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Modelling optimal strategies for decreasing nitrate loss with variation in weather – a farm-level approach

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Abstract

A farm-level framework for assessing the economic impact of measures to reduce nitrate loss by leaching is described. The framework links a database of crop treatments and nitrogen loss generated with the IACR SUNDIAL model for 10 years of weather and an economic model, Farm-adapt, for a root-cropping farm on sandy loam in the East Midlands of England. Weather induced variation in nitrate loss over time was greater than that resulting from differences in management practice. Limits on nitrate loss per hectare resulted in a relatively small annual mean cost to the farm when allowed to choose the optimal management practice (including doing nothing) in each year (e.g. £8 ha^{-1} for a 30 kg ha^{-1} limit, resulting in a 6.2 kg ha^{-1} and 3.2 mg l^{-1} reduction in mean nitrate-N loss and mean nitrate-N concentration, respectively). In no years was it feasible with the treatments tested to reduce concentration of nitrate-N to the EU limit of 11.3 mg l^{-1} in every week of the year. A mean annual loss of 11.3 mg l^{-1} was feasible in four out of 10 years at a mean cost of £10 ha^{-1}. The most cost-effective reductions of loss (in terms of £ kg^{-1} nitrate-N ha^{-1}) were achieved by targeted reductions in N application followed by a combination of reduced N and growing winter cover before spring crops. Untargeted limits (quotas) on nitrogen, nitrogen taxes and application of single management practices were less cost effective than combinations of practices. Three management strategies, based on these combinations, were imposed for all years. Mean costs were greater than where the farm could choose the optimal management practice in each year;

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a 4.67 mg l^{-1} reduction in nitrate-N concentration cost £19 ha^{-1} and a 5.88 mg l^{-1} reduction £33 ha^{-1}.

Keywords: Nitrate loss; Farm-level models; Decision making; Management strategies; Sandy soils

1. Introduction

Levels of nitrogen (N) loss from agriculture are a cause for concern because of the contribution to eutrophication by leached nitrate and the high global warming potential of nitrous oxide resulting from denitrification. Health concerns have led the European Union to impose a limit of 50 mg l^{-1} for nitrate (equivalent to 11.3 mg l^{-1} nitrate-N) in potable water for all member states (EEC, 1991). In the UK, the effectiveness of available policies and management techniques for minimising nitrate losses from farms have been extensively assessed by previous field trial and modelling studies (see review by Goulding, 2000). However, these studies have largely been at the field, catchment or national level; there have been few studies at the farm level. Farm-level studies are of value because recommendations on how to reduce nitrate loss must be compatible with existing farm systems and ideally have minimal impact on farm profitability. For example, a recommendation to substitute autumn for spring sown crops may lead to increased requirements for labour and machinery, making the recommendation relatively expensive for each unit reduction in nitrate loss.

Weather, particularly rainfall and temperature, has a large influence on nitrate losses from farms. Several UK studies, carried out over a number of years (Bacon et al., 1998; Bhogal et al., 1997; Davies et al., 1996; Powlson et al., 1986a) have found that leached nitrate quantities were highest in the wettest year of the study. Winter rainfall can be a good quantitative predictor of the amount of nitrate leached (Webb et al., 1997). Other studies have found that winter drainage, related to both winter rainfall amount and pattern, is a better predictor than winter rainfall alone (Shepherd and Lord, 1996) and this relationship between excess rainfall (i.e. drainage) and leaching has been modelled (Anthony et al., 1996). Similarly, high spring and summer rainfall can result in increased rates of spring and summer nitrate loss (McEwan et al., 1989; Powlson et al., 1992; Powlson et al., 1986b). The influence of weather means that it is difficult to compare the results achieved by applying practices and policies in different years or at different locations. Modelling studies often use mean climate data so the effect of extreme years, when nitrate losses are likely to be high, is ignored.

In this paper we present a modelling framework for assessing the impact of management practices and policies on farm profitability and nitrate losses at the farm level. The framework consists of a comprehensive database of treatments and associated nitrate losses linked to a farm economic model. To improve the robustness of the results to climate variation the database included nitrate losses for a range of years. Our starting point is a farm currently following 'good practice', i.e. following current UK guidelines on fertiliser and manure application and crop management. The framework was used to assess how, from this starting point, nitrate losses can be further reduced at minimum cost i.e. minimum profit foregone.

2. Materials and methods

2.1. Overview of approach

We have constructed a model framework (Fig. 1) which links a database of crop yields, crop N fertiliser requirements and nitrogen losses from crop and treatment combinations to a farm level economic model (Farm-adapt). We have gone to considerable lengths to capture variation in N losses that are in the control (cropping, fertiliser application, etc.) and out of the control (weather) of the farmer. To capture the effect of year-to-year climate variation and to avoid problems with using published results from trials from different years and with different combinations of

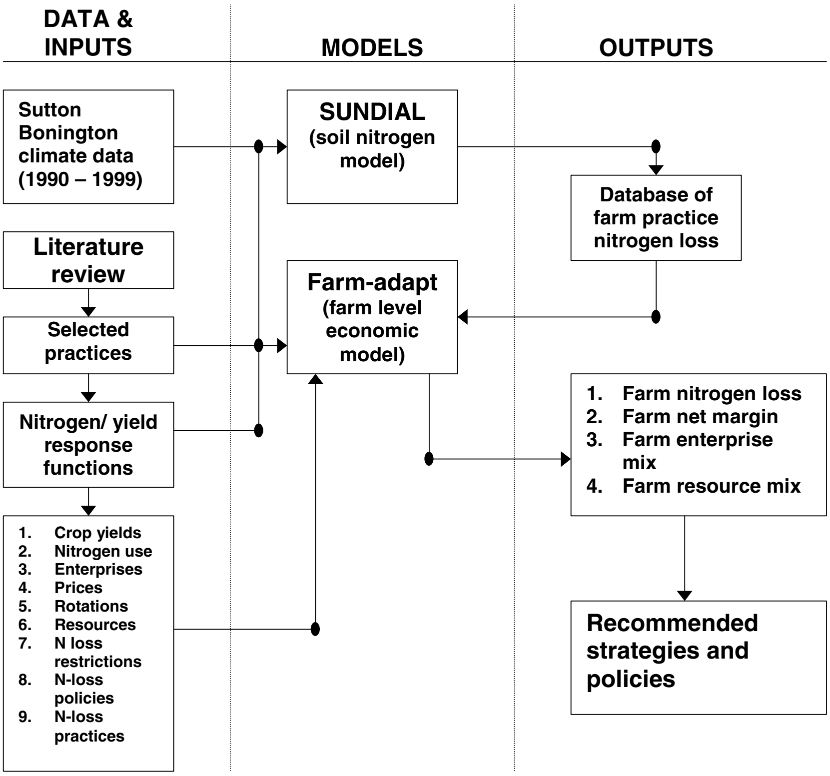

Fig. 1. Overview of the model framework.

practices, nitrate losses were calculated using the SUNDIAL soil N model (Smith et al., 1996). We have calculated losses for 10 years of climate data but have not attempted to run a sequence of years of data, our aim being to isolate the effect of individual years. This approach also means that, for example, a particular crop is not always grown in a dry year. Ten years of data reflect a necessary trade-off between capturing climatic variability and minimising the size of the database. We selected management practices to be modelled where there was clear evidence from the literature for a possible benefit. Included practices were: (1) changes in crop mix and rotation; (2) reduction in N fertiliser application; (3) use of winter cover crops; (4) delayed tillage prior to spring crops; (5) use of non-inversion tillage; (6) irrigation of root crops; (7) avoiding use of manures. We did not include practices where evidence of a net benefit was poor, such as the use of nitrification inhibitors.

As an example of the framework we present results from a simulated root-cropping farm in the English East Midlands growing potatoes (Sutton Bonington, UK grid reference SK505261) with and without irrigation capacity. We assumed that the simulated farm followed a four year rotation is purely arable and grows a mixture of combinable arable crops (cereal and break) and maincrop potatoes. The available cereals (winter wheat, winter barley and spring barley) and break crops (winter oilseed rape, winter field beans and spring combinable peas; wheat crops following break crops tend to have a higher yield, thus break crops are important in a rotation) reflect those typically grown on UK farms. Land set-aside as part of a requirement under the Common Agricultural Policy and uncultivated land were also modelled. Where a spring crop was grown, the farm could precede this crop with a 'cover crop' i.e. a crop sown to reduce nitrogen loss on land that otherwise be uncropped between one harvest period and the spring sowing period. We assumed that cropping occurred on a Sutton Bonington (SB) sandy-loam soil (75% sand, 10% silt, 15% clay) and that the farm had a cropping area of 345 ha, a minimum potato area of 15% of the farm area (51.75 ha), 6 full time labourers (including the farmer, 66% of whose time was spent on farm management), sufficient irrigation capacity to irrigate the potato area and sufficient machines to cultivate and harvest the land area.

2.2. SUNDIAL soil N model and N loss database

Using the soil and arable crop nitrogen model SUNDIAL and the selected practices described above, a database of nitrate loss with different crop combinations and practices was generated. SUNDIAL uses simple sub-models to simulate the major processes governing the N cycle in arable soils – mineralisation of soil organic matter, immobilisation of inorganic N, denitrification, ammonia volatilisation, nitrate leaching and crop uptake.

For all crops except legumes, three levels of N fertilisation treatment were available within the database. Within SUNDIAL crop N uptake is modelled as a degree-day driven logistic curve, the final value of which is determined by the expected crop yield. Hence, to run SUNDIAL expected crop yields and N application rates must be supplied. As our starting point we used the UK Ministry of Agriculture published guide for farmers and their advisers, which recommends N fertiliser rates for crops

Table 1
Cash crops modelled within SUNDIAL: assumed yields (t ha^{-1}) and nitrogen addition (kg ha^{-1}) for each fertiliser level

Crop	Code	Soil index	Level 3		Level 2		Level 1	
			Yield	Nitrogen	Yield	Nitrogen	Yield	Nitrogen
1st Winter wheat	WW1	0	7.13	175	6.97	149	6.53	105
		1	7.13	140	6.97	119	6.53	84
2nd Winter wheat	WW2	0	6.13	175	5.97	149	5.53	105
3rd Winter wheat	WW3	0	5.13	175	4.97	149	4.53	105
Winter barley	WB	0	5.80	160	5.69	136	5.31	96
		1	5.80	120	5.69	102	5.31	72
Spring barley	SB	0	5.03	125	4.97	106	4.76	75
		1	5.03	90	4.97	77	4.76	54
Oilseed rape	OSR	0	2.77	190	2.72	162	2.57	114
Winter field beans	WFB	0	–	–	–	–	2.93	0
Dried peas	DP	0	–	–	–	–	3.42	0
Maincrop potatoes	Pots	0	57.00	240	56.20	204	53.20	144
Sugar beet	Sbt	0	63.05	125	62.27	106	59.82	75

A 1 t ha^{-1} yield reduction is assumed for second winter wheat over 1st winter wheat and for 3rd winter wheat over 2nd winter wheat (Nix, 1999). Soil index refers to UK Ministry of Agriculture guidelines (Anon., 1994) which recommend lower levels of N application following a break crop (index of 1) than following other crops (index of 0). Levels shown exclude an additional 5% safety margin added to each nitrogen application.

taking into account rotation and soil type (Anon., 1994). We used these recommended levels as our maximum level of N fertilisation (hereafter termed Level 3; see Table 1), and simulated reduced application by reducing the recommended levels by 15% (Level 2) and 40% (Level 1). It was assumed that in reality risk aversion would lead farmers to over-apply N and application levels of N within SUNDIAL were increased by 5%. Crop yields for these N application levels were obtained from N response curves for sandy-loam soils derived from field experiments (Brian Chambers pers. commun. for potatoes and cereal crops; Gavin Lunn pers. commun. for oilseed rape yields). Annual atmospheric deposition of N was assumed to be 35 kg ha^{-1} (in addition to the farmer applied nitrogen), distributed evenly throughout the year. N was provided by mineral nitrate fertiliser for combinable crops and mineral nitrate alone or mineral nitrate and manure for potatoes (manure was applied immediately before planting of potatoes and it was assumed that no leaching took place before crop uptake). Where manure was added to the potatoes, it replaced half of the mineral N added. It was assumed that straw was incorporated for all cereal crops.

For all spring crops, a winter cover crop treatment was available within the database. The supplied version of SUNDIAL did not include a cover crop, so a cover crop was parameterised using data from Shepherd (1999). For the non-cash crops (set-aside and unused land) it was assumed that a small amount of natural cover established; both could also be sown with a cover crop.

Residual mineral nitrogen and organic matter from previous cropping have a large effect on nitrogen losses. This previous crop effect was modelled by including crops as pairs in the database: the 'previous' and 'current' crop. Trials with SUNDIAL indicated that with the exception of a small sugar beet effect, residue from crops planted before the previous crop had no effect on nitrate loss from the current crop (i.e. crop pairs were sufficient to capture rotational effects and triplets were unnecessary). The modelled crop pairs were determined by rotational restrictions. For example, 2nd winter wheat could only have 1st winter wheat as a previous crop while 1st winter wheat could have potatoes, winter field beans, set-aside or oilseed rape as previous crops. Following Anon. (1994), levels of N addition also depended on the previous crop. For example, winter wheat following oilseed rape was fertilised at a lower rate than winter wheat following winter barley. Within SUNDIAL, treatments that affected the amount of residual N at harvest (e.g. fertilisation level) were applied to the previous crop, while treatments that controlled loss (e.g. winter cover crops) were applied to the current crop. As an example, for a 1st winter wheat (previous crop) and potato (current crop) crop pair with reduced fertiliser and grown with winter cover, the reduced fertiliser would be applied to the winter wheat and winter cover to the potatoes. Winter cereal and root crops planted at sub-optimal times (e.g. winter wheat following potatoes) suffered a yield penalty (Green and Ivins, 1985; Green et al., 1985).

In the UK, the only widely irrigated crops are root crops (sugar beet and potatoes) and horticultural crops. Where irrigation is not applied and yields fall short of expectations large amounts of residual soil N will remain at harvest. The yield shortfall will depend on summer rainfall. Potatoes were therefore modelled as an irrigated and unirrigated crop. The effect of lack of irrigation on potato yield was included in the database by reducing the yield of irrigated potatoes by a yield adjustment fraction (Table 2). A yield fraction for sugar beet was calculated from a regression of SB annual unirrigated sugar beet yield on total rainfall between week 15 and week 35, between 1990 and 1999 ($n = 10$, $r^2 = 0.77$, i.e. when rainfall in this period was low yields were also low). The fraction was standardised so that the year with the highest yield had a yield fraction of 1.0. Hence, in the wettest year irrigated and unirrigated yields were the same. Potatoes are not grown at SB, therefore for potatoes, the sugar beet index was used, standardised at 0.9 rather than 1.0. A lower figure was used to reflect the larger irrigation requirement over sugar beet.

For all crops except potatoes conventional tillage (ploughing followed by power harrowing) and reduced tillage (power harrowing alone) treatments were available in the database. For potatoes, only conventional tillage was available. For spring crops autumn tillage and spring tillage treatments were available. To allow the simulation of delayed tillage a modified version of SUNDIAL (G. Dailey, pers. commun.) was used, which did not restrict ploughing to occur immediately after harvest but allowed the effect of different cultivation dates and types to be modelled.

In all, there were 497 rotationally feasible crop pairs with the available combination of treatments. To incorporate the effect of weather variation within the da-

Table 2
Summary of Sutton Bonington climate data used in the SUNDIAL model and drainage values for winter (October–March) each year

	Total rainfall (mm)	Total potential evapotranspiration (mm)	Drainage ($l\,ha^{-1} \times 1000$)
1990/91	497	638	876
1991/92	469	529	371
1992/93	674	538	1480
1993/94	701	484	1747
1994/95	654	546	2212
1995/96	486	596	1517
1996/97	447	546	522
1997/98	526	544	343
1998/99	731	497	2272
1999/00	720	541	2015
Mean	590	546	1336

Drainage figures are for an autumn-ploughed spring barley crop, with no winter cover crop, no manure and recommended (Anon., 1994) nitrogen applied.

tabase of nitrate loss, each of the 497 crop pairs/ treatment combinations was run with 10 years of weather data (1990–1999). In total, there were 258,440 records (10 years $\times$ 497 treatments $\times$ 52 weeks) within the database. For each SUNDIAL run, weekly drainage, quantity of nitrate-N leaching and concentration of nitrate-N leaching were recorded. Annual totals were calculated by summing weekly losses for quantity of leaching, and dividing total annual loss by total annual drainage for annual average concentration of leachate. As the farm economic model (see below) runs on an annual basis, the values from the 52 week period preceding the harvest of the current crop were included in the database. This period therefore captured the impact of the applied practices on both the current and previous crops. For example for a 1st winter wheat/2nd winter wheat crop pair with reduced fertiliser application the reduced application would apply to the 1st winter wheat (the previous crop), reducing both the residual mineral nitrogen at harvest and nitrogen losses from the 2nd winter wheat (the current crop). Therefore, the losses within the database largely reflect those from the residue from the previous crop.

2.3. Farm-adapt farm-level model and price assumptions

Farm-adapt is a mixed-integer-programming (MIP) model that maximises farm net margin (total value of output less variable, machinery and labour costs) by optimising crop, animal, labour, machinery, storage, housing and irrigation mix over the period of a year with a weekly time step (for more details see Ramsden et al., 1999, 2000; Ackrill et al., 2001). For the current study, Farm-adapt was modified to link with the database of nitrate losses and to include different cultivation practices, cover crops and different levels of fertilisation. Farm-adapt uses the linear approximation method (Hazell and Norton, 1986) so that linear combinations of yield and fertiliser between these three points are also represented in the model.

As the generated treatment and loss database determined the treatments available, all the treatment combinations described above were available within Farm-adapt. A standard four-year rotation was modelled; the model can choose different crops for different years of the rotation. As Farm-adapt is an annual model the four-year rotation is simulated by dividing the farm area into quarters. An example would be a rotation of oilseed rape, 1st winter wheat, 2nd winter wheat and winter barley, returning to oilseed rape. If maximum profitability is attained by allocating 25% of the farm area to these four crops, Farm-adapt would choose the four crop pairs that completely represent this rotation (i.e., with previous crop then current crop: winter barley – oilseed rape, oilseed rape – 1st winter wheat, 1st winter wheat – 2nd winter wheat, 2nd winter wheat – winter barley). The nitrate loss database also provided crop yields, timings and levels of fertiliser addition to Farm-adapt. Crop workrates (the time taken per hectare to carry out a field operation) were from Nix (1999). Crop prices and area payments were adjusted for Agenda 2000 reforms to the Common Agricultural Policy; these together with variable cost data, were also derived from Nix (1999).

2.4. Framework runs

The framework was run (a) unconstrained, (b) with constraints on nitrate loss, (c) with constraints on farm management practices, (d) with varying prices and (e) with recommended management strategies. For each run of the system each of (a)–(e) was run with each of the 10 years of climate data.

The unconstrained runs provided the economically optimal baseline results for farm net margin, farm nitrate loss, labour and machinery use, crops grown, N applied, cultivation timing and cultivation type. N applied is economically optimal under the assumption that the 5% 'safety margin' referred to in Section 2 results from risk aversion amongst farmers. The only objective was maximisation of farm net margin and the only constraints, other than those listed above, were available farm resources and policy constraints such as set-aside (10% of the area on which compensatable crops are grown i.e. excluding the area of potatoes). The results of all the other runs were compared to these baseline results and the difference in farm net margin recorded.

Constraining nitrate loss explored how the system responded to emission targets while maximising farm net margin. (1) Limits on total annual nitrate-N load (20, 30 and 40 $\mathrm{kg\,ha^{-1}}$), (2) maximum weekly concentration of nitrate-N in drainage (11.3, 35 and 50 $\mathrm{mg\,l^{-1}}$) and (3) annual average nitrate-N concentration (11.3 and 15 $\mathrm{mg\,l^{-1}}$) were applied. These runs provided information on the most cost-effective changes to farm management practice required to reduce nitrate loss to the applied limit. The runs also identified any farm/year combinations where there were no feasible solutions, i.e. it was not possible to reduce nitrate loss to the applied limit in that year.

Constraining individual farm management practices explored how specific practices affected nitrate loss and farm net margin. Farm management practices were: (1) all spring crops grown with winter cover; (2) all crops ploughed rather than using reduced cultivation; (3) limits on the farm-average amount of N applied, including manure N (100, 125 and 150 kg ha^{-1}); (4) no potatoes; (5) and potatoes grown with reduced fertiliser (level 1 and level 2). Note that for these runs Farm-adapt was constrained only by the management practice and resource constraints. Note also that as discussed above treatments and hence constraints that affect residual nitrogen at harvest are applied to the previous crop. Hence the solution was the most cost-effective way of adapting to the practice, regardless of nitrate loss.

Running the framework with varying prices explored how sensitive the farm plan, nitrate loss and net margin were to varying prices. Prices varied were: (1) N price (−50, −25, +10, +25, +50, +100 and +200%), (2) cereal price (+10, +25 and +50%) and (3) oilseed rape price (−50, −25 and −10%). Oilseed prices were reduced to capture the effect of substitution with legumes, while cereal prices were increased to assess the impact of historic (early 1990s) market price levels.

Informed by the framework runs with constraints on nitrate loss, three recommended management strategies were selected. The selected strategies followed the most cost-effective adaptations determined by Farm-adapt for reducing nitrate loss. The strategies ranged from a low-cost low-reduction strategy to a high-cost high-reduction strategy. Each strategy was imposed on the farm for each of the 10 years of climate to record the effect of the plans on nitrate loss. Finally, the selected management strategies and the baseline rotation, with and without manure, were run through SUNDIAL for a continuous 100-year period, with the 1994 climate data (the year with the highest nitrate-N loss), to record the long term effect of the strategies and baseline conditions on soil N levels and nitrate loss. With the exception of cover crops, SUNDIAL is unable to directly simulate rotations with more than two crops in one year; thus the rotation was simplified to exclude set-aside land.

3. Results

3.1. SUNDIAL generated nitrogen losses

Table 3 summarises the effect of crop and rotational position, across all treatments, on nitrate loss. As losses are measured up to harvest, residual N at harvest from the previous crop affects losses from the current crop. Hence, when comparing with field trial results and other studies the previous crop figure should be used. Losses from 1st winter wheat are relatively high when a current crop, as it follows break crops such as oilseed rape and potatoes and low when a previous crop when it is followed by 2nd winter wheat and spring and winter barley. Conversely, losses from potatoes as a current crop are low, as it follows cereals, but high as a previous crop. Standard errors for each crop pair are quite low, an

Table 3
Mean nitrogen loss from crops as a current and a previous crop across years and treatments (±SE)

	Number of data points in SUNDIAL database		Annual nitrate-N loss (kg ha^{-1})		Annual denitrification-N loss (kg ha^{-1})		Average nitrate-N concentration (mg l^{-1})	
	Current	Previous	Current	Previous	Current	Previous	Current	Previous
1st Winter wheat	600	390	30.7 ± 1.3	12.3 ± 0.5	20.1 ± 0.7	9.2 ± 0.4	20.9 ± 0.6	8.4 ± 0.3
2nd Winter wheat	180	750	15.2 ± 0.7	22.6 ± 0.6	11.9 ± 0.4	15.3 ± 0.4	10.3 ± 0.4	14.1 ± 0.3
3rd Winter wheat	120	60	25.3 ± 1.7	30.8 ± 2.7	24.0 ± 1.1	29.3 ± 1.6	15.8 ± 0.7	18.6 ± 1.1
Winter barley	180	810	14.9 ± 0.8	19.4 ± 0.5	8.4 ± 0.6	12.6 ± 0.2	10.2 ± 0.5	10.7 ± 0.2
Spring barley	1800	1800	29.9 ± 0.7	19.1 ± 0.3	15.8 ± 0.3	11.3 ± 0.2	12.7 ± 0.4	13.8 ± 0.2
Oilseed rape	140	60	24.2 ± 2.1	18.0 ± 1.4	14.2 ± 0.4	15.0 ± 0.8	15.8 ± 1.1	11.6 ± 0.8
Winter field beans	120	20	20.4 ± 1.2	55.2 ± 7.3	15.4 ± 0.6	35.7 ± 2.6	12.8 ± 0.7	33.1 ± 2.7
Spring peas	360	20	18.2 ± 0.7	60.6 ± 8.0	11.6 ± 0.2	44.7 ± 2.2	11.4 ± 0.4	35.6 ± 2.8
Maincrop potatoes	540	960	23.0 ± 0.7	42.9 ± 1.3	18.1 ± 0.4	28.4 ± 0.3	14.6 ± 0.3	27.7 ± 0.6
Set-aside land	360	40	17.2 ± 0.7	69.6 ± 7.2	10.9 ± 0.4	19.1 ± 1.0	10.8 ± 0.4	42.1 ± 2.6
Unused land	30	30	82.5 ± 9.8	82.5 ± 9.8	10.5 ± 0.5	10.5 ± 0.5	47.3 ± 3.6	47.3 ± 3.6

Current crop losses are calculated as the mean of all the crop pairs with the crop as a current crop. Previous crop losses are calculated as the mean of all the crop pairs with the crop as a previous crop.

indication of both large sample size for each crop pair and the small effect that different treatments have on nitrate loss relative to weather. Note the high levels of loss from set-aside and unused land and how few crops, on average, are below 11.3 mg l^{-1} nitrate-N.

3.2. Baseline farm-level results

Farm-adapt was linked with the treatment and nitrate loss database and the complete system run unconstrained to establish the economically optimal baseline results. The baseline optimal crop mix for each year consisted of a rotation of 1st winter wheat, spring barley and set-aside, winter barley and 1st winter wheat, potatoes and oilseed rape leading back into 1st winter wheat (Table 4). In this rotation,

Table 4
Baseline crop areas and nitrogen use per crop (a) crop areas and (b) nitrogen use

Crop	Area (%)	Nitrogen use (kg ha^{-1})
1st Winter wheat	33	184
Winter barley	17	168
Spring barley	17	112
Winter oilseed rape	10	200
Potatoes	15	252
Set-aside	8	0

44% of the 1st winter wheat was planted after the potato harvest and therefore suffered a yield penalty due to late sowing (planting starts on the 29th October). Annual farm net margin was £59,930 (£20,472 without irrigation). The mean level of mineral N addition for the farm was 146 kg ha^{-1} in each year; mean manure-supplied N was 19 kg ha^{-1} all applied to the potato crop at a rate of 126 kg ha^{-1}. All cash crops were fertilised at level 3 (highest level) except spring barley where the optimal level of N occurred at level 2 (the response curve for barley over nitrogen levels 2 and 3 is relatively flat: yield foregone is only 60 kg ha^{-1}). Annual nitrate loss was 28 kg ha^{-1} (SD 17 kg ha^{-1}), annual average nitrate-N concentration 21 mg l^{-1} (SD 6 mg l^{-1}) and maximum weekly nitrate-N concentration 45 mg l^{-1} (SD 17 mg l^{-1}). Without irrigation of the potato area, nitrate losses from the farm increased. As these figures suggest, there was considerable year-to-year variation in both nitrate-N concentration and nitrate load. Fig. 2 shows mean annual nitrate-N losses for the farm; these ranged from 2.8 kg ha^{-1} in 1991 to 50.3 kg ha^{-1} in 1994. Note that losses are generally higher without irrigation. Table 2 shows modelled mean drainage volumes and nitrate-N concentration for each year. There was no direct relationship between mean nitrate-N loss and concentration of nitrate-N (regression with concentration as the independent variable gives an adjusted R^2 of 0.2); nitrate loss was directly related to drainage volume (adjusted R^2 of 0.9). Low average annual drainage levels do not necessarily imply high concentration of nitrate: in 1991/92 for example, average drainage was low (371,000 l ha^{-1}), but nitrate N-loss was only 2.8 kg ha^{-1}, resulting in low concentration. In 1996/97, average annual drainage was also relatively low (522,000 l ha^{-1}), but nitrate N-loss was 16.0 kg ha^{-1} giving a concentration of 30.7 mg l^{-1}. The pattern of winter rainfall was the main reason for this difference – total

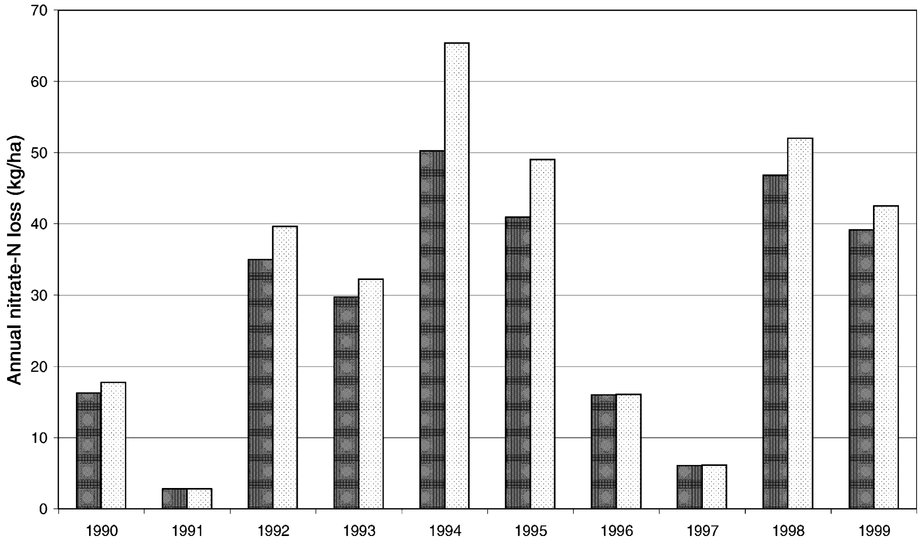

Fig. 2. Annual baseline nitrate-N loss from potato farm with >15% potatoes. Darkbars are with irrigation, light bars without.

Table 5
Effect of price variation on farm net margin and nitrogen loss

Price change	Whole farm cost (£)	Cost (£ ha^{-1})	Annual nitrate-N loss		Average nitrate-N concentration	
			$kg\,ha^{-1}$	Cost £ $kg^{-1}\,ha^{-1}$	$mg\,l^{-1}$	Cost £ $ha^{-1}\,mg^{-1}\,l^{-1}$
N fertiliser cost						
+200%	20485	59	−3.53	16.81	−2.29	25.88
+100%	11483	33	−3.48	9.57	−2.11	15.77
+50%	6052	18	−3.13	5.61	−1.80	9.74
+25%	3085	9	−0.75	11.89	−0.67	13.27
+10%	1247	4	−0.75	4.83	−0.67	5.42
−25%	−3220	−9	0.00	–	0.00	–
−50%	−6504	−19	0.04	−420	0.06	−337
Cereal price						
+50%	−45066	−131	0.18	−715	0.00	−54805
+25%	−22408	−65	0.05	−1370	0.03	−2048
+10%	−8963	−26	0.10	−258	0.05	−4780
Oilseed rape price						
−10%	1477	4	−0.82	5.21	−0.48	8.97
−25%	2752	8	3.45	−2.31	2.15	−3.71
−50%	2752	8	3.40	−2.35	2.10	−3.79

All figures are relative to the baseline results.

rainfall over the period September–December was 160 mm in 1991 and 191 mm in 1996, leading to earlier onset of modelled field capacity, drainage and therefore leaching.

3.3. Sensitivity to price variation

Changes in N fertiliser cost of between −50 and +25% had little effect on nitrate loss (less than 1 $kg\,ha^{-1}$, Table 5), whilst increases in cost of 50% and above did reduce nitrate loss. A cereal price increase up to 50% had little impact on nitrate loss but a large effect on farm net margin. A decrease in oilseed price of 25% and greater resulted in a substitution with legumes in the rotation and a corresponding increase in nitrate loss. Apart from the substitution of oilseed rape the cropping plan was insensitive to prices, the only other change occurred at +50% cereal prices when a small amount of 1st winter wheat and oilseed rape was substituted by spring and winter barley (thus allowing the total area of cereals to increase).

3.4. Constraints on N loss and farm management practice

Table 6 shows the mean cost and effect on nitrate loss of the applied loss limits and management restrictions: these mean figures are calculated from the optimal solutions for each year generated from Farm-adapt. Note that the number of years in

Table 6
Ten-year mean relative cost and change in nitrogen loss of limit and management strategies relative to the baseline results

Scenario	Whole farm cost (£)	Cost per year £ ha^{-1}	Affected years	Infeasible years	Annualnitrate-N loss		Average nitrate-N concentration	
					$kg\,ha^{-1}$	Cost £ $kg^{-1}\,ha^{-1}$	$mg\,l^{-1}$	Cost £ $mg\,l^{-1}\,ha^{-1}$
Limits on $N–NO_3^-$ loss								
20 $kg\,ha^{-1}$ (1992/93)	1666 (7322)	5 (21)	6	4	−4.16 (−15.0)	1.16 (1.41)	−2.71 (−10.1)	1.78 (2.10)
30 $kg\,ha^{-1}$ (1994/95)	2768 (7350)	8 (21)	5	0	−6.24 (−20.3)	1.29 (1.04)	−3.19 (−9.2)	2.51 (2.31)
40 $kg\,ha^{-1}$ (1994/95)	181 (1173)	1 (3)	3	0	−1.76 (−10.3)	0.30 (0.33)	−0.81 (−4.6)	0.65 (0.73)
Max. 11.3 $mg\,l^{-1}$	–	–	10	10	–	–	–	–
Max. 35 $mg\,l^{-1}$ (1994/95)	846 (0)	2 (0)	7	2	−1.63 (0.1)	1.50	−1.32 (0.1)	1.85
Max. 50 $mg\,l^{-1}$ (1994/95)	213 (0)	1 (0)	3	0	−0.39 (0.0)	1.59 (–)	−0.41 (0.0)	1.50 (–)
Av. 11.3 $mg\,l^{-1}$ (1994/95)	3551 (7540)	10 (22)	9	6	−4.65 (−6.3)	2.21 (3.47)	−4.88 (−7.2)	2.11 (3.04)
Av. 15 $mg\,l^{-1}$ (1994/95)	4427 (4233)	13 (12)	9	1	−8.61 (−17.1)	1.49 (0.72)	−5.21 (−7.7)	2.46 (1.59)
Management constraints								
Cover crops	4294	12	10	0	−3.44	3.62	−2.86	4.35
All ploughed	1559	5	10	0	−0.60	7.50	−1.80	2.51
Limit 100 $kg\,ha^{-1}$	7685	22	10	0	0.01	−1644	0.16	−136
Limit 125 $kg\,ha^{-1}$	2436	7	10	0	−4.14	1.70	−2.52	2.80
Limit 150 $kg\,ha^{-1}$	305	1	10	0	−2.96	0.30	−1.74	0.51
No potatoes	116483	338	10	0	−1.75	193	−1.06	318
Potato @ level 1	16264	47	10	0	−0.77	61.04	−0.64	74.05
Potato @ level 2	3313	10	10	0	−0.80	12.04	−0.72	74.05

An affected year is a year in which a change from the baseline plan is required to satisfy the applied limit or constraint. An infeasible year is a year in which no solution was possible under the applied loss constraints. Figures in brackets are for the feasible year with the highest nitrate loss.

which a change from the baseline solution was required changes among scenarios: in some years the baseline solution is sufficient to meet the specified restriction. Note also that for several of the loss-restriction scenarios, there were no feasible farm plans that could meet the restriction in some years. No solution in any year reduced the nitrate-N concentration in drainage to the EU drinking water limit of 11.3 mg l^{-1} in every week. With these restrictions, it was only possible to reduce the annual average nitrate-N concentration to 11.3 mg l^{-1} in four out of 10 years. As expected, the explicit limits on nitrate loss were more effective than the management constraints that did not affect nitrate loss directly. Of the nitrate-N loss limits, the 30 kg ha^{-1} restriction had the biggest reduction in total nitrate loss and the average 11.3 mg l^{-1} restriction the biggest reduction in average nitrate-N-concentration. Note that the mean reduction in nitrate loss for the 20 kg ha^{-1} limit was lower than the 30 kg ha^{-1} limit because there were no feasible solutions for the 20 kg ha^{-1} limit in the years with the highest N-losses. Of the management restrictions, limiting N application to 125 kg ha^{-1} had the largest reduction in total loss, while cover crops had the largest reduction in average nitrate-N concentration. Limiting N application to 100 kg ha^{-1} actually resulted in a small increase in nitrate loss and concentration over the baseline results as winter field beans were substituted for oilseed rape. The 40 kg ha^{-1} nitrate-loss limit and the 150 kg ha^{-1} N application limit were the most cost-effective limit and management restriction, respectively. The high cost of not growing root crops is a result of the large fixed annual investment in specialist root machinery and storage. Reducing the fertiliser input to root crops alone was not cost effective. On the soil type studied, ploughing the whole farm rather than using reduced cultivation for all crops except potatoes resulted in little change in nitrate loss.

To explore the system response to the nitrate loss limits in more detail Table 6 also presents results for the year with the highest annual nitrate-N loss and a feasible solution. This year was the year from all the feasible years where the most change was required to reduce total nitrate loss to the applied limit. For the 40 kg ha^{-1} nitrate-N limit, the only change from the baseline was a reduction in the amount of N applied to 1st winter wheat and oilseed rape. For the 30 kg ha^{-1} nitrate-N limit, there was a reduction in the amount of N applied to 1st winter wheat, winter barley, oilseed rape and potatoes; a small area of 1st winter wheat was ploughed and set-aside and potatoes were grown with a winter cover crop. The reduction in autumn cultivation of the potato land occurs because cultivation takes place after the winter cover. For the 20 kg ha^{-1} nitrate-N limit, the changes were very similar to the 30 kg ha^{-1} changes as the solutions in years with the highest losses were infeasible. For the annual average nitrate-N concentration in drainage limit of 15 mg l^{-1}, there was a reduction in N application to 1st winter wheat and oilseed rape, potatoes were grown with winter cover and some 1st winter wheat area was ploughed. For the annual average nitrate-N concentration in drainage limit of 11.3 mg l^{-1}, 2nd winter wheat substituted for the spring barley and some 1st winter wheat was replaced with winter barley (both 2nd winter wheat and winter barley have lower nitrate losses than the respective crops that they replace – see Table 3). There was also a reduction in N applied to 1st winter wheat, winter barley, oilseed rape and potatoes, while potatoes and set-aside were grown with winter cover. Where restrictions in nitrogen concentration

Table 7
Ten-year mean cost and nitrogen loss reduction for the recommended management strategies for the potato farm with minimum 15% potato area and irrigation

Management strategy	Change from baseline	Farm cost (£)	Cost (£ ha^{-1})	Annual nitrate-N loss		Average nitrate-N concentration	
				kg ha^{-1}	Cost £ kg^{-1} ha^{-1}	mg l^{-1}	Cost £ mg^{-1} l^{-1}
Strategy 1	1st Winter wheat and oilseed rape fertilised at level 2	316 (*895*)	1 (3)	−3.07	0.30	−1.73	0.53
Strategy 2	As S1 + potatoes and winter barley fertilised at level 2, oilseed rape at level 1, cover crop grown before potatoes and after set-aside	6540 (*7315*)	19 (21)	−6.85	2.77	−4.67	4.06
Strategy 3	As S2 + 2nd winter wheat fertilised at level 1 substituted for spring barley	11222 (*10,997*)	33 (32)	−8.48	3.83	−5.88	5.53

Bracketed figures in italics are the relative costs with cereal prices increased by 50% over the baseline levels.

in drainage were applied in every week (max. 50, max. 35 mg/l) there was little change in cropping pattern in the year in which losses were highest. Overall, therefore, the trend in optimal practices selected was (lowest cost and loss reduction first): (a) reduction in N addition to 1st winter wheat and oilseed rape, (b) reduction in N addition to other crops, (c) winter cover on set aside and potatoes and d) substitution of spring cropping (spring barley) with winter cropping (2nd winter wheat). Substitution of manure with mineral fertiliser did not occur and there was no consistent trend in timing (spring vs. autumn) and method of cultivation. For the more limiting restrictions on nitrate loss, most years require change from the baseline plan. As the farmer has no advanced knowledge of the weather, the above 'worst case' plans (and their associated costs) would have to be imposed in every year to ensure the constraints on nitrate loss are met.

3.5. Recommended management strategies and longer term impacts

To assess the impact of imposing set plans on the farm model, three management strategies were selected that followed the trend in adaptation discussed above (Table 7). Mean costs were greater than where the farm could choose the optimal management practice in each year; a 4.67 mg l^{-1} reduction in nitrate-N concentration cost £19 ha^{-1} and a 5.88 mg l^{-1} reduction £33 ha^{-1}. Increasing cereal prices by 50% had little effect on the relative cost of the management strategies. However, the nitrate-N concentration in drainage over the 10-year period still exceeds the EU limit in most years even with the most severe strategy (Fig. 3).

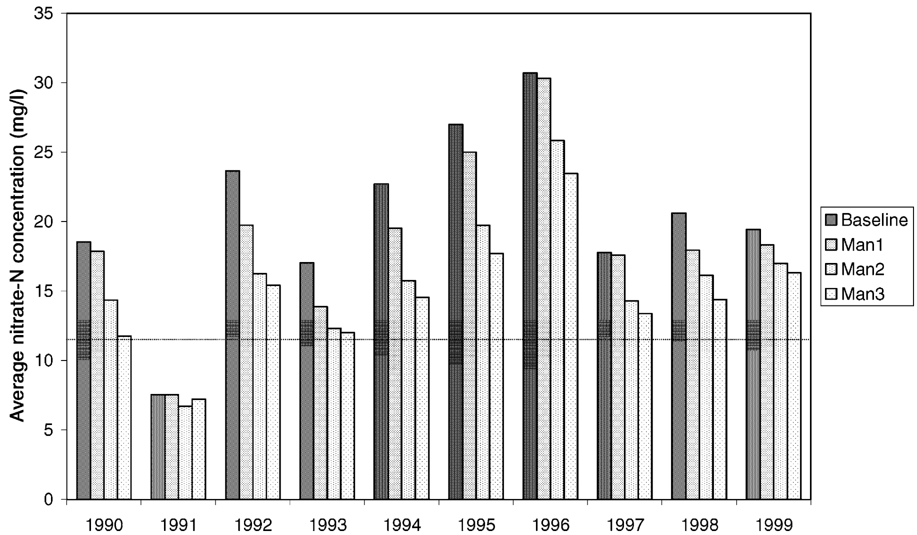

Fig. 3. Annual average nitrate-N concentration in drainage for each year of climate for the baseline results and the applied management strategies for the potato farm with irrigation and >15% potato area. Reference line is at 11.3 mg l^{-1}. Man 1 is management strategy 1, Man 2 management strategy 2 and Man 3 management strategy 3.

Table 8
Long term effect of baseline rotation, baseline rotation without manure and applied management plans on soil nitrogen and nitrate-N loss

	Nitrogen in humus and biomass (kg ha^{-1})			Annual nitrate-N loss (kg ha^{-1})		
	Year 4	Year 100	% Change	Years 5–8	Year 97–100	% Change
Baseline	3740	4983	+33.2	48.4	62.9	+29.9
No manure	3709	4640	+25.1	48.5	58.9	+21.4
Strategy 1	3738	4963	+32.8	44.9	59.1	+31.6
Strategy 2	3732	4899	+31.3	40.6	49.2	+21.1
Strategy 3	3766	5237	+39.1	39.0	53.4	+36.9

Note that nitrogen loss is from years 5–8 rather than 1–4 to allow 1st winter wheat to follow potatoes.

To assess the long term impact of the baseline rotation and applied management strategies; the three plans were run with SUNDIAL for a 100-year period (Table 8). The baseline rotation and management strategies all led to a long-term increase in soil N and nitrate loss. Substitution of spring barley with 2nd winter wheat (Strategy 3), while beneficial in the short term, led to increased losses in the long term because of the greater build up in organic matter. Note that while the detailed system runs suggested that use of manure had a small effect on nitrate loss, over a 100-year period use of manure led to greater nitrate loss, again due to build up of soil organic matter over time.

4. Discussion

4.1. Comparison with other studies

Taking the previous crop losses as a comparison, the SUNDIAL generated levels of annual nitrate loss, with the exception of oilseed rape, were in agreement with the literature (e.g. Goulding, 2000) where (level of nitrate loss, highest first) legumes = potatoes > oilseed rape = spring cereals > winter cereals. The relatively low losses from oilseed rape can partly be accounted for by reductions in recommended N levels for the crop: for example, farmers were applying an average rate of 261 kg ha^{-1} in 1986, 212 kg ha^{-1} in 1994 (Anon., 1995), as opposed to the 190 kg ha^{-1} used here (Table 1). Previous cropping has been noted to have significant effects on leaching (Shepherd and Lord, 1996). Mineralisation after set-aside, legumes and potatoes results in the relatively large mean post-harvest nitrate losses for 1st winter wheat which are shown in the SUNDIAL output for current crops (Table 3). However, Farm-adapt results show that 1st winter wheat following set-aside and potatoes are the preferred crop pairs, even in the most restrictive management strategies shown in Table 7, albeit at a lower level of applied nitrogen. Experimental work for a sandy soil rotation including potatoes and sugar beet (Shepherd and Lord, 1996) suggests that cover crops or winter sown wheat have limited impact on N leaching after potatoes, particularly in years when drainage starts before crops have time to establish (Shepherd, 1999). However, because there is sufficient labour and machinery in the optimal solution, wheat after potatoes in the Farm-adapt model is planted relatively early (end of October) and thus leaching output from SUNDIAL is reduced by crop uptake. Further, the system approach results in high value crops (1st winter wheat, potatoes) being maintained, whilst reductions in nitrate loss are achieved through less costly adaptations, such as lower applications of N.

The literature supports the growing of cover crops (e.g. Lord et al., 1999; Davies et al., 1996) before spring root crops, in line with the Farm-adapt results. The recommendations to reduce nitrogen applied also support results in the literature, however in contrast to e.g. Shepherd and Lord (1996), the economic implications of reducing nitrogen applied are quantified in Farm-adapt: the relatively flat portion of the response curves used in the model results in small reductions in yield, which when combined with low output prices, result in small reductions in profit. Type of tillage, cultivation time (spring or autumn) and time of sowing in relation to cultivations all had little impact on nitrate leaching in the SUNDIAL database and therefore on Farm-adapt results. Davies et al. (1996) found that delayed ploughing on a calcareous loam in East Anglia reduced leaching by 61% on 'bare' treatments, in a year with above average rainfall. Johnson et al. (2002) conclude that both delayed cultivation and manipulation of drilling dates can reduce leaching. To the authors' knowledge, the cultivation component of SUNDIAL has not been validated using field trial data and it is possible that this part of the model needs further development.

The framework constructed here has similar aims to those of other authors. Vatn et al. (1999) present results from the ECECMOD model that favour winter cover crops over fertiliser taxes on financial and minimisation of emission grounds, although no consideration is given to year-to-year variation. Alternative multiple objective frameworks include MODAM (Zander and Kächele, 1999; Kächele and Dabbert, 2002) which models at the farm and regional scale and the work of Pacini et al. (2003) which compares conventional, integrated and organic farming at the field and farm scale. In a review of Dutch studies, Ten Berge et al. (2000) emphasised the importance of stakeholder participation in implementing the findings of multi-objective models. The framework here differs from many of these studies by explicitly modelling several years of data enabling us to establish whether reductions are feasible in all years.

4.2. The farm-level system approach

The results illustrate the value of a farm level rather than a crop-level approach. Farm-adapt identified that relatively small, integrated changes to root cropping farms can substantially reduce nitrate loss, while maintaining the profitable root crop areas. As expected, the quantity of nitrate lost from the system was dominated by the effect of year-to-year weather variation (largely through its impact on overwinter drainage volume): the level of variation in nitrate loss attributable to weather exceeded any of the modelled farm practices. Initial experiments using SUNDIAL and mean climate data gave very low levels of leachate, as the effect of high winter rainfall, high drainage volume years was excluded. Management strategy 2 (Table 7) reduces nitrate lost on average by 6.85 $kg\,ha^{-1}$, and by more than 20 $kg\,ha^{-1}$ in 1994. As with recommendations based on field trial results (e.g. Johnson et al., 2002; Shepherd and Lord, 1996) the strategy would have to be applied across all years, including those where leaching was low. However, recommendations generated from the farm-level approach have two advantages over those generated from field trial results. First, the cost of the strategies is quantified for the whole farm system and second this cost is minimised for a given level of nitrate loss, for example by targeting nitrogen reduction and growing cover with specific crops. Other studies have suggested that adoption of effective management strategies leads to a considerable economic cost to the farmer (e.g. Fernandez-Santos et al., 1993). The results here suggest that, on sandy-soil root cropping farms, reductions in nitrate loss can be achieved at relatively low cost. This is an important finding, as for quality reasons, a substantial area of the UK potato crop is grown on soils with relatively high sand content.

4.3. Farm practices for reducing N loss

Despite the variation due to weather, changes in crop mix, reduction of fertiliser application, irrigation of potatoes and use of winter cover all resulted in reduced nitrate loss. These changes were in addition to current recommended management practice, so reduction in nitrate loss from farms where good practice has not been adopted (for example, where N applications are not matched to crop requirements) would be greater. Of the modelled practices, reduction in N application targeted at specific crops in combination with winter cover on specific crops was the most cost-effective strategy for nitrate loss reduction. Few crop mix changes reduced nitrate loss and the replacement of spring cereals for winter cereals, effective in the short-term, led to increased nitrate loss in the long term. The high financial return from potatoes resulted in little change in potato area. Replacement of manure with mineral fertiliser was ineffective in the short term, but decreased nitrate-loss in the long term. The low cost of cover crop establishment is a result of the large machinery and labour complements possessed by the modelled potato farm – there is surplus labour and machinery available at the time cover crops are sown. On other, non-root cropping farms, investment in labour and machinery may be required to achieve these practices. However, we believe that these results should be generally applicable to highly mechanised farms growing crops on sandy and sandy-loam soils. On other soil types the findings may not hold, for example delayed ploughing of spring crops may reduce losses from heavier soils.

The recommended management strategies all include some reduction in fertiliser application compared to Anon. (1994) recommended levels. Recently, the recommendations have been updated (Anon., 2000). While the new recommendations (with the exception of oilseed rape) have been reduced, they are still above Levels 1 and 2, the reduced level of application used for some crops in the management plans. The cost effectiveness of reduced fertiliser application reflects the current policy environment where, following the Agenda 2000 reforms, farmers receive lower crop prices for cereals, oilseeds and legumes.

The recommended changes reduced average nitrate-N concentrations to below the EU potable water level of 11.3 mg l^{-1} in few years. Further substantial reduction in nitrate losses would require, for example, substitution of cash crops with extensive permanent grassland (see Fig. 3).

5. Conclusions

Determination of cost-effective strategies for reducing nitrate loss from agriculture requires consideration of the range of practices available to the farmer at the farm level and their potential impact on farm profitability. In addition, the dominant effect of weather, particularly rainfall, on nitrate-loss requires consideration of climate variability. Linking estimates of nitrate loss from different management practices under different climates to the Farm-adapt model allows relatively low cost strategies to be identified; strategies that are robust – both in terms of profitability and reduction in nitrate-loss – to variation in weather. Model results show that targeted reductions in N applied to lower value cereal and oilseed crops, together with cover crops before spring-sown crops, could bring about moderate reductions in nitrate-loss and allow farms on sandy soils to continue growing potatoes. However, none of the strategies tested reduced nitrate-loss to EU limits on drinking water; furthermore, strategies that attempted to do this were relatively costly to the farm in profit foregone. The approach would benefit from further validation of the SUNDIAL model, particularly with respect to the timing and nature of cultivations and the impact that sowing date has on nitrate loss. Further work is also needed on the impact that controls on leaching have on nitrous oxide and ammonia emissions, as both these gases have arguably a greater impact on the environment than leached nitrate, through their contribution to global warming.

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