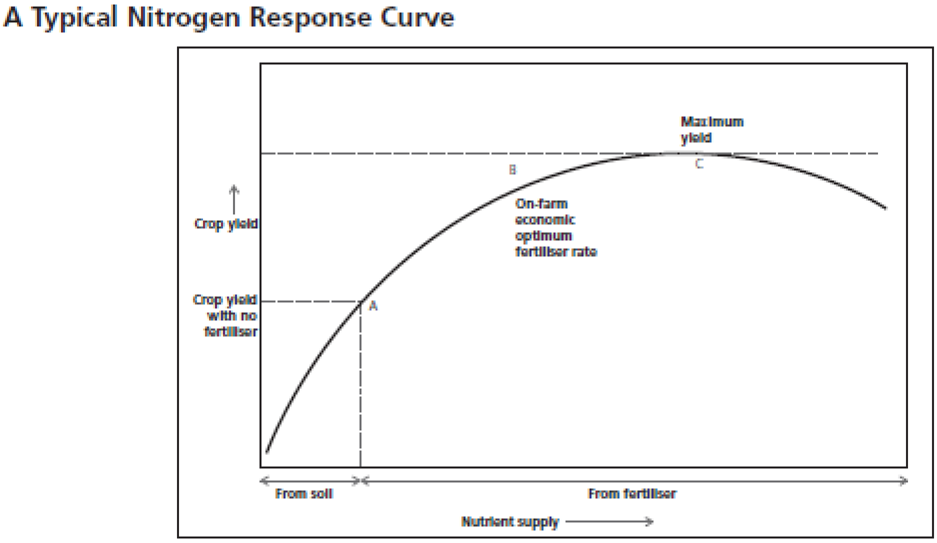
5.6 Relationship between fertiliser rate and crop yield (and offtake)

The NLT uses fixed parameter values of the nitrogen content of harvested arable crops. The calculated offtake is, therefore, the fresh weight yield (as entered by the user) multiplied by the crop N content.

The onus is on the user to make sure that all field parameters are consistent: fertiliser application rate, crop yield and crop N content.

Figure 3.2 shows a typical yield response curve (from RB209, Defra 2010).

Figure 3.2: Nitrogen response curve (Defra, 2010)



The N offtake is calculated in the NLT as the product of the yield and the crop N content (as a percentage of yield). The NLT provides 'standard' figures for fertiliser application rates, crop N content and yield. However, the user may wish to override these default figures in particular circumstances. For example, additional fertiliser applications may be made to milling wheat crops to increase grain protein content. In this case, the crop N content, and therefore offtake, should also be increased. Not accounting for this would result in a predicted soil N surplus and overestimated risk of leaching.

Similarly, crops with low fertiliser application rates (for example, organic crops that do not receive any inorganic N) may achieve low yields and, therefore, lower N offtake. Not reducing the yield value in the tool will result in an overestimate of crop N offtake and underestimate of risk of N leaching.

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Abbreviations

DM	Dry matter
FYM	Farm yard manure
FW	Fresh weight or field dried weight
HER	Hydrologically effective rainfall
NLT	Nitrate leaching tool
OSR	Oil seed rape
SMN	Soil mineral nitrogen
SNS	Soil nitrogen supply
SPR	Standard Percentage Runoff

Glossary

Biosolids	Treated sewage sludges are valuable fertilisers and soil conditioners, which have undergone processes to create a product suitable for beneficial use in agriculture.
Fresh weight yield	The yield of a marketable produce removed or expected to be removed from the field in commercial practice. Data is typically based on field experiments, reported returns in national surveys, or expert opinion for well grown crops.
Greenchop	Cut (grass) in order to bring to cattle or store as silage.
Soil mineral nitrogen	Nitrate – N (NO_3-N) and ammonium-N (NH_4-N) are often called mineral nitrogen. Both are potentially available for crop uptake, and the amount in the soil depends on the recent history of cropping, organic manure and nitrogen fertiliser use.
Soil nitrogen supply	The amount of nitrogen in the soil (apart from that applied for the crop in manufactured fertilisers and manures) that is available for uptake by the crop throughout its entire life, taking into account nitrogen losses.
Stover	The leaves and stalks of field crops such as maize, sorghum or soybean that are commonly left after harvesting the grain. It can be directly grazed by cattle or dried for use as fodder.

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