

***IACR-Rothamsted***  
*Integrated Approach to Crop Research*

---

**Modelling nitrogen cycling in the arable systems of Nepal  
using SUNDIAL**

IACR-Rothamsted Technical Report

Pete Falloon, Colin Pilbeam\* & Jo Smith

*Soil Science Department, IACR Rothamsted, Harpenden, Herts. AL5 2JO*

*\*Soil Science Department, University of Reading, Whiteknights, Reading*

December 1999

---

## **ABSTRACT**

This report describes modelling of the nitrogen cycle in the arable systems of Nepal, using SUNDIAL. This work was completed at IACR-Rothamsted under the Overseas Development Administration Research and Development Grant "Soil Fertility Management for Sustainable Hillside Farming Systems in Nepal". The work contributes to output 2 /activity 7, "Modelling of organic matter and nitrogen turnover using SUNDIAL, and the quantitative exposition of the effects of manure and fertiliser on long-term fertility of soils in the mid-hills of Nepal".

The Rothamsted SUNDIAL nitrogen turnover model has been used here to simulate data collected from the long-term experiment at Pakhribas, under a maize-millet intercrop. Since the model is not currently set up for millet crops or intercropping systems, only nitrogen cycling under the maize crop has been simulated. All seven treatments at Pakhribas have been simulated, with the addition of a short N-fertilizer recovery trial in a discard strip. The results have demonstrated that the SUNDIAL model works well under the conditions of Nepal, but further developments are needed to allow simulation of millet crops and the intercrop.

**Table of contents**

<b>ABSTRACT .....</b>	<b>1</b>
<b>1. INTRODUCTION .....</b>	<b>3</b>
<b>2. EXPERIMENTAL SITE DETAILS AND TREATMENTS .....</b>	<b>5</b>
<b>3. MODEL INPUTS .....</b>	<b>7</b>
<b>4. RESULTS &amp; DISCUSSION .....</b>	<b>8</b>
<b>5. CONCLUSIONS .....</b>	<b>17</b>
<b>6. ACKNOWLEDGEMENTS .....</b>	<b>17</b>
<b>REFERENCES .....</b>	<b>17</b>
<b>APPENDIX .....</b>	<b>20</b>

## 1. Introduction

Traditional farming systems of the mid-hills of Nepal closely integrate forestry, livestock husbandry and crop production, and require a balanced use of resources to achieve sustainability (Pilbeam *et al.*, 1999). Typically, farmers in the mid-hills of Nepal own a mix of rain-fed land on which millet is intercropped with maize, and irrigated land on which wheat is grown following rice (Sherchan *et al.*, 1999). Double cropping practices are common, but reduced inputs of organic manures and increased inorganic fertilizer use have led to concerns about the long-term sustainability of these systems. Long-term experiments using either manures or inorganic N fertilizers, singly or in combination have been established in the mid-hills of Nepal (Sherchan *et al.*, 1999; Pilbeam *et al.*, 1999). Modelling the dynamics of long-term changes in organic matter and nitrogen can provide insights into the sustainability of arable systems, and can be used to examine scenarios and time frames beyond the scope of experimental data.

The SUNDIAL fertilizer recommendation system (SUNDIAL-FRS; Smith *et al.*, 1996a; Smith *et al.*, 1998; Glendining *et al.*, 1998), developed at IACR - Rothamsted, is based upon a dynamic N turnover model derived from the Rothamsted Nitrogen Turnover model (Bradbury *et al.*, 1993). The model is closely related to the Rothamsted Carbon Model (RothC; Coleman & Jenkinson, 1996), is one of the most widely used fertilizer recommendation systems in the UK (Falloon *et al.*, 1999), and has been successfully applied in tropical systems (Bradbury & Leech, 1997). RothC has also previously been successfully applied in tropical ecosystems (Smith *et al.*, 1999; Jenkinson *et al.*, 1999a,b), and at the regional scale (Falloon *et al.*, 1998a).

SUNDIAL incorporates current scientific knowledge on the individual processes of nitrogen turnover, and integrates these processes to simulate what happens in the whole soil. It has a modular structure, each module representing one of the major nitrogen turnover processes. Inputs of nitrogen to the soil include those from fertilizer, manures, and crop residues and from the atmosphere. Nitrogen is transformed within the soil by mineralization and immobilization of organic matter and nitrification of ammonium, and removed from the soil by crop uptake, nitrate leaching and gaseous losses. SUNDIAL requires simple field specific information as input data: the soil texture class, previous cropping history, the current crop type together with its sowing and harvest dates. The crops currently supported are annual arable crops and some field-grown horticultural crops. It runs on a weekly time-step, using the weekly rainfall, evapotranspiration and mean weekly temperature as meteorological inputs. Major input data for SUNDIAL are given in Table 1.

The aims of this work were:

- 1) to determine whether the SUNDIAL model could successfully be applied under the environmental conditions of Nepal
- 2) Use SUNDIAL to integrate climate, crop and soil data collected at Pakhribas
- 3) Use SUNDIAL to investigate the sustainability of arable systems in Nepal
- 4) Identify weaknesses and future developments to be made to the model, to allow use as a fertilizer recommendation system in Nepal.

This report describes modelling exercises using the SUNDIAL model applied to the long-term experiment at Pakhribas, under a maize-millet crop. Since the model is not currently set up for millet crops or intercrop systems, only nitrogen cycling under the

maize crop have been simulated. All seven treatments at Pakhribas have been simulated, with the addition of a short N-fertilizer recovery trial in a discard strip.

*Table I. Major input data for SUNDIAL*

<b>Data Type</b>	<b>Required Input Variables</b>	<b>Useful Additional Data</b>
Soil	Type: Sand Loam Clay or Texture Class (Hall, 1977) Depth (cm) Previous Crop Type Previous Crop Yield ( $t\ ha^{-1}$ ) Period under grass in the previous 10 years	Total C ( $kg\ C\ ha^{-1}$ ) Mineral N on specified date to a specified depth ( $kg\ N\ ha^{-1}\ cm^{-1}$ ) Minimum Amount of Mineral N in Soil ( $kg\ N\ ha^{-1}\ 5cm$ ) Available Water at Field Capacity ((mm water) (150cm soil))
Weather	Total rainfall (mm/week) Total evapotranspiration over grass (mm/week) Average air temperature ( $^{\circ}C\ week^{-1}$ )	Soil Temperature on Specified Date to Specified Depth ( $^{\circ}C$ ) Soil Water Content on Specified Date to Specified Depth (mm)
Crops & Fertilizers	Type Sowing Date (week) Harvest Date (week) Yield Number of Fertilizer Applications... ... For Each Application Date (week) Amount ( $kg\ N\ ha$ ) Type(% $NO_3^-$ ; % urea; % non-urea $NH_4^+$ )	N in Crop at Harvest ( $kg\ N\ ha^{-1}$ ) N in Crop on Specified Date ( $kg\ N\ ha^{-1}$ ) N in Straw or Haulms ( $kg\ N\ ha^{-1}$ )
Organic Manures	Type Application Date (week) Amount ( $t\ manure\ ha^{-1}$ )	Dry Matter Content ( $t\ ha^{-1}$ ) Water Content ( $t\ ha^{-1}$ ) Total N in Manure ( $kg\ N\ ha^{-1}$ ) N Available in First Year ( $kg\ N\ ha^{-1}$ ) Total C in Manure ( $kg\ C\ ha^{-1}$ )



## 2. Experimental site details and treatments

Details of the experimental site are given by Sherchan *et al.* (1999). Briefly, the field site was at South Farm, Pakhribas Agricultural Centre, Dhankuta, eastern Nepal (lat 27°17'N, long 87°17'E), at an altitude of 1450m. The soil is a Dystochrept (USDA system), with a sandy clay loam texture (Table 2), a reddish brown colour and a deep profile.

*Table 2: Soil Textural Characteristics at Pakhribas*

<b>Depth (cm)</b>	<b>% sand</b>	<b>% silt</b>	<b>% clay</b>
0-25	62.10	25.90	12.00
25-50	63.40	24.00	12.60
50-75	63.00	23.60	13.40
75-100	61.30	25.50	13.20

*Table 3: Soil Bulk Density and Organic Matter at Pakhribas*

<b>Depth (cm)</b>	<b>Bulk Density</b>	<b>% U.M.</b>
0-25	1.47	1.33
25-50	1.56	0.95
50-75	1.50	0.87
75-100	1.50	0.77

Soil pH is 5.3, with an organic matter content of 1.9% (Sherchan *et al.*, 1999). The organic matter characteristics and bulk density of the experimental soil profile are given in Table 3. The soil contains on average 62.45% sand, 24.75% silt, and 12.8% clay, over 100cm depth, with a rooting depth of 50cm or more. The annual average rainfall (over 8y) is 1554 ( $\pm$  195) mm, and mean annual temperature (8y) is 22TC (Sherchan *et al.*, 1999). Previous crops were maize/millet in 1995, and maize/mustard in 1996. The data simulated here are for 2 years of a maize-millet intercrop (1997-1998). Maize was sown 15/4/97 and 16/4/98, and harvested 30/9/97 and 6/9/98. Millet was sown 14/7/97 and 18/7/97, and harvested 3/12/97 and 26/11/98. Farmyard manure contained, on average, 47.4% organic matter, 1.28% N, and 46% dry matter. Treatments were as shown in Table 4:

*Table 4: Experimental Treatments at Pakhribas*

<b>Treatment</b>	<b>Manures (kg N/ha)</b>	<b>Inorganic N fertiliser (kg/ N/ha)</b>
0 (Discard strip)	0	45 (in 1998)
1	0	0
2	0	90
3	90	0
4	45	45
5	0	45
6	45	0
7	22.5	22.5

Mineral N fertiliser was split 50:50 basal application to top dressing, and manures were applied basally. Top dressings of urea were applied in May, and the basal

dressings of DAP and urea were applied at sowing time. Fertilizer compositions were as in Table 5 (kg/ha of (00 kg N equivalent):

*Table 5: Fertilizer composition*

<b>Treatment</b>	<b>DAP</b>	<b>Urea</b>	<b>Urea top dressing</b>
2	150	39	98
4	75	19.5	49
5	7.5	19.5	49
7	37.5	9.75	24.5

Crop yields for 1997 and 1998 are given in Table 6. Measured N in grain + straw for 1997 and 1998 are given in Tables 7 and 8. There are 2 sets of differing data: the first measured in Nepal and the second measured in the UK for plots with mineral N applications only.

*Table 6: Maize and millet grain yields for 1997 and 1998 (kg/ha)*

<b>Treatment</b>	<b>Maize Yield, 1997</b>	<b>Millet Yield, 1997</b>	<b>Maize Yield, 1998</b>	<b>Millet Yield, 1998</b>
1	2931	1838	1369	1848
2	4144	1956	2335	1978
3	3549	2265	1861	2106
4	4051	1808	2186	2028
5	3632	1865	1844	1970
6	3155	1888	1.323	2332
7	3670	1943	1832	1965

*Table 7: Maize N uptake data for 1997 and 1998 (kg N/ha)*

<b>Treatment</b>	<b>N in grain + straw, 1997 (Nepal)</b>	<b>N in grain + straw, 1997 (UK)</b>	<b>N in grain + straw, 1998 (Nepal)</b>	<b>N in grain + straw, 1998 (UK)</b>
1	67.3	-	53.4	-
2	96.5	-	72.2	46.24
3	71.2	-	50.0	-
4	78.2	-	63.4	41.90
5	88.2	-	56.2	35.04
6	68.8	-	47.6	-
7	71.7	-	63.9	31.67

*Table 8: Millet N uptake data for 1997 and 1998 (kg N/ha)*

<b>Treatment</b>	<b>N in grain + straw, 1997 (Nepal)</b>	<b>N in grain + straw, 1997 (UK)</b>	<b>N in grain + straw, 1998 (Nepal)</b>	<b>N in grain + Straw, 1998 (UK)</b>
1	38.6	-	32.2	3160
2	38.8	-	32.3	24.07
3	39.9	-	37.4	33.97
4	42.0	-	36.4	29.54
5	38?	-	33.0	31.38
6	35.9	-	43.6	31.99
7	48.0	-	34.1	27.21

### 3. Model inputs

#### *Weather data*

Mean weekly temperature and total weekly rainfall data collected at the experimental site during 1997 and 1998 were used. Since evapotranspiration data were not collected at the site, long-term averaged data from Katmandu (Mueller, 1982) were used. Mean annual rainfall (1800 mm) and temperature (18.7°C) at Kathmandu (lat 24°42'N, long 85°12'E), are similar to that at Pakhribas (Mueller, 1982).

#### *Soil Data*

A user-defined soil type was used, based on the soil characteristics observed at Pakhribas. Variables used included: texture (62.45% sand, 24.75% silt, and 12.8% clay), rooting depth (50cm), previous crop grain maize in 1996, and atmospheric N deposition, estimated at around 14 kg N ha<sup>-1</sup> y<sup>-1</sup>.

Measured soil organic matter (SOM) and bulk density (BD) data (Table 3) were used to calculate stocks of soil organic carbon (SOC) in the 0-25cm and 25-50cm layers, which were summed to calculated stocks in the 0-50cm layer, as below. The factor 0.58 was used to convert SOM to SOC:

$$\begin{aligned} \text{SOC in layer} &= (\text{SOM} * 0.58) * \text{BD} * \text{layer thickness} \\ \text{0-25cm layer:} \quad \text{SOC} &= 1.33 * 0.58 * 1.47 * 25 = 28.34 \text{ t C ha}^{-1} \\ \text{25-50cm layer:} \quad \text{SOC} &= 0.95 * 0.58 * 1.56 * 25 = 21.48 \text{ t C ha}^{-1} \\ \text{Total SOC in 0-50cm layer} &= 28.34 + 21.48 = 49.83 \text{ t C ha}^{-1} \end{aligned}$$

A regression approach, based on radiocarbon data, was then used to calculate inert organic carbon (IOM) in the 0-50cm layer (Falloon *et al.*, 1998b):

$$\begin{aligned} \text{IOM} &= 0.049 * \text{SOC}^{1.139} \\ \text{IOM} &= 0.049 * 49.83^{1.139} = 4.204 \text{ t C ha}^{-1} \end{aligned}$$

Total active C was then calculated as below:

$$\begin{aligned} \text{Total active C} &= \text{Total organic C} - \text{Inert Organic C} \\ \text{Total active C} &= 49.83 - 4.204 = 45.63 \text{ t C ha}^{-1} = 45633.42 \text{ kg C ha}^{-1} \end{aligned}$$

#### *Crop data*

Observed yield data were used to set expected yields for SUNDIAL (Table 6). SUNDIAL set-up files were created with correct sowing and harvest dates for the maize crop. Crop N uptake data were used as inputs to the model (Table 7). Crop N uptake measured in Nepal (1997 and 1998, Tables 7 & 8) were used for the model runs presented in Figures 1 and 2, and the first 8 N balance sheets in the Appendix. <sup>15</sup>N-recovery data for crop and soil in 1998 were used for the model runs presented in Figures 3-6 and the second set of N balance sheets for plots 2,4,5 and 7 in the Appendix.

### *Management data*

Inorganic fertilization and manuring amounts and timing were set in SUNDIAL set-up files to reflect actual management practices. Total manure and fertilizer amounts and timings are given in Tables 4 and 5. The amount of manure applied was set to input the correct amount of N to the system (in SUNDIAL, cattle FYM consists of 25% dry matter that contains 2.8% N) thus:

11.25 kg N supplied by 1607 kg FYM  
22.5 kg N supplied by 3214 kg FYM  
45 kg N supplied by 6428 kg FYM  
90 kg N supplied by 12857 kg FYM

### *General*

SUNDIAL set-up files for each of the 7 treatments were created, using the data outlined above. Since the  $^{15}\text{N}$ -recovery experiment was carried out following application of  $^{15}\text{N}$  labelled top dressing to the maize crop in 1998, the tracer option was used in the SUNDIAL set-up files to follow the fate of this application. A further set-up file was created for during a short  $^{15}\text{N}$  recovery experiment on a discard strip (7 days), assuming the same parameters as the control plot, but with 45 kg labelled mineral N applied (17/6/98). Crop N uptake data and results of a  $^{15}\text{N}$  recovery experiment (applied as a top dressing in 1998) were used to determine total crop N uptake, crop N derived from fertilizer (cdf), crop N derived from soil (cfs), and soil N derived from fertilizer (sdf). Values used were means (and standard errors) for treatments, across experimental plots. The soil mineral N measured over 7 days during a short  $^{15}\text{N}$  recovery experiment on a discard strip was also used to validate the model.

## **4. Results & Discussion**

We have not attempted any statistical evaluation of the discrepancy between model predictions and observed data (Smith *et al.*, 1996b) for several reasons. Firstly, mineral N data were scarce for evaluating the simulation; secondly there were discrepancies between the two sets of N uptake data, measured in the UK and Nepal; thirdly we have only simulated the maize crop of a maize-millet intercrop system. Any comparisons of simulations with measured data are thus largely qualitative rather than quantitative.

Figures 1 and 2 show the time series of SUNDIAL-simulated soil mineral N at Pakhribas. The only measured data for comparison with the model predictions are from the Discard Plot'  $^{15}\text{N}$  recovery experiment, and are shown in Figure 1. In comparison to these data, the peak of soil mineral N derived from the application of 45 kg  $^{15}\text{N}$ -labelled fertiliser as predicted by the model is somewhat lower than the observed data points. However, little can be said about the comparison of these data with the simulation, since crop yields and specific management data were not available for the discard strip, which was simulated as the nil treatment (Treatment 1), with the addition of 45kg  $^{15}\text{N}$ -labelled fertiliser in 1998. However, in general the model simulations show several trends:

- 1) Increasing soil mineral N during the year, with a peak in June/July (the time of fertilizer applications)

2) Generally low background levels of soil mineral N in the profile in the late autumn/spring.

This pattern is explained firstly by the application of N in organic or mineral form during the summer. Secondly, the highest rainfall and air temperatures were observed during the summer months, increasing the rate of soil N mineralization and N turnover processes. The treatment with the largest amounts of soil mineral N was the 90kg Mineral N treatment - otherwise, amounts of soil mineral N in the profile were similar amongst the other treatments. One reason for this similarity could be that the N loss and uptake processes were able to remove N from the system at the lower levels of mineral N available shortly after N application in the cases of Treatments 1,3,4,5,6 and 7. However, the large amounts of mineral N in the profile could not be taken up or lost shortly following application (Fig. 1).

Balance sheets for the SUNDIAL simulations are given in the Appendix for each treatment, with a second set of balances for plots 2,4,5 and 7, since separate runs were completed for these plots to compare with soil and crop N-recovery experiment (1998, measured in the UK).

Table 9 shows N leaching, total N losses, N uptake, change in soil N, and N inputs for the seven treatments simulated at Pakhribas in 1998. Additionally shown are the Sustainability Index, Efficiency Index, and Environmental Impact Index (Scholefield & Smith, 1996; Smith *et al.*, 1998), calculated from the formulae below:

Sustainability Index (S.I.) = Total N input / (N removed in product + other losses)

Efficiency Index (E.I.) = N in product / N input as fertilizer

Environmental Impact Index (Env.I.) = Total N losses / N in product

Table 9: Leaching, total N losses, total N uptake, total N inputs, sustainability, efficiency and environmental impact of different treatments at Pakhribas (1998). Figures in brackets are fertilizer/manure N applications;  $\Delta$ Soil, N is from harvest of 1997 to harvest 1998

Trt no	Manures (kg N/ha)	Inorganic N fertiliser (kg N/ha)	Leaching (kg N/ha)	Total Losses (kg N/ha)	Total Uptake (kg N/ha)	Total N inputs (kg/ha)	$\Delta$ Soil N (kg/ha)	S.I.	Ef.I.	Env.I.
1	0	0	26	61	51	14(0)	-89	0.09	Inf.	1.20
2	0	90	64	117	72	104(90)	-73	2.51	0.80	1.63
3	90	0	30	94	50	104(90)	-31	1.86	0.55	1.88
4	45	45	41	104	63	104(90)	-53	2.21	0.70	1.65
5	0	45	48	94	56	59(45)	-80	3.49	1.24	1.68
6	45	0	35	86	48	59(45)	-67	3.08	1.07	1.79
7	22.5	22.5	27	70	62	59(45)	-64	3.29	1.38	1.13

A value of less than 1 for the Sustainability Index indicates the system is undergoing net loss of N and is not sustainable over the long term. A high Efficiency Ratio indicates a more productive system, and a high value of the Environmental Impact Index indicates greater potential damage to the environment per unit of product.

Treatment 2 (High Inorganic N) had the greatest N leaching and N losses, as would be expected: lowest losses were found in the nil treatment, although N losses and N leaching were only a little higher in Treatment 7 (Low FYM + Inorganic N). The highest uptake was observed in the High Inorganic N treatment (7). All Treatments were predicted to have undergone a net loss of Soil N, with the largest losses from the High Inorganic N (2) and High Split Inorganic Manure N (5) treatments. In terms of sustainability, the Nil Treatment was predicted to be unsustainable in the long term,

since it was undergoing a net loss of N - whilst all other treatments were predicted to be sustainable in the long term. The highest sustainability indices were obtained for Treatments 5 and 7, Low Inorganic N and Low Inorganic N + FYM. All of the High N Treatments (2,3,4) were low efficiency systems by comparison to the Low N treatments (5,6,7), with Treatment 7 (Low Inorganic N + FYM) showing the highest efficiency. Treatment 7 also had the lowest environmental impact in comparison with the other systems.

Figure 3 shows the simulated and measured total N uptake data for the  $^{15}\text{N}$  recovery experiments (data measured in the UK). Total N uptake as predicted by SUNDIAL was similar to that measured (simulations all within the standard error of measurements), with a similar trend to measured data. A good model fit to these data is expected, since total N uptake data were used as model inputs. Most N was taken up by Treatment 2, followed by 4,5, and 7.

Figure 4 shows simulated and measured crop-N derived from fertilizer. In general, SUNDIAL predicted more crop-N derived from fertilizer than was measured, with the difference being of the order of 2-6kg N. All simulated values were outside the standard error of measured data. The model predicted a similar trend to the measured data, with the most crop-N derived from fertilizer in Treatment 2, followed by 4,5, and 7. Since we have only simulated the maize crop of a millet-maize intercrop system, it was expected that the model would predict more N derived from fertilizer in the crop than was observed: some of this N would have been taken up by the millet intercrop. Measured values of N uptake by the Millet crop (Table 8) were around 20-40 kg N - rather greater than the discrepancy between our modelled and measured N uptake data for the maize crop. This indicates a more complex interaction in the cropping system than simple addition of N uptake from the two crops. Therefore, it may also be unreasonable to consider the two crops in isolation, N being competed for by the crops from both fertilizer N and soil N supply.

Figure 5 shows simulated and observed crop N derived from soil. In general, the model predicted a little less N uptake from soil than was measured, with the difference between observed and predicted values being of the order of 2-10kg N. The model again predicted a similar trend between treatments to the measured data - with the most N derived from soil being observed in Treatment 2, followed by 4,5, and 7. Model predictions were close to the standard error of the measured data. We would expect the model to simulate less N in the crop derived from soil, since in the intercrop system, the maize crop would have had to have taken up more N from the soil due to competition for fertilizer N with the millet crop. Despite the limitations of simulating only the maize crop, for the most part, the model simulations are within the standard error of the measured data.

Figure 6 shows simulated and measured soil N derived from fertilizer. There are no clear differences between simulated and observed results - in Treatments 2 and 4 the model underestimated soil N derived from fertilizer, and in Treatments 5 and 7 the tendency was to overestimate measured data. However, the differences were small, and modelled results were and all within the (large) standard error of the measured data.

Figure 1: Measured and simulated soil mineral N (0-25cm) at Pakhribas

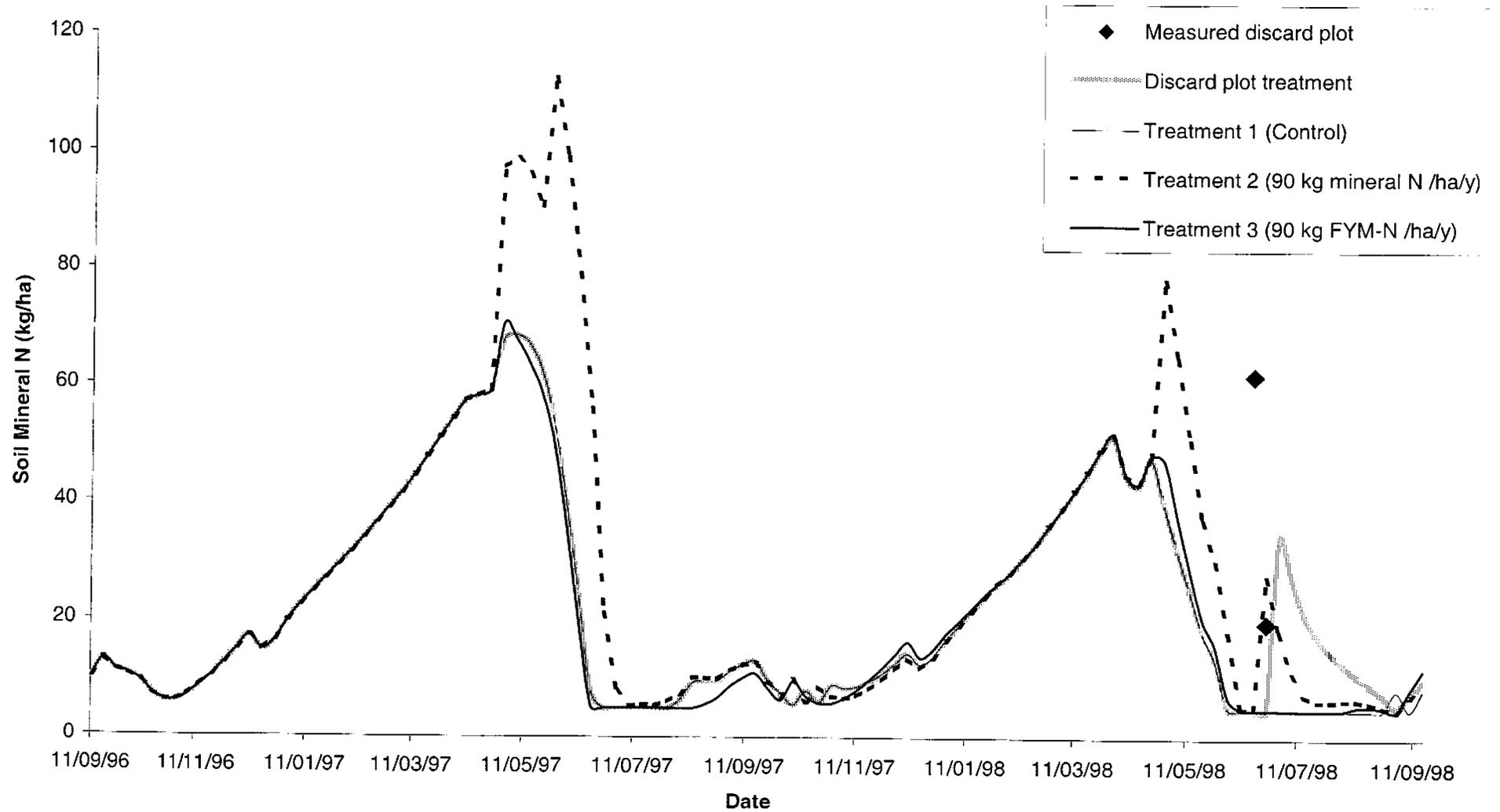


Figure 2: Simulated soil mineral N (0-25 cm) at Pakhribas

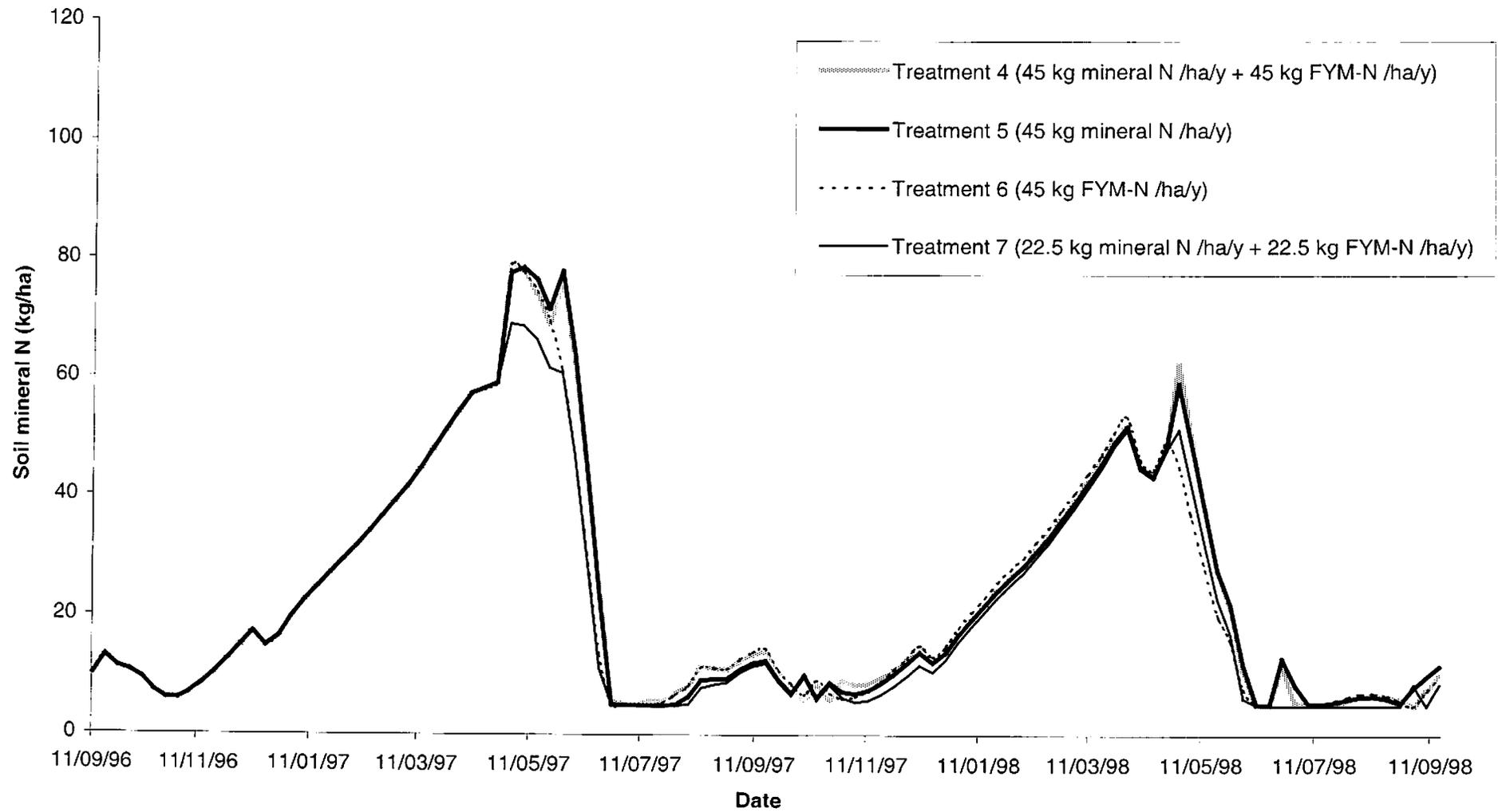


Figure 3: Measured and simulated total Crop N uptake (grain + straw) at Pakhribas, Harvest 1998

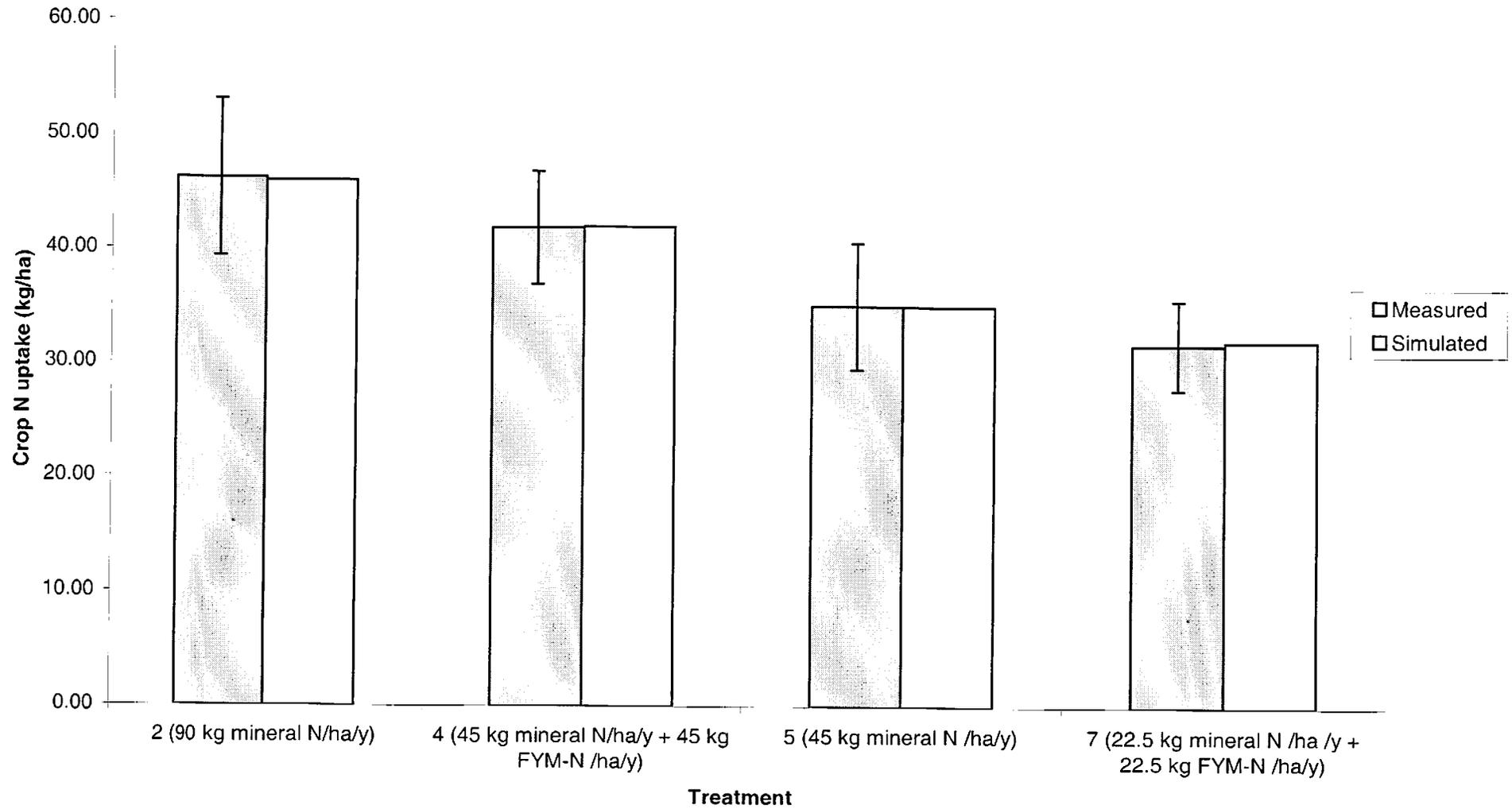


Figure 4: Measured and simulated Crop N derived from fertilizer at Pakhribas, Harvest 1998

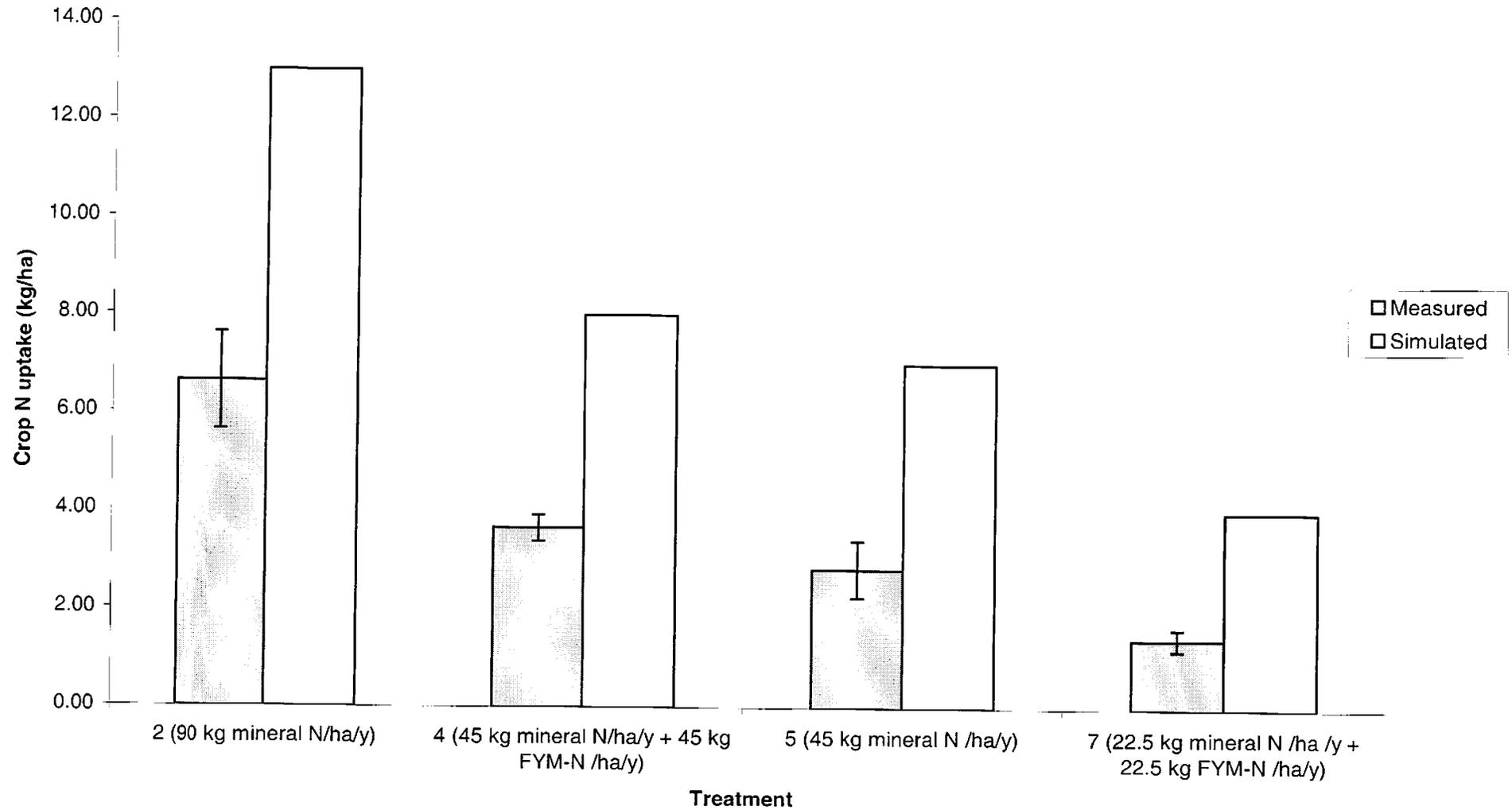


Figure 5: Measured and simulated Crop N derived from soil at Pakhribas, Harvest 1998

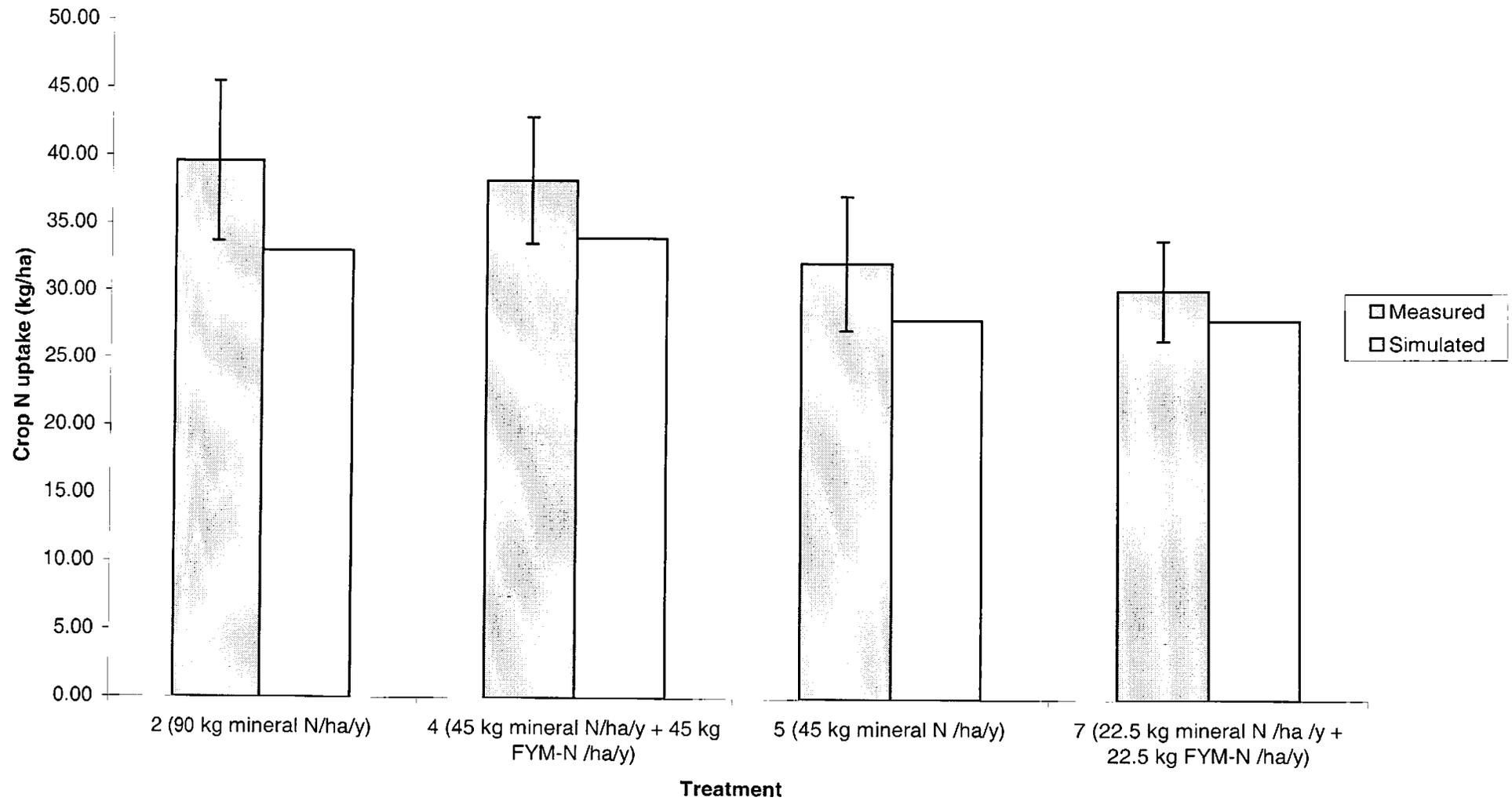
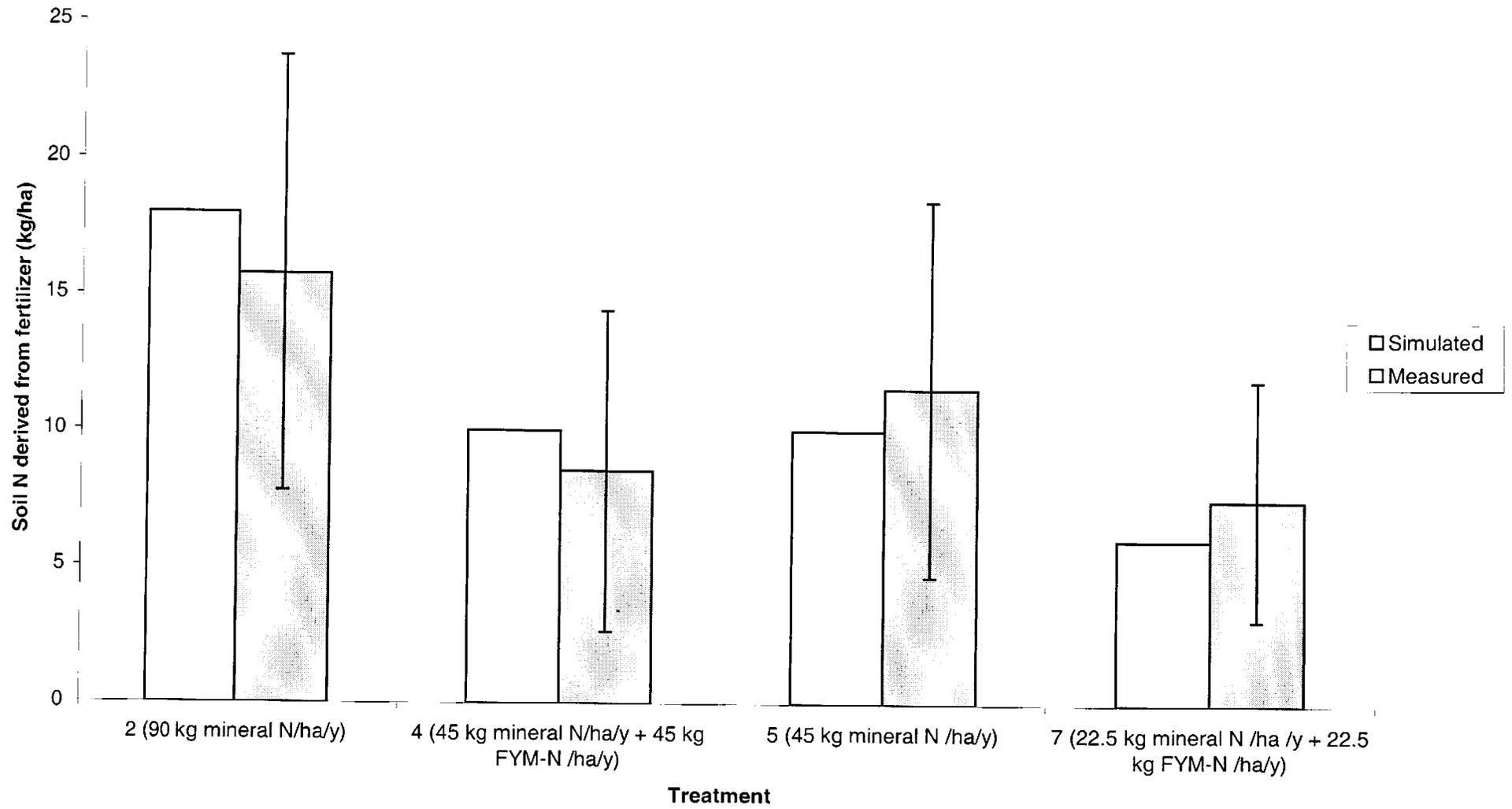


Figure 6: Measured and simulated soil N derived from fertilizer at Pakhribas, Harvest 1998



## 5. Conclusions

It has been demonstrated that the SUNDIAL model provides an acceptable simulation of nitrogen cycling under maize at the Pakhribas site. The model predictions of soil mineral N, N uptake from soil and fertilizer, and soil N derived from fertilizer were all in reasonable agreement (generally within the standard error) with available measured data. This agreement was obtained despite the fact that a) the millet crop had not been simulated and b) the model had not been adapted for the intercrop system.

In examining the simulations of the  $^{15}\text{N}$  labelled fertilizer applications (Treatments 2,4,5,7), it was clear that simulation of the two crops in isolation would not account for the interactions observed in the intercrop system. The model would need further development to allow for two crops growing simultaneously, for competition between crops, and effects such as shading. In terms of other general model developments and further work, simulation of other field sites, particularly testing in dryland and wetland rice-based systems, would allow more a comprehensive assessment of the arable systems of Nepal.

The SUNDIAL simulations also allowed a simple assessment of the sustainability, efficiency and environmental impact of different forms and amounts of fertilization on the maize crop. It has previously been suggested that in many regions, sustainable crop production with acceptable yields can only be achieved using appropriate amounts of both inorganic and organic fertilizers (Scherchan *et al.*, 1999). The SUNDIAL simulations suggest that, at least for the maize crop, the Low Input system at Pakhribas with both inorganic and organic N combined high levels of sustainability and efficiency with a low environmental impact. The high input treatments, especially that using only mineral N, generally had greater environmental impact, lower sustainability and lower efficiency in comparison with the low input systems.

## 6. Acknowledgements

Thanks to M.Glending (IACR) for assistance with SUNDIAL model simulations, and to J. Gaunt (IACR), S.Fortune and P.Smith (IACR) for useful discussions.

## References

- Bradbury NJ, Whitmore AP, Hart PBS, Jenkinson DS (1993) Modelling the fate of nitrogen in crop and soil in the years following the application of  $^{15}\text{N}$  - labelled fertiliser to winter wheat. *Journal of Agricultural Sciences* 121: 363-379.
- Bradbury, NJ and Leech, PK. (1997) Optimization of nitrogen fertilization of maize in the West African savannah zone. In: Rapport Semestreil no. 6, Project STD3 no. TS3-CT94-0262, 'Raisonnement de la fertilisation azotee chi mais en zone de savane ouest africaine en fonctionne des conditions pedoclimatiques. Juin 1997. p29-32.
- Coleman K, Jenkinson DS (1996) RothC-26.3 - A model for the turnover of carbon in soil. In: Powlson DS, Smith P, and Smith JU. (Eds.), Evaluation of soil organic matter models using existing, long-term datasets. NATO ASI Series I, Vol. 38, Springer-Verlag, Heidelberg, pp. 237-246.

- Falloon PD, Smith P, Smith JU, Szabo J, Coleman K, and Marshall S (1998a) Regional estimates of carbon sequestration potential: linking the Rothamsted Carbon Turnover model to GIS databases. *Biology and Fertility of Soils* 27: 236-241.
- Falloon P, Smith P, Coleman K, and Marshall S (1998b) Estimating the size of the inert organic matter pool for use in the Rothamsted carbon model. *Soil Biology and Biochemistry* 30: 1207-1211.
- Falloon PD, Smith JU and Smith P (1999) A Review of Decision Support Systems for fertiliser application and manure management. *Acta Agronomica Hungarica* 47: 227-236
- Glendining M, Bailey N, Smith JU, Addiscott TM, Smith P (1998) *SUNDIAL-FRS User Guide Version 1.0*. IACR-Rothamsted, Harpenden, Herts, UK.
- Jenkinson DS, Harris HC, Ryan J, McNeill, AM, Pilbeam CJ, and Coleman K (1999a) Organic matter turnover in a calcareous clay soil from Syria under a two-course cereal rotation. *Soil Biology and Biochemistry* 31: 687-693.
- Jenkinson DS, Meredith J, Kinyamario JI, Warren GP, Wong MTH, Harkness DD, Bol R, Coleman K (1999b) Estimating net primary production from measurements made on soil organic matter. *Ecology* (accepted).
- Mueller, MJ. (1982) Selected climatic data for a global set of standard stations for vegetation science. Tasks for Vegetation Science 5. Dr W Junk Publishers, The Hague. 306pp.
- Pilbeam CJ, Gregory PJ, Tripathi BP, and Munankarmy RC (1999) Nitrogen fluxes through sustainable farming systems in the mid-hills of Nepal. Chapter in: *Sustainable Management of \* Soil Organic Matter' BSSS99 Conference Proceedings*. CABI, Wallingford, UK (in press)
- Scholefield, D, Smith, JU (1996) Nitrogen flows in ley-arable systems. *Legumes in Sustainable Farming Systems*, Craibstone.
- Sherchan DP, Pilbeam CJ, and Gregory PJ (1999) Response of wheat-rice and maize/millet to fertilizer and manure applications in the mid-hills of Nepal. *Experimental Agriculture* 35: 1-13.
- Smith JU, Bradbury NJ, Addiscott TM (1996a) SUNDIAL: A PC-based system for simulating nitrogen dynamics in arable land. *Agronomy Journal* 88: 38-43.
- Smith, JU, Smith, P, Addiscott, TM (1996b) Quantitative methods to evaluate and compare soil organic matter (SOM) models. In: Powlson, D.S., Smith, P., Smith, J.U. (Eds.), Evaluation of soil organic matter models using existing, long-term datasets. NATO ASI Series I, Vol. 38, Springer-Verlag, Heidelberg, pp. 183-202.
- Smith JU, Dailey AG, Glendining MJ, Bradbury NJ, Addiscott TM, Smith P, Bide A, Boothroyd D, Brown E, Cartwright R, Chorley R, Cook S, Cousins S, Draper S, Dunn M, Fisher A., Griffith P, Mayes C, Lock A, Lord S, Mackay J, Malone C, Mitchell D, Nettleton D, Nicholls D, Overman H, Purslow J, Scholey A, Senior S, Sim L, Taylor P (1997). Constructing a nitrogen fertiliser recommendation system: what do farmers want? *Soil Use and Management* 13: 225-228.
- Smith, J, Scholefield, D, Glendining, M, Stockdale, E (1998) Using models to optimise the efficiency of nitrogen across whole farm rotations. In: Keulen, H. van, E.A. Lantinga & H.van Laar (eds) *Proceedings of an International Workshop on mixed farming systems in Europe*, Dronten/Wageningen, The Netherlands 25-28 May 1998. Ir. A.P.Minderhoudhoeve-series no. 2.

Smith P, Falloon P, Coleman K, Smith J, Piccolo M, Cerri C, Jenkinson D S, Ingram J S I, and Szabo J (1999) Modelling soil carbon dynamics in tropical ecosystems *Advances in Soil Science* (in press).

## Appendix

1. SUNDIAL annual N balances for all treatments at Pakhribas (units are kg/ha)

Pakhribas Discard Plot N balance

---

	Harvest of <b>Year 1997</b>		Harvest of Year 1998	
	Total	Labelled	Total	Labelled
<b>HUM+BIO</b> N pool	5304	0	5219	11
RO N pool	17	0	13	3
Soil N03	19	0	25	4
Soil NH4	15	0	16	0
Sub-Total	5355	0	5272	18
Fertilizer	45	45	47	8
Stubble N	8	0	44	7
			2	1
Atms. input	14	0	53	14
(Mineraln.)	141	-6	47	5
Sub-Total	67	45	150	27
Grand Total	5423	45	5423	45

Pakhribas Treatment 1 N balance

---

	Harvest of <b>Year 1997</b>		Harvest of Year 1998	
	Total	Labelled	Total	Labelled
<b>HUM+BIO</b> N pool	5304	0	5219	11
RO N pool	17	0	13	3
Soil N03	19	0	25	4
Soil NH4	15	0	16	0
Sub-Total	5355	0	5272	18
Fertilizer	45	45	47	8
Stubble N	8	0	44	7
			2	1
Atms. input	14	0	53	14
(Mineraln.)	141	-6	47	5
Sub-Total	67	45	150	27
Grand Total	5423	45	5423	45



Pakhribas Treatment 3 N balance

	Harvest of Year 1997		Harvest of Year 1998	
	Total	Labelled	Total	Labelled
HU14+BIO N	5312	0	5237	9
RO N pool	18	0	17	5
Soil NO3	20	0	22	2
Soil NH4	15	0	16	0
Sub-Total	5365	0	5292	16
Fertilizer	90	45	54	5
Stubble N	12	0	(Root N return)	11
			Senescence	1
Atms. input	14	0	Crop	20
(Mineraln.)	149	-2	Leaching	4
Sub-Total	116	45	189	29
Grand Total	5481	45	5481	45

Pakhribas Treatment 3 N balance

	Harvest of Year 1997		Harvest of Year 1998	
	Total	Labelled	Total	Labelled
HUM+BIO N pool	5360	0	5325	0
RO N pool	19	0	17	0
Soil NO3	17	0	23	0
Soil NH4	15	0	16	0
Sub-Total	5412	0	5381	0
Fertilizer	90	0	Denitrif.	0
Stubble N	9	0	(Root N return)	0
			Senescence	0
Atms. input	14	0	Crop offtake	0
(Mineraln.)	171	0	Leaching	0
Sub-Total	113	0	144	0
Grand Total	5525	0	5525	0



Pakhribas Treatment 4 N balance

---

	Harvest of Year 1997		Harvest of Year 1998		
	Total	Labelled	Total	Labelled	
HUM+BIO N pool	5338	0	5285	5	
RO N pool	19	0	17	3	
Soil N03	21	0	21	1	
Soil NH4	15	0	16	0	
Sub-Total	5392	0	5339	9	
Fertilizer	90	23	Denitrif.	60	1
Stubble N	90		(Root N return)	58	7
			Senescence	3	1
Atms. input	140		Crop offtake	63	11
(Mineraln.)	158	-1	Leaching	41	0
Sub-Total	114	23		167	14
Grand Total	5506	23		5506	23

Pakhribas Treatment 5 N balance

---

	Harvest of Year 1997		Harvest of Year 1998		
	Total	Labelled	Total	Labelled	
HUM+BIO N pool	5310	0	5221	5	
RO N pool	18	0	18	3	
Soil N03	17	0	25	1	
Soil NH4	15	0	16	0	
Sub-Total	5360	0	5280	9	
Fertilizer	45	23	Denitrif.	44	2
Stubble N	11	0	(Root N return)	53	7
			Senescence	3	0
Atms. input	14	0	Crop offtake	56	11
(Mineraln.)	152	-1	Leaching	47	1
Sub-Total	70	23		150	14
Grand Total	5430	23		5430	23



Pakhribas Treatment 6 N balance

---

	Harvest of Year 1997		Harvest of Year 1998	
	Total	Labelled	Total	Labelled
HUM+BIO N pool	5332	0	5271	0
RO N pool	17	0	12	0
Soil NO3	22	0	21	0
Soil NH4	15	0	16	0
Sub-Total	5387	0	5320	0
Fertilizer	45	0	Denitrif.	49
Stubble N	8	0	(Root N return)	0
			Senescence	2
Atms. input	14	0	Crop	48
(Mineraln.)	153	0	Leaching	35
Sub-Total	68	0		134
Grand Total	5454	0		5454

Pakhribas Treatment 7 N balance

---

	Harvest of Year 1997		Harvest of Year 1998	
	Total	Labelled	Total	Labelled
<b>HUM+BIO</b> N pool	5325	0	5259	3
RO N pool	18	0	17	2
Soil NO3	16	0	19	0
Soil NH4	15	0	16	0
Sub-Total	5375	0	5311	4
Fertilizer	46	11	Denitrif.	43
Stubble N	9	0	(Root N	58
			Senescence	0
Atms. input	14	0	Crop offtake	62
(Mineraln.)	152	0	Leaching	27
Sub-Total	68	11		132
Grand Total	5443	11		5443

Pakhribas Treatment 2 N balance (UK 15N data)

---

	Harvest of Year 1997		Harvest of Year 1998		
	Total	Labelled	Total	Labelled	
HUM+BIO N pool	5312	0	5237	10	
RO N pool	18	0	17	5	
Soil NO <sub>3</sub>	20	0	26	3	
Soil NH <sub>4</sub>	15	0	16	0	
Sub-Total	5365	0	5296	18	
Fertilizer	9045		Denitrif.	61	7
Stubble N	120		(Root N return)	60	11
			Senescence	2	1
Atms. input	140		crop offtake	46	13
(Mineraln.)	149 -4		Leaching	76	7
Sub-Total	116	45		186	27
Grand Total	5481	45		5481	45

Pakhribas Treatment 4 N balance (UK 15N data)

---

	Harvest of Year 1997		Harvest of Year 1998		
	Total	Labelled	Total	Labelled	
HUM+BIO N pool	5338	0	5284	6	
RO N pool	19	0	17	3	
Soil NO <sub>3</sub>	21	0	24	1	
Soil NH <sub>4</sub>	15	0	16	0	
Sub-Total	5392	0	5342	10	
Fertilizer	90	23	Denitrif.	64	2
Stubble N	90		(Root N return)	58	8
			Senescence	2	0
Atms. input	14	0	Crop offtake	42	8
(Mineraln.)	158	-1	Leaching	57	2
Sub-Total	114	23		165	12
Grand Total	5506	23		5506	23



Pakhribas Treatment 5 N balance (UK 15N data)

---

	Harvest of Year 1997		Harvest of Year 1998	
	Total	Labelled	Total	Labelled
HUM+BIO N pool	5310	0	5229	6
RO N pool	18	0	15	3
Soil N03	17	0	24	1
Soil NH4	15	0	16	0
Sub-Total	5360	0	5284	10
Fertilizer	45	23	49	3
Stubble N	11	0	53	7
Atms. input (Mineraln.)	14	0	35	7
	147	-2	60	2
Sub-Total	70	23	146	12
Grand Total	5430	23	5430	23

Pakhribas Treatment 7 N balance (UK 15N data)

---

	Harvest of Year 1997		Harvest of Year 1998	
	Total	Labelled	Total	Labelled
HUM+BIO N pool	5324	0	5260	4
RO N pool	19	0	17	2
Soil N03	22	0	22	0
Soil NH4	15	0	16	0
Sub-Total	5380	0	5315	6
Fertilizer	46	11	49	1
Stubble N	7	0	58	5
Atms. input (Mineraln.)	14	0	32	4
	149	0	49	0
Sub-Total	66	11	131	5
Grand Total	5446	11	5446	11

