The development of systems of milk production and grazing management based on low stocking rates and very low artificial nitrogen inputs.

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Abstract

There is increasing pressure on to reduce nitrogen (N) inputs to agricultural production systems within the European Union. This three-year experiment examined the impact of lowering N-input/ha on milk output, carrying capacity and N losses. In Ireland, a dairy cow is classified as excreting 85 kg organic N per year. There were four treatments involving annual stocking rates and fertilizer N inputs as follows: (1) 2.5 cows/ha & 350 kg/ha (Intensive), (2) 2.5 cows/ha & 250 kg/ha (Moderate), (3) 2.1 cows/ha & 175 kg/ha (Extensive) and (4) 1.75 cows/ha & 80 kg/ha (Minimal). Swards were initially composed predominantly of perennial ryegrass and contained white clover. The primary aim was to supply sufficient pasture to meet the feed requirements of the lactating cows during the main grazing season. Subject to meeting this requirement the objective was to produce enough grass to meet winter-feed requirements as grass-silage. Production of grass-silage was indicative of carrying capacity. There were 18 cows per treatment each year. Concentrates fed were 595 kg/cow/year.

There were no significant differences in yields (mean ± SEM kg/cow/year) of solids-corrected milk (6210 ± 97), fat (263 ± 4.4), protein (225 ± 3.3) and lactose (301 ± 5.2) between treatments combined over years. Silage production was sufficient to meet winter-feed requirements (i.e. 1.40 t DM/cow) on all treatments except Moderate, which was 0.87 of requirement. Measurement of soil mineral N concentrations indicated largest losses from Intensive during the winter. However, measurement of nitrate N in drainage water during the winter indicated low concentrations (mg/litre) from all treatments; 2.4 from Intensive, 2.0 from Mininal, 0.9 from Moderate and 0.9 from Extensive. The comparably high mean concentrations associated with Minimal were attributed to the high proportion of white clover in these swards and the breakdown of clover stolon releasing mineral N into the soil during the winter months.

The main findings were:

(1) No difference in milk output per cow even under low fertilizer N inputs

(2) A relationship between requirement for fertiliser N and stocking rate along the line:

$$\text{Fertilizer N req.} = (\text{SR} \times 300) - (300 + \text{background-N})$$

Where SR is stocking rate in cows per ha and background N is the release of N from net mineralization of soil organic matter N. The average value for background-N is around 130 kg/ha.

(3) Very high levels of productivity from grass + white clover swards receiving 80 kg N/ha/year with around 80% of the carrying capacity of the Intensive treatment.

(4) Very low losses of nitrate-N in drainage water under organic N loads of up to 300 kg/ha. Losses of nitrate-N in drainage water accounted for less than 5% of N losses in the experiment except on the clover-system. It is likely that denitrification and losses of di-nitrogen (N_2) and nitrous oxide (N_2O) gasses were the main pathways for loss. This is consistent with the heavy wet imperfectly drained soils, high rainfall, intermittent soil saturation and the mild conditions experienced at Solohead.

Introduction

There is increasing pressure to lower N inputs to dairy production within the European Union. The objective of the Nitrates Directive (91/676/EEC) is to curtail nitrate losses from agriculture to surface and ground waters. The Irish government is also committed to lowering ammonia emissions under the National Emissions Ceilings Directive (2001/81/EC) and nitrous oxide emissions under the National Climate Change Strategy (DAFRD, 2002). In the future meeting the requirements of the Water Framework Directive will create further pressure to lower nutrient emissions for agriculture. This three-year experiment (2000 to 2003) examined the impact of lowering N-inputs (organic and fertilizer N) to permanent grassland on milk output per cow, stock carrying capacity, soil mineral N concentrations and nitrate N concentrations in drainage water during the winter.

One of the objectives of this experiment was to investigate the quantity of fertilizer N required on dairy farms stocked at 2.5 cows/ha. The official Teagasc recommendation (Gately, 1994) was 225 kg fertilizer N/ha, whereas unofficial recommendations from Moorepark were around 350 to 380 kg N/ha (*e.g.* Dillon *et al*., 1995). One of the objectives of this experiment was to resolve this issue in conjunction with research being conducted in Project No. 4984 and more recently Project No. 5001 & 5150, which are concerned with fertilizer N use on grassland. A second objective was to investigate the quantity of fertilizer N required on dairy farms stocked at around 2.1 cows/ha. The official Teagasc recommendation (Gately, 1994) was 100 kg fertilizer N/ha whereas National Farm Survey data indicated that around 175 kg fertilizer N/ha was being applied on dairy farms stocked at around 2.0 livestock units (LSU) per ha (Coulter *et al*., 2002). This was another discrepancy that needed to resolved particularly because the official Teagasc recommendations are being integrated into legislation within the Action Programme being implemented to meet the requirements of the Nitrates Directive.

Part of the reason for the above discrepancy may have been due to the official Teagasc recommendations being based on experiments in which white clover made a considerable contribution to productivity at lower fertilizer N input and stocking rate systems. White clover is not abundant in Irish grassland. Therefore the relevance of recommendations based on experiments involving grass + white clover swards is questionable. A third objective of this experiment was to examine the potential contribution of white clover in dairy systems that are compatible with the requirements of the Rural Environment Protection Scheme (REPS). Under this scheme the total allowable N input is 260 kg/ha. Of this total N the organic N input cannot exceed 170 kg/ha. Furthermore, the fertilizer N input/ha cannot exceed the input of organic N/ha. In this experiment the treatment compatible with REPS was stocked at 1.75 cows per ha. In Ireland, a dairy cow is classified as excreting 85 kg organic N per year. Therefore this stocking rate is the equivalent of an organic N load of 149 kg N/ha. Fertilizer N input was 80 kg/ha giving a total N of 229 kg/ha, which is well within the REPS limit outlined above. Dillon *et al*. (2003) and Donworth & Maher (2003) showed that REPS was an option worth consideration by medium-sized average-cost diary producers where the amount of quota available per ha is medium to low. This represents a considerable number of dairy farmers when it is taken into account that more than two-thirds of milk production takes place on farms stocked at less than 2.0 LSU/ha (Connolly *et al*., 2002).

In the past, in many experiments looking at the potential role of white clover in dairy production systems (Ryan, 1989; Bax, 1990; Schils, 1996) the white clover swards were sown down before the commencement of the experiment. Therefore comparisons between grass-only and clover-based systems were made on the basis of newly sown grass + clover swards. Experiments conducted on this basis are of little relevance to the vast majority of farmers in Ireland. In Ireland 91% of the agricultural area is under permanent grassland. Only enough grass-seed is sold to reseed around 2% of the agricultural area each year. A considerable proportion of this seed is sown on land in arable rotation etc. Taking these factors into account it is reasonably obvious that only a very small proportion of Irish grassland is renovated as a ‘grass-to-grass’ re-seed each year and most of this is likely to take place on more intensively managed farms.

White clover can only have a useful role on extensively managed farms in Ireland if it can be introduced into permanent grassland at little cost. It is known that white clover seed can be successfully established following broadcasting the seed into permanent grassland (Sheldrick, 2000). This approach was adopted as a long-term strategy at Solohead. This approach is considered to be most appropriate to conditions in Ireland where 90% of agricultural area is under permanent grassland, around one third of farmers are in REPS and <10% of farms stocked at rates of >2.0 LSU/ha) (Connolly *et al*., 2002). This approach to clover management is subject to further investigation (Project No. 5150).

One of the questions arising during the initiation of this experiment was whether it would be possible to maintain milk output per cow from grassland receiving low inputs of fertilizer N. Under low N fertilisation, low crude protein in pasture can lead to a drop in pasture intake by grazing cows and lower milk production

(Delaby *et al*., 1996; Delagarde *et al*., 1997; Delagarde *et al*., 1999; Peyraud *et al*., 2001). Therefore one of the key issues examined in this experiment was the impact of lowering fertilizer N inputs to grassland on milk output per cow under Irish conditions.

A second key issue was the effect of fertilizer N input on carrying capacity as outlined above. However, there was potential for complication between elucidating the effects of lowering fertilizer N inputs on (1) milk output per cow and (2) carrying capacity per ha. To overcome this problem it was decided at the start of the experiment that the primary objective of grassland management was to maintain pasture supply in line with cow requirements during the grazing season on each of the treatments. Producing sufficient grass-silage for the winter period was a subordinate objective. Therefore any shortfall in grassland productivity due to the difference in N-input would be recorded as insufficiency in the quantity of silage produced (and vice versa). Therefore the production of grass-silage was used to give an indication of carrying capacity of the various treatments imposed in this experiment.

One of the central mechanisms of the Nitrates Directive to control nitrate losses from agriculture is to restrict organic N loading to 170 kg/ha (or a stocking rate of 2.0 cows/ha) in Ireland. Therefore an important objective of this experiment was to measure losses of N from the various organic N loadings imposed focusing particularly on nitrate losses in drainage water. Losses of N were examined (1) from the perspective of a whole farm balance for each of the treatments, (2) mineral N (nitrate and ammonium) availability in the soil of each of the treatments in late September, late November and early February of the winters of 2001/02 and 2002/03, and (3) nitrate-N in drainage water at 1 m depth in the soil of each of the treatments during the winters of 2001/02 and 2002/03.

Summary of Objectives

- To examine the impact of lower fertilizer N inputs on milk output/cow
- To establish fertilizer N requirements of grassland at different stocking rates of dairy cows
- To evaluate the usefulness of white clover introduced into permanent grassland
- To determine N losses from a range of different N-input (organic N loads and fertilizer N) systems and to assess losses of nitrate-N to drainage water under the soil and climatic conditions at Solohead. The soils of Solohead are representative of around 18% of the agricultural land area of Ireland (Walsh, 1984).

Materials and Methods

Site Characteristics

This experiment was carried out at the Moorepark Research Station, Solohead in Co. Tipperary (Latitude 52°51'N, Longitude 08°21'W) between January 2000 and March 2003. The topography of the site is relatively flat. The soil type is a mixture of Grey-Brown Podzolic (Elton) and Gley (Howardstown) soils (Gardner & Radford, 1969). The soils has 131 g/kg organic matter in the topsoil (0 to 200 mm) and a total soil N content of 10.8 t/ha in the upper 200mm (Table 1). This soil has the capacity to release around 120 kg N/ha through net mineralization of soil organic matter during the main growing season extending from mid-February to the end of October (O'Connell *et al*., 2003).

Table 1. Soil Characteristics at different depths in the soil at Solohead

Soil Depth (mm)	Bulk Density (g/cm^3)	Organic Matter (g/kg)	Total N (t/ha)
0 to 200	1.001	131	10.81
200 to 400	1.278	96	8.69
400 to 600	1.472	74	6.18
600 to 800	1.507	60	4.52

Drainage is impeded contributing to waterlogged conditions under high rainfall. The average annual rainfall over the three years 2000 to 2002 was 1016.5 mm.

At the start of this experiment swards were initially composed primarily of perennial ryegrass (>750 g/kg). The white clover content of swards varied between being undetectable to up to 50 g/kg in the sward DM in the spring 2000.

Experimental Treatments

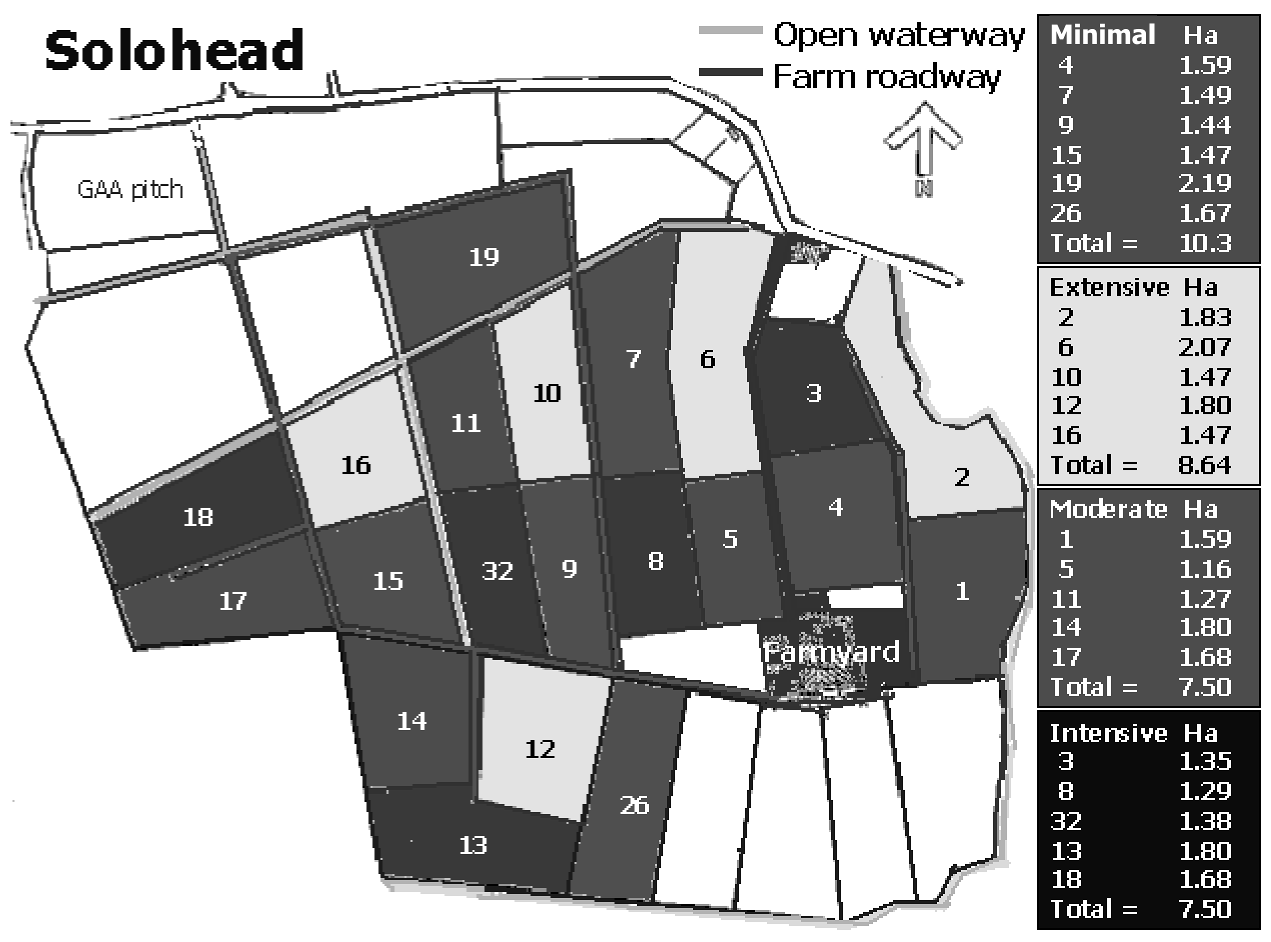
There were four treatments. The control was based on the Moorepark blueprint for spring-calving dairy herds (Dillon *et al*., 1995) and involved fertilizer N inputs of 350 kg/ha/year applied to grassland stocked at rates of 2.5 cows/ha/year (Intensive). The second had the same stocking rate (2.5 cows/ha/year) but lower fertilizer N of 250 kg/ha/year (Moderate). The third had a stocking rate of 2.1 cows/ha/year and fertilizer N inputs of 175 kg/ha/year (Extensive). The fourth treatment had a stocking rate (1.75 cows/ha/year) and fertilizer N inputs (80 kg/ha/year) compatible with the requirements of the REPS (Minimal). The equivalent 'book-value' (DAFF 1996) organic N-loading per ha on each treatment is presented in Table 2.

Table 2. Stocking rate, fertilizer N input and organic N loading per ha on each of the experimental treatments

Treatment	**Minimal**	**Extensive**	**Moderate**	**Intensive**
Fertilizer N (kg/ha/year)	80	175	250	350
Stocking rate (cows/ha/year)	1.75	2.10	2.5	2.5
Organic N-loading (kg/ha/year)	149	178	210	210

Assignment of dairy cows to treatments

There were 18 cows per treatment each year. Each spring cows were divided into four main groups on the basis of lactation number (1, 2, 3 & ≥4) and then sub-divided into sub-groups of four on the basis of calving date. From within each sub-group one cow was randomly assigned to each herd. The same procedure was followed each spring. Herds were randomly assigned to each treatment each spring. Mean calving date was 28 February.



Minimal	Ha
4	1.59
7	1.49
9	1.44
15	1.47
19	2.19
26	1.67
Total =	10.3

Extensive	Ha
2	1.83
6	2.07
10	1.47
12	1.80
16	1.47
Total =	8.64

Moderate	Ha
1	1.59
5	1.16
11	1.27
14	1.80
17	1.68
Total =	7.50

Intensive	Ha
3	1.35
8	1.29
32	1.38
13	1.80
18	1.68
Total =	7.50

Figure 1. Layout of experimental paddocks.

Layout of the Experimental Area

The experimental area was divided into five blocks of land. Within each block there were four paddocks and one of these was randomly assigned to each treatment. An additional paddock was assigned to Minimal (Figure 1). This layout was necessitated by the constraints imposed by the systems of field drains and roadways on the farm and by the need to have paddocks of sufficient size to accommodate modern silage-harvesting machinery etc. Therefore there were five paddocks assigned to the Intensive, Moderate and Extensive and six assigned to Minimal. Treatment areas were 7.5 ha for both Intensive and Moderate, 8.64 ha for Extensive and 10.3 ha for Minimal.

Fertilizer nitrogen application strategies

As outlined in the Introduction, the primary aim was to supply sufficient pasture to meet the feed requirements of the lactating cows during the main grazing season. Subject to meeting this requirement the objective was to produce enough grass to meet winter-feed requirements as grass-silage.

The production of silage entails substantial costs at farm level and much of this cost is due to contractor charges for harvesting the grass for silage. This is generally charged on a per-ha basis. Hence, it makes economic sense to ensure that high yields of grass DM are harvested per ha, while concomitantly taking care to maintain the nutritive value of the silage produced. Supplying sufficient fertilizer N to achieve high yields per ha is an important component of achieving this objective. Therefore regardless of the overall fertilizer N input to each treatment, supplying optimum or close to optimum fertilizer N for first and second cut silage was prerequisite. Furthermore, best response to applied fertilizer N is achieved during April and May under normal Irish conditions (Gately *et al*., 1984). Therefore, in so far as it was possible, the area harvested for first cut silage was maximised and the area harvested as second cut silage and baled silage was minimised in each treatment (Table 3).

On Intensive, the stocking rates imposed during the grazing season and the rates of application of fertilizer N on the grazing area were based on the approach outlined by Dillon *et al*. (1995). The rates of fertilizer N applied for first and second cut silage on Intensive were based on the recommendations of Gately (1994) (Table 3). On the other treatments target stocking rates during the grazing season and quantities of fertilizer N used on the grazing area and for first and second cut silage are based on a modelling exercise conducted prior to the initiation of this experiment. A refinement of this is presented in Humphreys *et al*. (2003). On Moderate, lower fertilizer N was applied in February for early grazing than on Intensive. Furthermore, Fertilizer N input on the grazing area was substantially lowered during the second half of the grazing season. Input of fertilizer N was also lowered for second cut silage in Moderate (Table 3).

Table 3. Target stocking rates on the grazing area during the grazing season and fertilizer N input strategies on each of the experimental treatments

Treatment	**Minimal**	**Extensive**	**Moderate**	**Intensive**
	Target stocking rates on the grazing area (cows/ha)			
February, March & early April	1.75	2.10	2.50	2.50
Late April, May & June	3.75	4.20	4.55	4.55
Late June, July & August	1.75	2.50	3.60	3.60
September, October & November	1.75	2.10	2.50	2.50
	Target proportion of farm closed for silage			
First-cut silage	0.53	0.50	0.45	0.45
Second cut silage	0.00	0.15	0.30	0.30
	Fertilizer N applied on the grazing area (kg/ha)			
February		29	29	58
March	29	29	58	58
April	29	29	58	58
May		35	35	35
June			17	35
July		17		35
August			17	35
September		17	17	35
Total on grazing area	*57*	*156*	*230*	*350*
	Fertilizer N applied on the silage area (kg/ha)			
Early grazing on silage area*	29	29	29	58
First cut silage (applied March & April)	86	115	115	115
Second cut silage (applied early June)	0	86	86	104

*Applied in February or March for early grazing during February, March & early April

Slurry management

During the winter housing period cows were housed and fed together as one group. Similarly, replacement heifers were also housed and fed together as one group. All of the slurry produced from cows and heifers was contained in a single storage tank. In order to ensure that the appropriate volume of slurry was applied back to each treatment standard values for slurry production per cow were used (DAFF, 1996). The calculated volume of slurry per treatment was recycled back to each treatment. Slurry was applied after first and second cut silage and in certain circumstances following the harvest of baled silage when it was necessary to maintain equal application rates across treatments.

Pasture cover and management of pasture supply

Swards were rotationally strip-grazed. Pasture was allocated for periods between 12 and 48 hours depending on weather and ground conditions. Post-grazing height was the principal determinant of grazing intensity imposed. Target post-grazing heights were between 45 and 80mm (rising plate meter) depending on ground conditions and time of year. Residual pasture on grazing swards of all treatments was mechanically defoliated (topped) to a height of approximately 55mm immediately after grazing during late May and early June and again during July.

Pasture cover was used to estimate the sufficiency of pasture supply during the grazing season. Each week between late January and the end of the grazing season the mean sward compressed height of each paddock on each treatment was determined using a rising plate meter. In each paddock 40 measurements were made at random while traversing in a zigzag throughout each paddock. On the basis of these measurements each 10mm of available pasture above 50mm was designated as 250 kg DM/ha. Pasture availability on each treatment area was determined and expressed as kg DM/cow. Target pasture covers per cow were the same for each treatment between turnout to grass and early August (Fig. 2). Higher pasture covers per cow were targeted on Minimal and Extensive between early August and mid September. The objective on all treatments during this period was to achieve a pasture cover of around 1200kg DM/ha during early September.

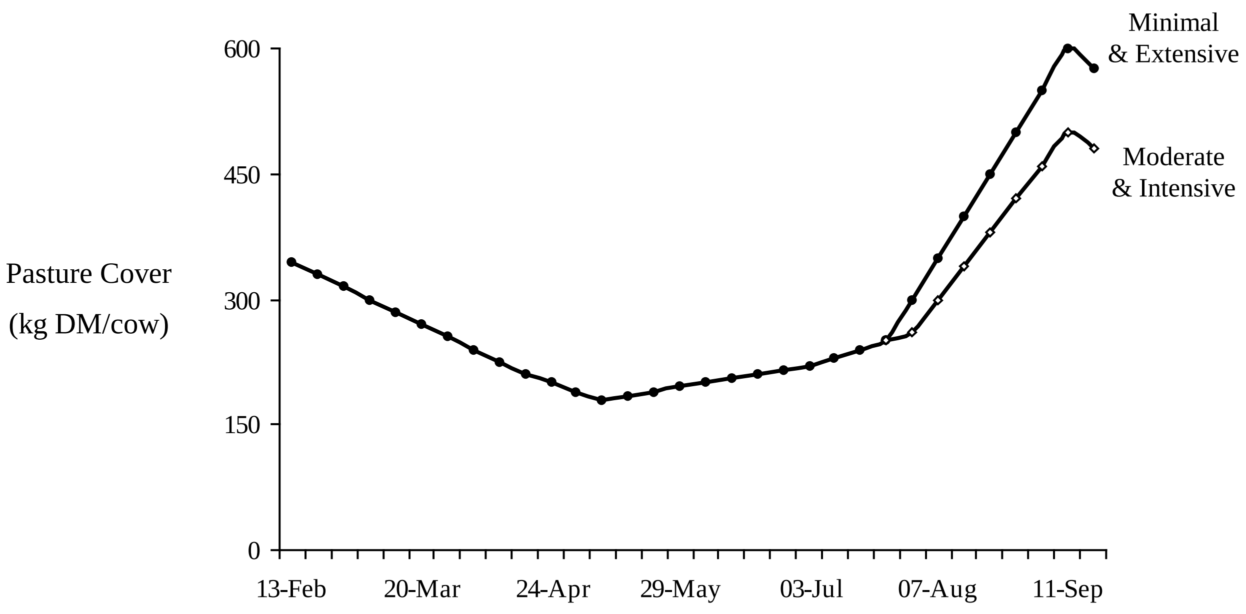


Figure 2. Target pasture covers at various stages during the grazing season

The attainment of pasture cover targets determined when to allow the cows out to graze by day and night, the extent of concentrate supplementation and when to close up for first-cut silage during the spring. Between late April and mid August the accumulation of pasture cover exceeding the target pasture cover by more than 10% on two consecutive weeks triggered the decision to remove surpluses from the grazing area as baled silage. The area harvested was determined by calculating the quantity of pasture needed to be removed in order to bring pasture cover back to the target value. When the pasture cover declined below target on two consecutive weeks supplementary feeding was introduced. Under sub-normal growing conditions deficiencies in pasture supply were influenced by ambient growing conditions (ambient temperature, incidental solar radiation and soil water availability being the fundamental determinants of pasture accumulation under normal Irish conditions) and hence tended to coincide across treatments. Under such circumstances supplementary feeding was provided as concentrate feed supplied equally to each cow on each treatment.

Under certain circumstances insufficiency of pasture supply was confined to individual treatments. This was generally a consequence of insufficiency of soil N supply (or, in other words – a treatment effect). Under such circumstances one of two alternative remedial actions were instigated. The favoured option was to graze areas allocated to silage production and to bring this area into the grazing rotation until such time as the pasture cover returned to target values. Under certain circumstances this option was not available because

(1) Swards closed for silage were in an advanced stage of maturity and therefore difficult to utilise effectively under grazing management,
(2) Swards had been recently harvested for silage and hence unavailable for grazing, and
(3) Towards the end of the grazing season when the whole of each treatment was under grazing management.

Under these circumstances supplementary feeding consisted of providing baled silage previously harvested from the relevant treatment.

Herbage production for ensilage and silage production

The area to be harvested for first cut silage on each treatment was progressively closed up during March and early April as pasture supply came in line with requirements on the remaining grazing area. After first cut in late May or early June, areas on each treatment were closed for second cut and harvested in late July or early August. Surplus grass on the grazing area was also harvested as baled silage at times when pasture supply was surplus to requirements (as outlined above).

Prior to harvesting the silage, each silage paddock was divided into three sections. Within each section four strips of herbage were harvested using an ‘Agria’ auto-scythe. The length of each strip was 5 m x the cutting width of 1.1 m. The herbage harvested within each section was bulked and weighed and two samples were taken; one for dry matter determination and the other for analyses of chemical composition. This harvesting procedure was followed within each section of each silage paddock including sections of paddocks harvested for baled silage in times of excessive pasture supply. Dry matter was determined by drying at 100°C for 16 hours. Samples for analyses of chemical composition were dried at 40°C for 48 hours. Analyses included crude protein (CP), organic matter digestibility (OMD), acid detergent fibre (ADF), and ash concentrations in the herbage dry matter (DM).

In the intervening period between mowing and pick-up of the mown sward by the forage harvester, four bales of silage were made in each paddock. Sections of the silage swaths were baled at random locations distributed throughout each paddock. These bales were wrapped and stored until the winter period. During December three of each of these four bales from each paddock were selected and a sample taken from each by driving a two meter long probe down through the bale. (Four bales of silage were produced and only three were sampled to allow for the risk of damage and spoilage of bales due to handling or wildlife *etc*.) The sample of silage from each bale was frozen and sent for analyses of chemical composition. These analyses included pH, DM, CP and DMD.

Table 4. Silage requirement per cow over the winter

Period	**Days**	**Herd Management**	**Herd Status**	**DM Allowance**	**Silage** (kg)
November	30	In by night	All milking	6 kg/cow	180
December	31	In day & night	Milking until 23 Dec	12 kg/cow	370
January	31	In day & night	All dry	12 kg/cow	370
February	28	Milkers out by day from 14 Feb	55% milking by end February	4 kg/milker 12 kg/dry-cow	290
20 March	20	Milkers out day & night from 20 March	85% milking by end March	0 kg/milker 12 kg/dry-cow	110
End April	41		100% Milking		80*
			Total Silage requirement (kg DM/cow)		**1400**

*In most years silage is not required until the end April but is needed as insurance for exceptionally late springs.

The estimation of silage production on each treatment was therefore based on yields of herbage harvested for silage. It is well known that considerable losses of DM take place between harvesting of grass and the production of the final preserved grass-silage. Padraig O’Kiely of Teagasc, Grange (pers. comm.) estimated losses between harvest and preservation as follows: 3% field-losses, 3% due to respiration during harvesting and filling, 4% via fermentation, 3% via effluent, 8% lost due to respiration during storage and feeding out. Gordon (1988) recorded losses of 10.4% during harvesting grass for silage and 13.5% during the ensiling process. Therefore these estimates indicate losses between harvest and feeding ranging between 21 and 24%.

(A further 7 or 9% can be attributed to losses associated with feeding and rejection by the feeding livestock). For the purposes of this study it is estimated that 25% of herbage DM harvested for silage was lost between harvest and preservation and therefore the quantities of silage produced were 750 g/kg of herbage DM harvested from each paddock. The target quantity of silage that was required from each treatment for the winter period was 1.4 t DM/cow/year (Table 4).

Pasture production on the grazing area

As outlined above the experimental area was composed of 5 blocks of land and one paddock from each block was assigned to each treatment (Fig. 1). Each year two blocks of the experimental area were assigned solely for grazing management; (Approximately half of each treatment was harvested for first cut silage each year). Each paddock within each of these ‘grazing’ blocks was divided into three sections. The two sections furthest from each other within each paddock were designated for measurement purposes. On this basis there were four designated measurement sites widely distributed within each treatment. Furthermore, each of the designated measurement sites within each treatment was located at relatively close proximity to a similar site in each of the other treatments. Therefore each designated site within each treatment served for the purpose of comparable replicated measurements within each treatment. Each year the blocks allocated to silage or grazing management was changed and therefore these designated sites changed from year to year although the selection procedure remained the same.

Measurements of pasture consumed by the grazing cows throughout the grazing season were made at each designated site. Prior to grazing, four pre-grazing strips each 5 m long and 0.55 m wide were harvested using a Honda HRH-536 lawn-mower set at a cutting height of 50mm above ground level. These were bulked and weighed and samples were taken for DM determination and assessment of nutritive value. Immediately following grazing four post-grazing strips were harvested directly adjacent and parallel to the pre-grazing strips. These were bulked and weighed and were taken for DM determination and assessment of nutritive value. Dry matter content was determined as above. The samples for nutritive value were freeze dried for 48 hours. Ash, CP and OMD were determined.

To overcome the problem of soil contamination particularly of the post-grazing stubble, the ash contents of both the pre- and post-grazing harvested DM were deducted to give both the pre- and post-grazing yields of organic matter (OM). The post-grazing OM was deducted from the pre-grazing OM at each grazing to give an estimated of the quantity of OM consumed by the grazing cows. The yields of OM consumed during each grazing were summed to give annual consumption of OM at each designated site. The utilisation of OM by the grazing cows at each grazing was calculated as follows:

$$\text{OM utilisation} = (\text{pre-grazing OM} - \text{post-grazing OM}) \div \text{pre-grazing OM}$$

Annual N off-take by the grazing cows was calculated as follows. The N content of the pre-grazing pasture was multiplied by the yield of the pre-grazing pasture to give the uptake of N in the pre-grazing sward. Likewise the N content of the post-grazing pasture was multiplied by the yield of the post-grazing pasture to give the N remaining in the residual sward. N uptake minus the sward residual N gave the N off-take at each grazing. The N off-take at each grazing was then summed to give annual off-take of N from each treatment.

Soil mineral N concentrations

Soil sampling was carried out on three occasions during the winter period to measure the quantity of mineral-N (nitrate-N and ammonium-N) available at different depths in the soil. These measurements were made in the four designated sites in each of the four treatments outlined above. Sampling took place in late September, late November and early February of the winters of 2001/02 and 2002/03. At each sampling date, fifteen cores per site were taken to a depth of >800mm using a hydraulic auger. Each core was subdivided into four depths (mm): 0 to 200, 200 to 400, 400 to 600 and 600 to 800 and samples were bulked at each depth within each plot. The remaining deeper soil was discarded.

Immediately after sampling, each soil sample was broken up and crumbled by hand and mixed to get a representative sub-sample. Large stones, large roots, and plant material were removed as far as possible. Two hundred grams of each sample was extracted in 400ml of 2*M* KCl (1:2 ratio w/v), shaken continuously for 2 hours. Following shaking, the sample was left to stand for five minutes before filtering through Whatman No.2 filter paper. The samples were then stored at 4°C before analyses for Nitrate-N and Ammonium-N. Soil moisture content was measured by drying 200g of soil at 100°C for 16 hours.

Soil Bulk Density

The bulk density of the soil was measured in order to convert the above mineral-N concentrations from mg N/kg of soil to kg N/ha at each depth. Soil bulk density was measured using a modification of the cylinder method described by Blake and Harge (1986). Soil samples for bulk density measurement were taken from four sampling depths (mm): 0 to 200, 200 to 400, 400 to 600 and 600 to 800 from six trial pits randomly distributed throughout the experimental area. Three samples were taken at each depth in each trial pit. A steel cylinder (internal diameter 150 mm and length 100 mm) was pushed into the soil at the required depth in the trial pit sufficient to fill the sampler but not so far as to compress the soil within the sampler. The sampler was removed from the soil and soil extending beyond the end of the sampler was trimmed with a knife. Each sample was weighed before and after drying at 100°C for 16 hours. After drying, the sample was left to cool before weighing. The bulk density was finally determined by dividing the soil dry weight by the cylinder volume:

$$\text{Bulk Density (g soil/cm}^3\text{)} = \text{Soil dry weight} \div \text{Cylinder volume}$$

Nitrate-N concentrations in drainage water

During the winters of 2001/02 and 2002/03 the nitrate concentrations in water draining from the designated measurement sites were also measured at 1m depth in the soil. At 1m depth, the water is regarded as been of no further potential use to the growing crop since it has moved well beyond rooting depth. At each site four vertical holes were drilled to a depth of 1 m using a hydraulic auger. Plastic piping, 20mm internal diameter and 1.2m in length were installed vertically into the prepared holes allowing approximately 0.2m of the pipe protruding above the soil surface. This was to prevent surface water or other contaminants from entering the pipes. The holes drilled were a diameter similar to the external diameter of the pipes to ensure that the pipes were a tight fit when installed. Bentonite was placed around the pipe at the soil surface. Bentonite is a clay material that expands when wetted to seal any gap around the sampling unit. This prevented surface water from channelling down the outside of the pipe. These 'dip-wells' were left settle until sampling of water commenced.

There were four dip-wells at each of the four designated sites within each of the four treatments. During 2001/02 water samples were taken at intervals of approximately 10 days. During 2002/03 water samples were taken twice weekly. In both years sampling took place between early October and early March. On each sampling date, each of the dip-wells were emptied in the morning; all of the water standing in each well was pumped out and discarded. In the intervening period of around 2 hours the wells were allowed to recharge; water seeped back into the well from the surrounding soil via the bottom of the pipe. This 'recharged' water in each well was sampled. Around 300ml of water was taken from each well and water from each of the four wells at each site was bulked. After sampling, each sample was filtered and stored at 4°C while being sent for analyses. Each sample was analyses for its nitrate-N, ammonium-N, nitrite-N and P concentrations.

The white clover content of swards

The white clover content of each paddock was determined during April and August each year. At 25 locations, randomly selected at each sampling date within each paddock, a strip of pasture 100mm wide by 150mm long was cut at a height of 50mm above ground level using a 'Gardenia' hand shears. All of the harvested pasture was collected and bulked for each paddock. The clover herbage in each bulked sample was separated from the remainder of the herbage (which mostly consisted of perennial ryegrass). The clover and the remaining herbage were dried at 100°C for 16 hours. The clover content of the pasture was determined by dividing the dry weight of clover by the combined dry weight of the clover, grass and other herbage and multiplied by 1000 to adjust to g/kg DM.

Dairy cow performance

Milk yield/cow was recorded at each milking and the milk composition of each cow was measured for a morning and evening milking once a week. Body condition score (BCS) of each cow was recorded each fortnight and live-weight (LW) of each cow was recorded once a week.

Results and Discussion

Grassland management

Cows were turned out to grass during mid February or early March and remained at grass until housing during late October and November depending on ground and weather conditions and grass supply (Table 5). The delay in initial turn out date until 9 March 2000 was due to delays associated with the start up of this experiment (fencing paddocks etc.). During the spring of 2001, cows were not let out by day and night until 11 April due to a relatively slow grass growth caused by unseasonably low soil temperatures (Fig. 3). In Figure 3 annual rainfall and soil temperatures are presented in cumulative terms because this makes it easier to see differences between years and because the greatest impacts of weather conditions are usually cumulative.

Table 5. The dates of turn-out to grass in the spring and housing for the winter between 2000 and 2002

Year	Out by day	Out day & night	Housed by night	Housed full-time
2000	9 March	18 March	4 October	27 October
2001	14 February	11 April	27 October	26 November
2002	13 February	21 March	25 October	20 November

Cows were housed earlier in 2000 than in the other two years because of the exceptionally wet conditions experienced during September and October (Fig. 3). It can be seen in Figure 3 that total annual rainfall during 2000 and 2002 were more-or-less the same at between 1100 and 1150 mm/year. However during 2000 a high proportion of the rainfall occurred from mid-September onwards. In contrast, during 2002 there were above average levels of rainfall throughout the spring and summer months. This created difficult grazing conditions during this period of 2002. Rates of rainfall were closer to normal later in the growing season of 2002.

Rainfall and soil temperatures during the spring each year exerted an influence on concentrate supplementation and lactation length. Concentrates fed per cow were 525 kg during 2000, 565 during 2001 and 695 during 2002. Poor grass growth during the spring 2001 meant that cows were in by night on silage until 11 April and therefore needed increased concentrate supplementation during this period. The year 2002 was a difficult year in terms of pasture production and utilisation. Higher rates of concentrate supplement were required until early July. Cows were housed for 10 nights during May, 11 nights during June and 7 nights during July due to very wet ground conditions and the necessity to avoid excessive damage to the pastures. Lactation length during 2002 was also shortened due to poor cow condition. Lactation length averaged for each herd over the three years (mean ± SD) was 287 ± 3.7 days. Concentrate supplementation averaged over the three years amounted to 595 kg/cow/year.

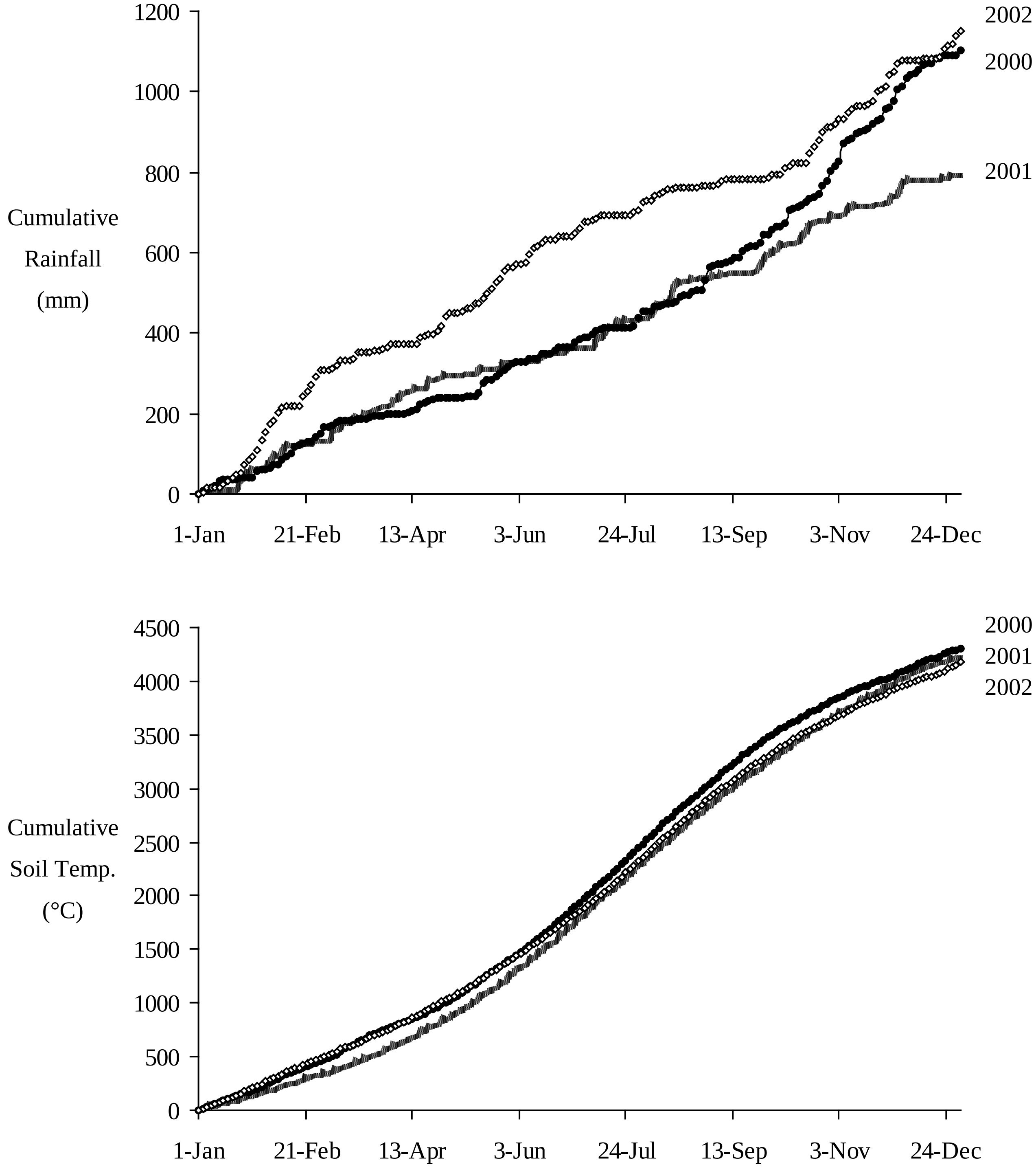


Figure 3. Cumulative Rainfall and soil temperatures at 100 mm at Solohead between 2000 and 2002

Dairy cow performance

Table 6. Milk production and composition (three years data combined)

Treatments:	**Minimal**	**Extensive**	**Moderate**	**Intensive**	**Sig.**	**SEM**
			(kg/cow/year)			
Milk yield	6435	6270	6288	6354	NS	106
Solids corrected milk yield	6283	6213	6078	6260	NS	97
Fat yield	266	264	256	266	NS	4.4
Protein yield	226	225	221	226	NS	3.3
Lactose yield	306	298	297	302	NS	5.2

Table 7. Body condition score (BCS) and live weight (LW) during lactation (three years data combined)

Period	**Minimal**	**Extensive**	**Moderate**	**Intensive**	**Mean**
			BCS (Scale: 1 = very thin to 5 = very fat)		
28 Feb. to 2 April	3.18	3.12	3.09	3.18	***3.14***
10 April to 14 May	3.02	2.96	2.97	3.04	***2.99***
22 May to 26 June	2.95	2.87	2.90	2.96	***2.92***
3 July to 8 August	2.95	2.90	2.89	2.95	***2.92***
14 Aug. to 18 Sept.	2.99	2.89	2.89	2.97	***2.94***
25 Sept. to 30 Oct.	3.00	2.90	2.87	2.99	***2.94***
6 Nov. to 11 Dec.	3.02	2.93	2.87	3.01	***2.96***
Mean	***3.01***	***2.94***	***2.93***	***3.01***	
	Treatment:		NS	SEM = 0.035	
	Treatment x Period:		NS	SEM = 0.020	
	Period:		$P < 0.001$	SEM = 0.010	
			LW (kg/cow)		
28 Feb. to 2 April	569	572	563	570	***568***
10 April to 14 May	558	550	550	555	***553***
22 May to 26 June	561	557	552	563	***558***
3 July to 8 August	572	569	558	567	***567***
14 Aug. to 18 Sept.	588	581	574	580	***581***
25 Sept. to 30 Oct.	608	612	591	604	***604***
6 Nov. to 11 Dec.	621	612	595	617	***611***
Mean	***582***	***579***	***569***	***580***	
	Treatment:		NS	SEM = 6.0	
	Treatment x Period:		NS	SEM = 3.6	
	Period:		$P < 0.001$	SEM = 1.8	

There were no significant differences in milk, fat, protein and lactose output per cow between N-input treatments (Table 6). Furthermore, while both BCS or LW differed significantly at different stages during lactation, as is to be expected, both BCS and LW were not significantly affected by treatment including interactions within and between years (Table 7) although there were differences between years (data not shown) as pointed out above.

- *Overall, the N-input treatments imposed did not have a detectable impact on dairy cow performance in this experiment.*

Silage production

The proportion of the land-area within each treatment harvested for silage (including baled silage) before mid-June tended to be similar on each treatment: 0.54 (Minimal), 0.49 (Extensive) to 0.47 (Moderate) and 0.49 (Intensive). The proportion of each treatment harvested between mid-June and mid-August; 0.11 (Minimal), 0.15 (Extensive), 0.16 (Moderate) and 0.30 (Intensive) increased significantly with increasing N-input/ha ($P < 0.05$; SEM = 0.03). A summary of areas harvested are presented in Table 8. The area harvested on Minimal during the second half of the growing season greatly exceeded the targets outlined in Table 3, whereas Extensive was below target and Moderate was substantially below target.

Table 8. The area of each treatment and areas harvested for silage, including baled silage, before mid-June and between mid-June and mid-August

Treatments:	**Minimal**	**Extensive**	**Moderate**	**Intensive**
		(ha)		
Total area per treatment	10.30	8.64	7.50	7.50
Harvested before mid-June	5.56	4.23	3.53	3.68
Harvested mid-June to mid-August	1.13	1.30	1.20	2.25
Area harvested	**6.70**	**5.53**	**4.73**	**5.93**

There was no significant difference in the yields of herbage per ha harvested for first or for second cut silage (main harvests and not including yields of baled surpluses) or in the weighted-mean yields of herbage per ha harvested for silage between treatments (Table 9). The DM and OMD of herbage harvested for silage was not significantly affected by treatment. Intensive had higher ($P < 0.05$) CP in the herbage DM and both Moderate and Intensive had higher ($P < 0.01$) ADF concentrations.

There was no detectable difference in the DM, pH or CP of the silage ensiled in bales between the different treatments. The lower N-input treatments, Minimal and Extensive, had silage of significantly ($P < 0.05$)

higher DMD than the higher N-input treatments. The reasons for this are unclear. There was a tendency towards better preservation as indicated by lower pH in the lower N-input treatments, whereas there was a tendency towards lower DM in herbage on Intensive and a tendency to higher ADF on Moderate and Intensive as pointed out above. The combination of these factors may have contributed to the difference in silage DMD. Overall, however, when combined over the three years there were remarkably little differences in the harvested silage yields per ha or nutritive value of the silage between the treatments.

Table 9. Yields and characteristics of herbage harvested for silage, characteristics of the silage produced and yields of silage stored per cow allowing 250 g/kg losses between harvest of herbage and final preservation (three years data combined)

Treatments:	**Minimal**	**Extensive**	**Moderate**	**Intensive**	**Sig.**	**SEM**
			Silage yields (kg DM/ha)			
Yields of first-cut	7182	7145	7158	7258	NS	343
Yields of second-cut	3798	4660	4969	4834	NS	498
Weighted-mean yields	6646	6623	6558	6423	NS	206
			Characteristics of herbage harvested for silage			
Dry Matter (g/kg)	168	169	167	163	NS	2.9
Crude Protein (g/kg)	130	131	133	142	$P < 0.05$	3.1
OMD (g/kg)	767	767	767	768	NS	3.6
ADF (g/kg)	300	299	312	309	$P < 0.01$	3.1
			Characteristics of the silage produced			
Dry Matter (g/kg)	176	176	176	166	NS	4.8
pH	3.9	3.9	4.1	4.0	NS	0.05
Crude Protein (g/kg)	144	146	142	145	NS	3.4
DMD (g/kg)	735	738	721	720	$P < 0.05$	4.9
			Silage stored per cow			
Silage (t DM/cow/year)	1.80$^{\Psi}$	1.38	1.22	1.50	$P < 0.05$	0.047

$^{\Psi}$Not included in ANOVA due to large variation from year to year attributed to white clover content of swards

The quantity of silage stored per cow was significantly different between treatments. Silage production was below target on Moderate and marginally sufficient on Extensive and sufficient on Intensive (Table 9). On average over the three years, more than enough silage was produced on Minimal, however, this increased from 1.3 t DM/cow in 2000 to 1.9 t DM/cow in 2001 to 2.2 t DM/cow in 2002. This was due to the substantial increase in the white clover content of swards on this treatment between 2000 and 2002 (see below), and subsequent positive impact on soil N availability.

- *Overall there were no differences in harvested yields per ha and little or no differences in the nutritive value of silage produced between the different treatments.*
- *Moderate resulted in insufficient silage production per cow indicating inadequate carrying capacity on this treatment. Extensive resulted in marginally sufficient silage production indicating that this treatment was questionable in terms of carrying capacity. The other two treatments had sufficient carrying capacity.*

Pasture Production

The actual amount of N applied on the designated grazing areas in each treatment is presented in Table 10. These are similar to the targets outlined in Table 3. Off-take of N from the soil in the pasture removed by the grazing cows from the grazing area of each of the treatments is also presented in Table 10. It is clear that in Minimal that the sward took up far more N than was applied as fertilizer N (no slurry was applied to these designated grazing areas).

Table 10. Annual input of fertilizer N and off-take of available soil N in pasture consumed by the grazing cows on the grazing area of each of the treatments. (Three years data combined)

Treatments:	**Minimal**	**Extensive**	**Moderate**	**Intensive**	**Sig.**	**SEM**
			Fertilizer N application (kg/ha/year)			
2000	60	148	220	333		
2001	44	161	235	367		
2002	46	154	230	338		
Mean	**50**	**154**	**229**	**346**		
			Interaction year x N-input		$P < 0.01$	7.8
			N off-take in pasture (kg/ha/year)			
2000	176	232	262	354		
2001	194	232	283	385		
2002	264	224	284	324		
Mean	**211**	**230**	**262**	**354**		
			Interaction year x N-input		$P < 0.001$	15.6

As outlined above the soil at Solohead has the capacity to release approximately 120 kg N/ha during the main growing season; mid-February to late October (O'Connell *et al*., 2003). This provides useful insight into two issues:

(1) Apparent recovery of available soil N was 84% on Extensive, 79% on Moderate and 76% on Intensive. This is based on the 'difference method' where apparent recovery of available soil N was calculated as:

(N off-take in pasture ÷ (Applied fertilizer N + background release of soil N)) x 100

(2) Nitrogen fixation by *Rhizobium* bacteria in association with white clover on Minimal can be estimated as being negligible during 2000, approximately 30 kg/ha during 2001 and 98 kg/ha during 2002.

Annual pasture production on the grazing area measured in terms of the pasture consumed by the grazing cows is presented in Table 11. Pasture production was influenced by an interaction between treatment and year. During 2000 and 2001 pasture DM and OM yields clearly increased with increasing fertilizer N input. However, during 2002, Minimal had exceptionally high production whereas Intensive had lower yield compared to the previous two years. Part of the explanation for this was probably partly due to exceptionally high rainfall during 2002 grazing season (Fig. 2). The high rainfall combined with the heavy soil conditions at Solohead lead to higher pasture damage, particularly under the high stocking rates. These conditions probably also contributed to substantial denitrification of available soil nitrate lowering the responsiveness to applied fertilizer N during the exceptionally wet summer months. Furthermore, on Minimal during 2002, fixation by white clover made a substantial contribution to soil N supply. This N is less immediately susceptible to denitrification and it seems that this N made a considerable contribution to the high levels of production recorded on Minimal during 2002 (Table 10).

Table 11. Dry matter (DM) and organic matter (OM) production, pre-grazing pasture mass and OM utilisation (three years data combined)

Treatments:	**Minimal**	**Extensive**	**Moderate**	**Intensive**	**Sig.**	**SEM**
			Annual Pasture Production (kg DM/ha)			
2000	5964	6953	7485	9772		
2001	5585	6642	7818	9480		
2002	8453	7100	8097	8887		
Mean	**6667**	**6898**	**7800**	**9380**		
			Interaction year x N-input		$P < 0.01$	445
			Annual Pasture Production (kg OM/ha/year)			
2000	5553	6142	6940	8974		
2001	5254	6526	7297	8864		
2002	7761	6725	7758	8654		
Mean	**6189**	**6464**	**7332**	**8831**		
			Interaction year x N-input		$P < 0.05$	393
Pre-grazing mass (kg DM/ha)	1680	1565	1714	1854	$P < 0.001$	35
OM utilisation	0.54	0.51	0.53	0.58	$P < 0.05$	0.013

The utilisation of OM in terms of the proportion of available OM consumed at each grazing by the grazing cows ranged between 51% on Extensive and 58% on Intensive. This proportion was clearly influenced by the pre-grazing DM mass; a higher proportion of available pasture was grazed by the cows with increasing pre-grazing pasture mass. This stands to reason as it becomes increasingly difficult for cows to graze pasture below a height of 70mm (Le Du *et al*., 1979). The greater the availability of pasture above 70mm the greater the amount of pasture that can be readily removed by the grazing cows (Peyraud *et al*., 2001). Humphreys et al. (2001) recorded a similar relationship between pasture utilisation and pre-grazing mass.

Table 12. Digestibility (OMD) and crude protein concentration in the pre-grazing pasture and the crude protein concentration in the pasture consumed by the grazing cows (three years data combined)

Pre-Grazing OMD (g/kg)							
2000	799	806	809	826			
2001	809	811	815	823			
2002	819	798	816	820			
Mean	**809**	**805**	**813**	**823**			
					Interaction year x N-input	$P < 0.05$	4.5
Pre-Grazing Crude Protein (g/kg DM)							
2000	150	167	177	202			
2001	183	196	203	226			
2002	183	174	196	203			
Mean	**172**	**179**	**192**	**211**			
					Interaction year x N-input	$P < 0.05$	4.6
Crude Protein of Pasture Intake (g/kg DM)							
2000	184	208	220	228			
2001	217	225	238	261			
2002	202	212	240	237			
					Interaction year x N-input	NS	10
Mean	**201**	**215**	**232**	**242**		$P < 0.001$	5.7

One of the problems of this method of measuring pasture production is that there can be two or three days between when the pre- and post-grazing pasture masses are measured. A certain amount of growth is likely to take place during this period that is not accounted for and hence both pasture production and utilisation is likely to be underestimated. Swards are likely to be grazed between seven and nine times per year. Furthermore, average annual growth rates during the grazing season are between 30 and 50 kg DM/ha/day depending on the rate of fertilizer N input. Hence, it can be assumed that the production data presented in

Table 11 underestimates the actual quantity of pasture consumed by between 10 and 15%. Although an average of between 50 and 60% of available OM above 50mm is removed at each grazing a large proportion of the residual pasture contributes to future pasture production. Generally speaking on an annual basis overall utilisation of pasture in the course of a grazing season is in the region of 70%. Hence, in crude terms, annual total DM production can be estimated as 9.5 t/ha on Minimal, 9.9 t/ha on Extensive, 11.1 t/ha on Moderate and 13.4 t/ha on Intensive.

Failure to utilise 30% of available pasture might seem high. However it is important to consider that on average around 16% of the sward will be impacted by dung, ranging from 4% during the spring up to 24% in mid-season and falling to 14% in the autumn (Wilkins & Garwood, 1986). This can result in loss of pasture through smothering and poor utilisation due to taint and may account for around half of total annual wastage. Poor pasture intake can also be associated with soiling of the pasture by treading especially under wet conditions. Seed-head production can also cause wastage of pasture. Cows could be forced to graze this pasture but it is likely to be counter-productive. This wasted pasture needs to be topped off in order to maintain sward quality.

Table 13. The white clover content of swards in April and August each year and estimated DM production of white clover each year.

Treatments:	**Minimal**	**Extensive**	**Moderate**	**Intensive**	**Sig.**	**SEM**
Year		**White Clover Content** (g/kg)				
2000	133	45	23	21		
2001	248	39	27	9		
2002	232	38	13	5		
Sampling date			Interaction year x N-input		*P* < 0.01	18
April	76	16	8	5		
August	333	65	34	18		
			Interaction date x N-input		*P* < 0.001	12
Mean	**204**	**41**	**21**	**12**		
		Annual production of white clover (kg DM/ha)				
2000	793	313	172	205		
2001	1385	259	211	85		
2002	1961	270	105	44		

Both the OMD and the CP concentrations of the pre-grazing pasture clearly increased with increasing fertilizer N input (Table 12) although these relationships were influenced by the white clover content of the swards (Table 13). During 2000 when there were relatively low levels of white clover on Minimal, there was a very obvious increase in OMD and CP with increasing fertilizer N input across the four treatments. However, by 2002, when white clover as making a substantial contribution to production on Minimal, there was no significant difference in OMD concentrations between Minimal and Intensive.

The white clover contents of the Intensive, Moderate and Extensive remained low and not significantly different from each other during the experiment. In all years and at all times the white clover content of Minimal was significantly higher than in the other treatments. The clover content of swards alone does not provide a complete assessment of the contribution of white clover to pasture productivity. When examined in terms of white clover DM production it can be seen that the white clover DM production increased substantially with each year from 2000 to 2002 (Table 13). These levels of white clover DM production tally quite well with the estimates of N fixation outlined above. It is well known that the extent of N fixation is closely related to the biomass of white clover per ha (Parsons & Chapman, 2000).

- *Apparent recovery of available soil N in the pasture tended to decline with increasing fertilizer N inputs from 84% for input of approximately 155 kg N/ha/year to 76% for inputs of approximately 350 kg N/ha/year.*
- *In the absence of substantial quantities of white clover in the sward pasture production increased with increasing fertilizer N input up to inputs of approximately 350 kg N/ha/year.*
- *In the absence of substantial quantities of white clover in the sward the OMD and CP concentrations in the pasture DM increased with increasing fertilizer N input up to inputs of approximately 350 kg N/ha/year.*
- *The productivity of white clover component of the Minimal swards increased substantially between 2000 and 2002. Estimated N-fixation increased from 0 to 98 kg/ha during this period.*
- *The presence substantial quantities of white clover in sward more-or-less completely ameliorated the negative impact of low fertilizer N input on sward digestibility and partially ameliorated the negative impact of low fertilizer N input on sward CP.*

Pasture Covers

Generally speaking pasture covers on Minimal and Extensive tended to be well above target during the spring, whereas pasture availability on Moderate and Intensive was much closer to target during this period (Fig. 4). During the period between mid-June to mid-August, pasture covers were maintained close to target on all treatments except Minimal. Towards the end of the grazing season it was possible to maintain pasture covers close to target on Minimal and Intensive. However, during this time of the year it was consistently not possible to maintain pasture covers on Extensive and Moderate with the level of N-inputs being applied to these treatments. It was necessary to supplement the cows on these two treatments with baled silage during October and November each year. The quantities of baled silage fed were deducted from total silage production each year.

Pasture covers on the lower stocking rate treatments (Minimal and Extensive) were easily maintained during the spring-time (mid-February to mid-April). This is because pasture cover, particularly in the early spring, is partly due to pasture accumulation over the winter period. This process is not highly dependent on fertilizer N inputs; grass growth is poorly responsive to fertilizer N inputs during the period between October and January. In general, the lower the stocking rate per ha the greater the pasture availability per cow during the spring. Furthermore, during March, April and May, as the responsiveness of pasture production to fertilizer N input greatly increased, it was still possible to maintain high pasture availability per cow with lower fertilizer N inputs than applied on Moderate and Intensive. This is because stocking rates on the grazing areas of Extensive and Minimal were considerable lower than on the higher-stocked treatments (see Tables 3 & 8).

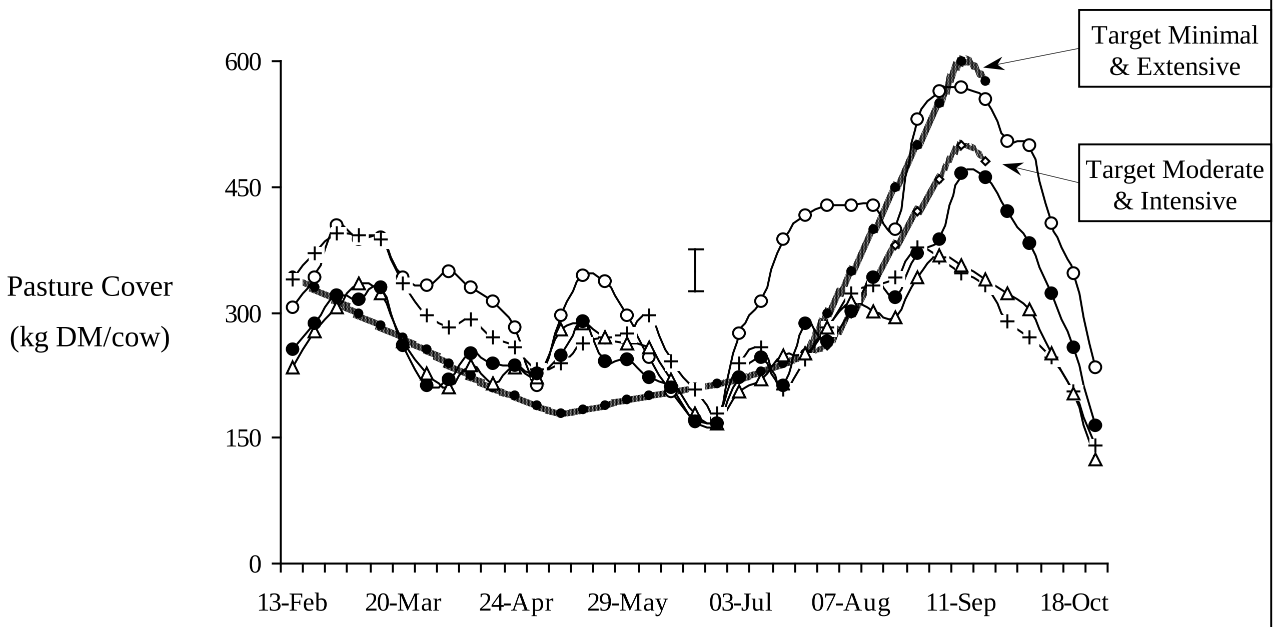


Figure 4. Pasture covers compared to targets at various stages during the grazing season. (mean of three years). Treatments: Minimal ^{O}, Extensive $^{+}$, Moderate $^{\Delta}$ and Intensive $^{\blacklozenge}$. Treatment, *P* < 0.05; SEM = 18, Date, *P* < 0.001; SEM = 26. No treatment x date interaction. I = SEM for date.

During the period between mid-June and mid-August an important consideration was maintaining the balance between maintaining pasture supply per cow and attempting to meet silage production targets. Pasture covers were maintained close to target at this time of year on all treatments except Minimal. This is because with the exception of 2000, more than enough silage was produced earlier in the growing season (see above).

Overall during this experiment it was possible to meet target pasture covers on Minimal and Intensive during the autumn. On Minimal this is attributed to the relatively low stocking rate combined with the contribution of white clover to soil N supply during the summer and early autumn. On Intensive relatively high fertilizer N inputs on the grazing area during the summer and early autumn allowed the target pasture covers to be reached in early September. Reaching pasture cover targets in early September is a crucial component of maintaining pasture supply during the late autumn and early winter. It is clear that the levels of fertilizer N input applied on the grazing areas of Extensive and Moderate were inadequate to meet pasture supply targets towards the end of the grazing season.

- *Low stocking rates facilitated high pasture availability per cow during the spring even when this was combined with relatively low fertilizer N input.*
- *Low stocking rates combined with adequate soil N supply (from fixation in this experiment) facilitated high pasture availability per cow during the autumn.*
- *The rates of N fertilisation applied from mid-summer onwards on Extensive and Moderate were insufficient to produce enough pasture to meet pasture cover targets in early September – particularly in comparison with Intensive. This has clear implications for N fertilisation strategies.*

Nitrogen Losses

Large amounts of N are lost from intensive grassland-based dairy production each year. These losses can occur through a range of different pathways. The major pathways are (1) losses of di-nitorgen (N_2) or nitrous oxide (N_2O) gasses following denitrification of nitrate in the soil. (2) Losses of ammonia (NH_3) gas following the application of slurry, following urination by cows or during housing and from slurry storage. (3) Leaching of nitrate (NO_3) during the spring and autumn when rainfall greatly exceeds evapotranspiration. Most leaching losses occur from vulnerable soils during the early winter when the commencement of surplus rainfall washes out residual N that had accumulated in the soil during the summer months.

Fully accounting for losses is difficult primarily because, under typical Irish conditions, most N is lost due to denitrification and a substantial proportion of this N is lost as N_2 gas to the atmosphere. Approximately 79% of the atmosphere is composed of N_2 gas and therefore losses by this pathway are virtually impossible to measure using existing technology. Nevertheless, it is reasonably certain that any surplus N that is generated by dairy production is lost by one way or another. Surplus N is the difference between total N inputs to a system (generally N in fertilizer and in feedstuffs bought onto the farm) minus the outputs from the system (N in milk and livestock sold off the farm). A small proportion of this surplus N is sequestered into the soil organic matter. However, this is unlikely to be much greater than 20 kg N/ha/year except under exceptional circumstances (e.g. Dutch Polders) because this would require huge accumulation of organic matter in the soil; well in excess of that recorded in Irish soils. The change in quantity of N that is held in soil organic matter from one year to the next under permanent grassland soils is virtually negligible compared to other N transformations.

Therefore the quantity of surplus N generated by a farming system can be roughly equated with losses (Jarvis & Aarts, 2000). In the present experiment fertilizer N was the most important input to each of the treatments, except perhaps Minimal during 2002 (Table 14). Concentrate fed was the same per cow and hence increased with increasing stocking rate. The contribution of white clover to soil N supply was only of importance on Minimal during 2001 and 2002 (Table 10). Output of N from each treatment was mainly in the form of milk, which increased with increasing stocking rate. Calves and cull cows exported from each treatment also contributed to N-output (Table 14).

Table 14. Nitrogen (kg/ha/year) inputs and outputs, surplus N and the efficiency of N-use on each of the four treatments.

	Minimal	**Extensive**	**Moderate**	**Intensive**
		Nitrogen Input (kg/ha/year)		
Fertilizer	80	175	250	350
Concentrate	30	36	43	43
White Clover (WC)	30 & 98*	*Negligible*	*Negligible*	*Negligible*
Total N Input excl. WC	**110**	**211**	**293**	**393**
Total N Input incl. WC	**140 & 208***			
		Nitrogen Output (kg/ha/year)		
Milk	61	74	88	88
Exported Livestock	4.03	4.83	5.75	5.75
Total N Output	**65**	**78**	**93**	**93**
		Nitrogen Surplus (kg/ha/year)		
N Surplus excluding white clover	**45**	**133**	**200**	**300**
N Surplus including white clover	**75** & **143***			
		N-use Efficiency (%)		
N-Use efficiency excl. WC	59	37	32	24
N-Use efficiency incl. WC	47 & 31*			

*2001 & 2002 respectively

Surplus-N was closely related to N input. On Minimal, the contribution of white clover had a major bearing on N input and N surplus being approximately 45 kg/ha in 2000, 75 kg/ha in 2001 and 143 kg/ha in 2002. Surplus N increased from 133 kg/ha on Extensive to around 300 on Intensive. Overall N-use efficiency was lowest on Intensive at 24% and increased with lower N inputs to an average of 49% on Minimal.

Soil mineral N and nitrate-N in drainage water

Highest soil mineral N concentrations in late September were recorded under Intensive (Fig. 5). It was apparent that soil nitrate in the upper layers of the soil declined substantially during the winter. There was little difference between treatments by the following spring. Losses of mineral N from the soil were estimated from mineral N lower in the soil than 200 mm in September plus the change in N in the topsoil >200 mm between September and February. Nitrogen contained in the soil profile below the rooting zone 0 to 200 mm at Solohead is beyond normal rooting depth and will be flushed from the soil by surplus rainfall during the winter (amounting to around 550 mm (Fig. 3 & Fig. 13) over the following months. On this basis, total losses of mineral N were 66 kg/ha from Intensive, 27 kg/ha from Moderate, 18 kg/ha from Minimal and 12 kg/ha from Extensive.

Similarly, nitrate-N concentrations in drainage water were higher ($P < 0.01$) on occasions from Intensive during both winters (2001/02 & 2002/03) and also from Minimal during the winter of 2002/03 (Figure 6). High concentrations of nitrate-N in drainage water from Intensive were clearly related to the high mineral N recorded in the soil compared to the other treatments.

Sub-optimal fertilisation of Moderate from mid-summer onwards caused the depletion of available soil N leaving little residual N available in the soil during the autumn. Therefore most of the losses of N from Moderate are likely to have taken place earlier in the growing season where losses due to denitrification and volatilisation of ammonia were probably the main pathways. For the same reasons very low residual N was recorded under Extensive during the autumn.

In contrast, although a relatively low surplus-N were associated with Minimal, it seems likely that the presence of white clover contributed substantially to the comparatively high residual N recorded in the soil under this treatment during November (Fig. 5). In Table 13 it can be seen that the white clover content of the Minimal swards were substantially higher during August than in April. While grass growth commences at soil temperature of around 6°C, substantial growth of clover does not occur until soil temperatures reach around 9°C (Murphy, 1985). Therefore white clover makes the greatest contribution to pasture production from mid-summer onwards, particularly during August and September. Most N-fixation also takes place during this time of the year.

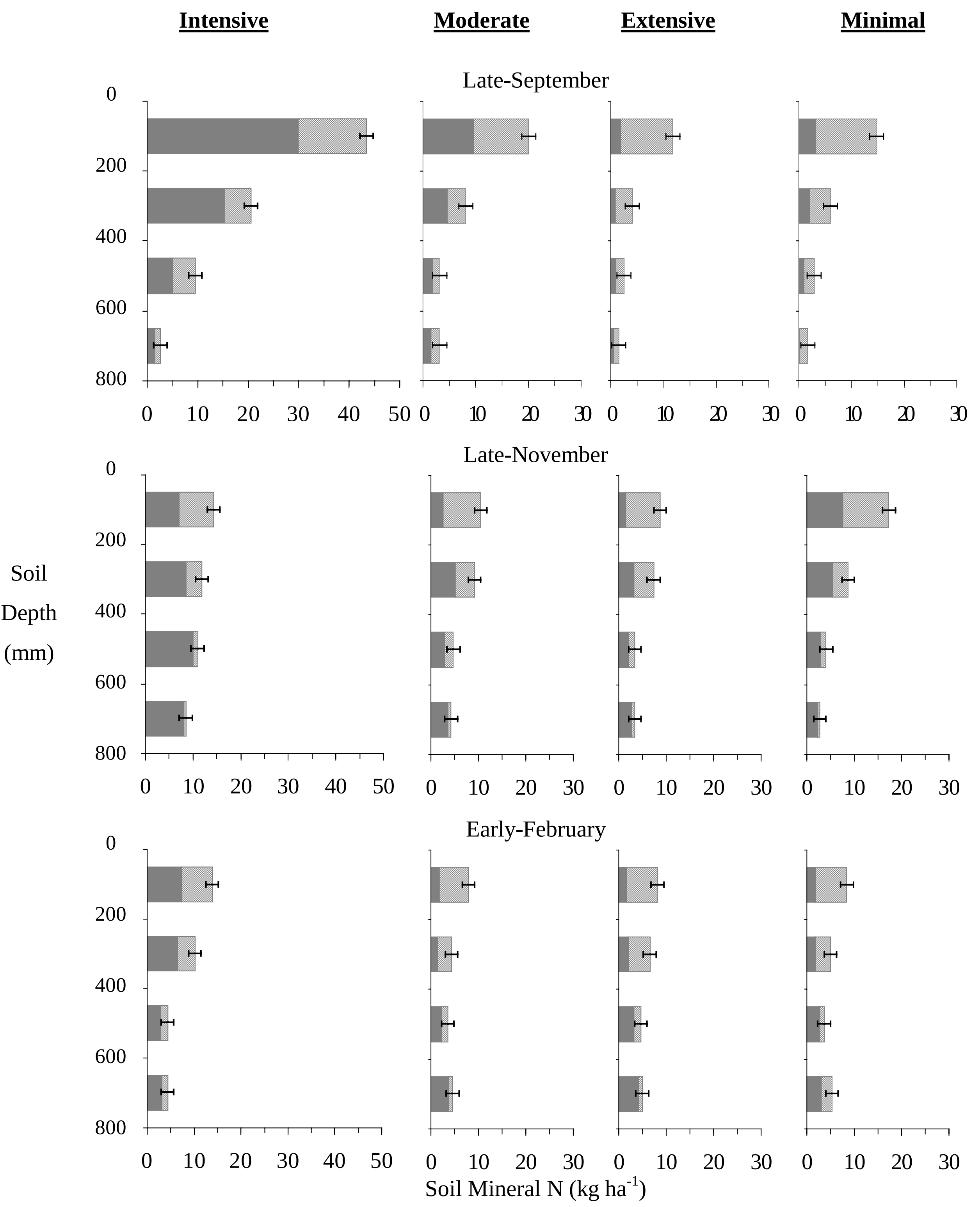


Figure 5. **Soil mineral N concentrations (nitrate ■ & ammonium ▨) at four depths in the soil on three dates during the winter** (data are means of three years; Interaction between treatment x sampling date x soil depth, $P < 0.001$, I = ± SEM of mineral N).

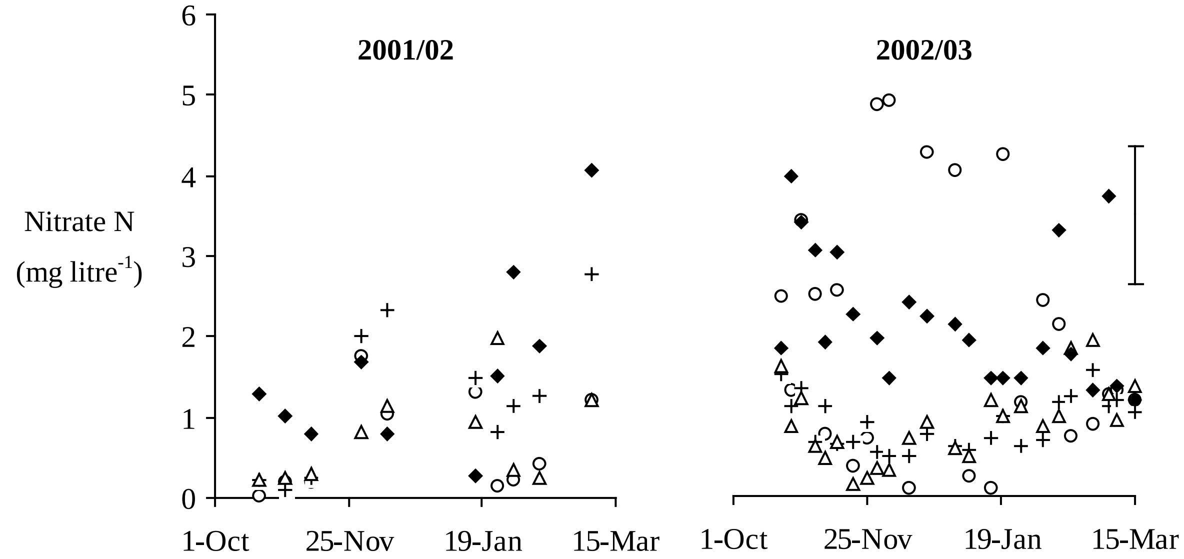


Figure 6. Nitrate N concentrations in drainage water during the winters of 2001/02 & 2002/03. Treatments were as follows: Minimal ○, Extensive +, Moderate Δ and Intensive ◆. (Interaction between treatment x sampling date, $P < 0.01$, I = ± SEM).

In the present experiment, substantially higher levels of N-fixation were recorded during 2002 than the preceding years. This tallies with the relatively elevated nitrate-N concentrations in drainage water from this treatment during the winter of 2002/03. Furthermore, there is generally a large decline in the clover content of swards between the autumn and the following spring (Table 9). Previous work (Humphreys *et al*., 1997) has shown that the amount clover stolon per ha can decline by as much as 75% during the winter period releasing substantial quantities of mineral N into the soil. The sporadic peaks in nitrate-N in drainage water under Minimal can be attributed to this source of mineral N.

Assuming that effective drainage (rainfall – evapotranspiration) at Solohead during the winter period was 550 mm it is possible to estimate the quantity of N lost as nitrate in the drainage water during the winter 2002/03. On this basis 13.3 kg N/ha was lost from Intensive, 11.0 kg/ha from Minimal, 5.0 kg/ha from Moderate and 5.0 kg/ha from Extensive. These quantities are consistent with, although lower than, the losses of mineral N from each of the treatments outlined above. Not all of the mineral-N lost from the soil was lost as leached nitrate during the winter. It is more than likely that these differences were due to gaseous losses following denitrification during the winter months.

Generally speaking nitrate-N concentrations in the drainage water from each of the treatments were low compared to the maximum allowable concentration (MAC) under the Nitrates Directive of 11.3 mg/litre or the guide concentration of 5.65 mg/litre. Average concentrations in drainage water during the winter 2002/03 were 2.4 mg/litre from Intensive, 2.0 mg/litre from Minimal, 0.9 mg/litre from Moderate and 0.9 mg/litre from Extensive. These concentrations are similar to general concentrations in drainage water entering and leaving Solohead farm of (mean ± SD) 2.2 ± 0.6 mg/litre. These generally low concentrations of nitrate N recorded in drainage water indicate that N losses were mostly due to denitrification of oxidized-N in the soil. This is consistent with the heavy soil and mild wet winters experienced at Solohead.

- *Nitrate leaching was a relatively minor pathway for N losses from the treatments in this experiment. This is consistent with the heavy soil and mild wet conditions experienced at Solohead.*

Synthesis and General Discussion

Dairy cow performance

Milk production during this experiment was mostly based on grazed pasture. Both the CP and OMD of pasture increased significantly with increasing fertilizer N input except where white clover made a substantial contribution to production. It therefore might seem a bit surprising that there was no difference in milk output per cow, in the composition of the milk produced or on BCS of the cows on the different treatments. However, mean CP concentrations in pre-grazing pasture ranged between 172 g/kg on Minimal and 211 on Intensive (Table 12). These CP concentrations are within the range of well-managed pasture, which are normally in the range 175 to 250 g/kg DM (28 to 40 g N/kg DM) and sufficient to meet the demand of grazing cows (Muller & Fales, 1998; Peyraud & Astigarraga, 1998).

Peyraud *et al*. (2001) concluded that, under very low N inputs, the CP concentration in the pasture DM can be limiting for grazing dairy cows when concentrations fall below a threshold value of 140 g/kg DM. Higher concentrations of 160 to 180 g/kg DM are generally recommended for the diets of dairy cows (NRC, 2001). Therefore it seems that the low CP concentrations in the pre-grazing pasture on Minimal during 2000 (mean of 150 g/kg DM, Table 12) was close to the minimum threshold for milk production. However, the pasture removed by grazing livestock generally contains higher CP concentration than the pre-grazing pasture on offer (Humphreys *et al*., 2001). This can be explained by the capacity of cows to select the pasture ingested. Evidence of this selection pressure in the present experiment can be seen in Table 12 where ingestion of OM ranged between 51 and 58% of the pasture on offer at each grazing. These values are within the normal range of 50 to 60% (Wilkins & Garwood, 1986; Parsons & Chapman, 2000). In the present experiment the CP in ingested pasture was higher than that in the pre-grazing pasture across all the treatments and, on average, was 201 g/kg DM on Minimal (Table 12), which is more than adequate to meet the cows requirements.

There were also significant differences in OMD concentration in pre-grazing pastures ranging from low mean values of 798 g/kg on Minimal and Extensive to high values of 826 g/kg on Intensive. However, even the low values in this experiment were relatively high and were probably sufficiently high as not to place a restriction on intake. In a similar experiment, Delaby *et al*., (1998) applied three rates of fertilizer N 320, 100 and 0 kg N/ha on a fertile site in Normandy. They found that both CP (225, 177 and 158 g/kg DM, respectively) and digestibility of the pre-grazing grass (740, 710 and 700 g/kg respectively) declined with decreasing fertilizer N input. However, they found that in spite of this small decrease in nutritive value of the grass the average individual milk yield, milk fat and protein contents were not different between the three treatments. The extent to which cows selected available pasture has been pointed out above. It was not possible to accurately measure the OMD concentration in residual pasture in this experiment and therefore it was not possible to estimate the OMD of ingested pasture. Nevertheless, it stands to reason that cows selected pasture of higher nutritive value than the pre-grazing pasture. This accounts for the absence of any statistically detectable difference in dairy cow performance in this three-year experiment. There was a tendency towards lower milk output per cow and poorer BCS on Moderate during this experiment (Tables 6 & 7). However, this trend cannot be attributed to the nutritive value of the sward in this treatment. It was probably due to supplementation with baled silage late in the grazing season.

Carrying capacity and fertilizer N requirements

Silage production expressed in terms of the quantity of silage produced per ha of the whole treatment area (total silage production ÷ whole treatment area) increased linearly with increasing fertilizer N input once the potentially confounding contribution of white clover is excluded (Fig. 7a). Similarly, pasture production in terms of t OM consumed by the dairy cows from the grazing area also increased linearly with increasing fertilizer N input up to 350 kg N/ha once the contribution of white clover is excluded (Fig. 7b). The importance of these relationships is that production responses were linear up to fertilizer N inputs of 350 kg N/ha. This is an important consideration when it comes to assigning fertilizer N requirements to various stock carrying capacities (stocking rates).

The level of fertilizer N input on Intensive (350 kg N/ha/year) comfortably met the requirements of a stocking rate of 2.5 cows/ha/year. In fact there is evidence to suggest that there was scope to use less fertilizer N at this stocking rate. This comes from two sources.

(1) Silage production on Intensive was 1.5 t DM/cow. The required quantity was 1.4 t DM/cow or 3.46 t DM/ha of whole treatment area. Line B, presented in Figure 7, is concerned only with the treatments stocked at 2.5 cows/ha in this experiment:

Silage production per ha of the treatment area = fertilizer N (kg/ha) x 0.0066 + 1.296 ($R^2 = 0.92$; $P < 0.001$)

Using this equation it is possible to calculate that the target quantity of silage required could have been achieved with a total fertilizer N input of 320 kg N/ha.

(2) Pasture cover data presented in Figure 4 indicates that there was little difference in pasture covers/ha between Moderate and Intensive between the months of February, March and April although there was a difference in fertilizer N input of 29 kg N/ha between these treatments in February. Furthermore, there was little difference in the areas harvested for silage before mid-June (Table 8) or in the quantities of silage harvested for first cut silage (Table 9) although again there was a difference in fertilizer input of 29 kg N/ha between these two treatments in February. Therefore there was scope on Intensive to lower fertilizer N input by around 30 kg N/ha/year. It is apparent that the best opportunity to lower fertilizer N input from Intensive would have been to apply 29 kg/ha rather than 58 kg/ha in February.

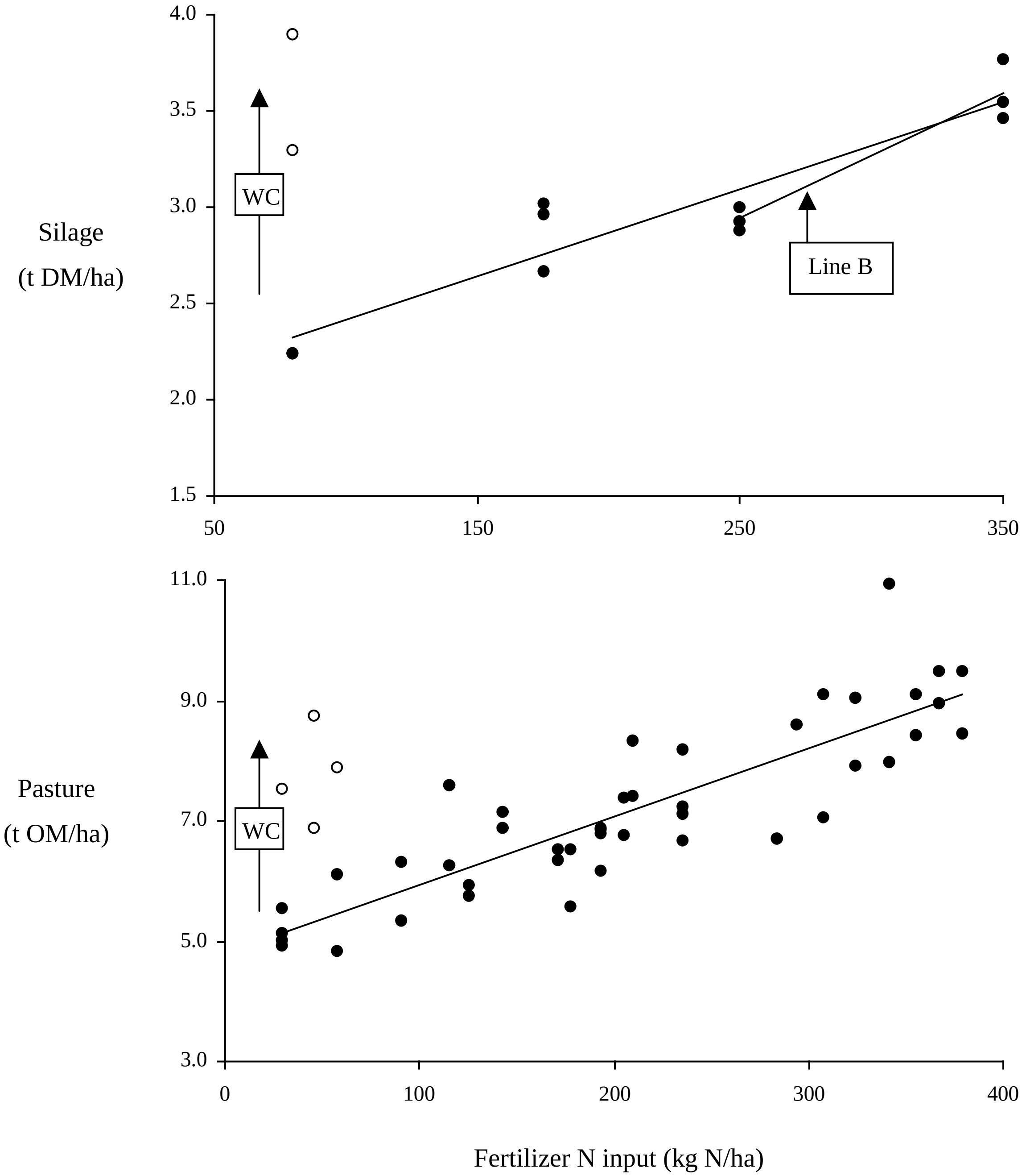


Figure 7. The impact of increasing fertilizer N input on (a) silage production and (b) pasture production. Silage production per ha of the treatment area increased with increasing fertilizer N input along the line: fertilizer N (kg/ha) x 0.0045 + 1.96; $R^2 = 0.85$, $P < 0.001$. Pasture production per ha increased with increasing fertilizer N input along the line: fertilizer N (kg/ha) x 0.0114 + 4.79; $R^2 = 0.75$, $P < 0.001$. Swards containing high contents of white clover [°WC] were excluded from these analyses.

On average, silage production on Extensive was inadequate (Table 9). Furthermore, pasture covers from late August onwards were below target (Fig. 4). The cows on this treatment required supplementary feeding. These results indicate 175 kg N/ha was inadequate for grassland-based dairy production stocked at 2.1. cows/ha. Higher inputs of fertilizer N were required and these are best directed towards pasture production during the autumn. There is another way of looking at this. The quantity of silage produced from this treatment is sufficient to supply 1.44 t DM/cow if this treatment was stocked at 2.0 cows/ha. This provides two likely fertilizer N requirements at two stocking rates: (1) 170 kg N/ha for a stocking rate of 2.0 cows/ha and 200 kg N/ha for a stocking rate of 2.1 cows/ha.

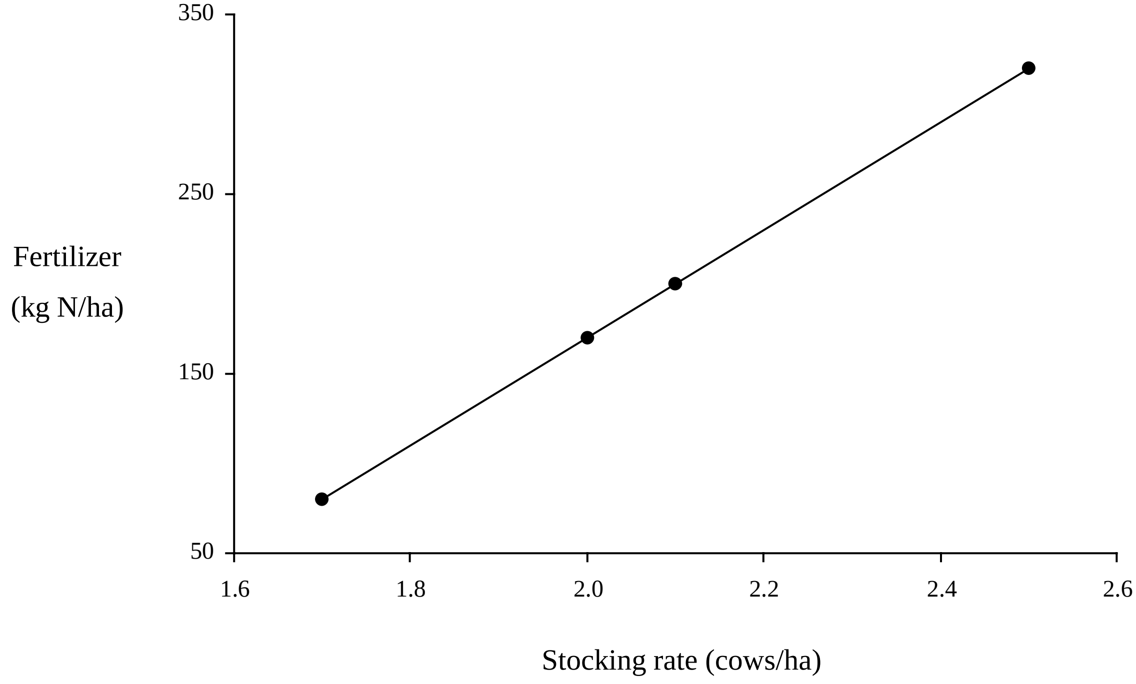


Figure 8. Stocking rate and the requirement for fertilizer N at Solohead

During 2000, white clover made a negligible contribution to soil N supply on Minimal. Silage production was below target at 1.3 t DM/cow. Otherwise pasture supply was sufficient. There is only one years data available but it indicates that 80 kg N/ha would probably have been sufficient to meet the feed requirements of 1.7 cows/ha. This designation and the above designations at 2.0 and 2.1 cows/ha are roughly assigned, however, when these points are examined together it is apparent that there is a linear relationship between stocking rate and fertilizer N requirement (Fig. 8). For every increase in stocking rate by 0.1 cows/ha there is an increase in the requirement for fertilizer N of 30 kg/ha. It stands to reason that this relationship is linear because (1) silage production per ha of treatment area, and (2) pasture production, increased linearly with increasing fertilizer input up to 350 kg N/ha/year (Fig. 7).

When this relationship is compared with the 1994-Teagasc recommendations (Gately, 1994) a remarkable difference becomes apparent: the lines are virtually parallel within the comparable ranges of both sets of data (between 2.1 and 2.5 cows/ha) (Fig. 9). In other words, at Solohead it was found that for every increase in stocking rate by 0.1 cows/ha an extra 30 kg N/ha was required and the recommendations of Gately (1994) are based on the exact same relationship. The big difference is that 1994-Teagasc recommendations are about 95 kg/ha lower than Solohead at each stocking rate within this range.

There are a large number of reasons why differences between different data sets should exist, such as the type of cow used in various experiments etc., and these have been outlined by Gately *et al*. (1984). However, that these two lines are parallel is no mere coincidence. Both indicate a clear and consistent stocking rate response to fertilizer N. By far the most plausible explanation for the constant difference of 95kg N/ha is that there were substantial differences in the capacity of different soils to supply background-N.

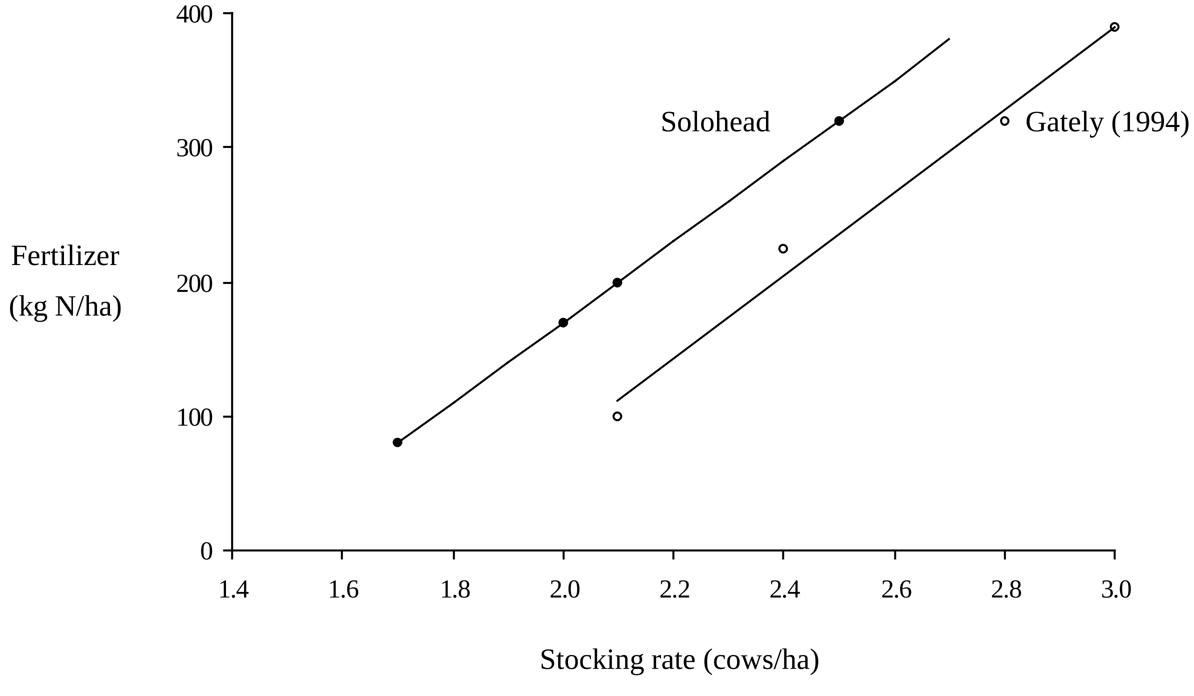


Figure 9. Comparison of the relationship between stocking rate and fertilizer N requirement at Solohead and the Teagasc fertilizer N recommendations for grazed swards (Gately, 1994)

Background supply of N obviously has an important bearing on fertilizer N requirements of different soils. For example, at Solohead background supply of N is around 120 kg/ha and under the high stocking rate of 2.5 cows/ha around 320 kg fertilizer N/ha is required. These add up to a total soil N supply of 440 kg N/ha/year. Background-N accounts for 27% of total soil N requirement. This is a substantial contribution. It seems likely that the 1994-Teagasc recommendations are based on a more fertile soil scenario than that at Solohead. The obvious national figure to use for background-N comes from Ryan (1976) where an average of 219 kg of background N was recorded on 26 sites around the country over a four-year period. If results of the present experiment are compared to the 1994-Teagasc recommendations in terms of total soil N supply where:

(1) background N supply is 219 kg/ha for the 1994-Teagasc recommendations (Ryan, 1976)

(2) background N supply is 120 kg/ha at Solohead (O'Connell *et al*., 2003),

Then the relationship between stocking rate and soil N supply becomes virtually indistinguishable between these two utterly independent data sets (Fig. 10).

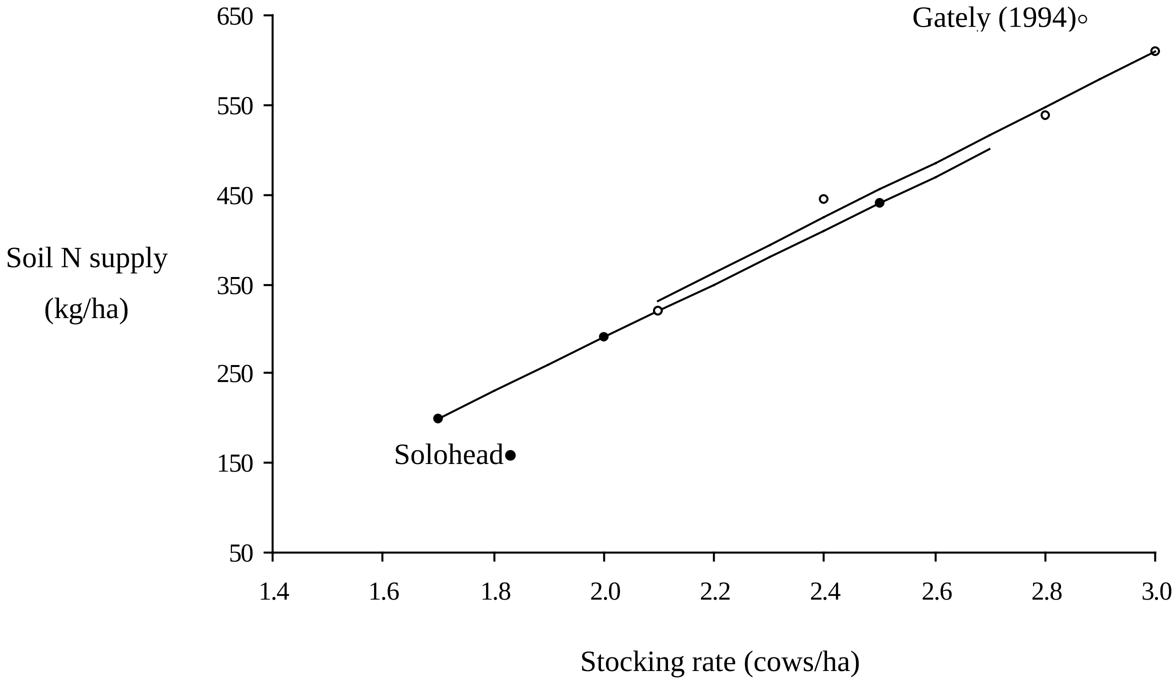


Figure 10. **Comparison of the relationship between stocking rate and N supply from the soil at Solohead and Gately (1994) when N requirements are supplied by fertilizer N plus net mineralised SOM-N (background-N)**

Examining the data from the perspective of total soil N supply provides the potential for a far more rational set of fertilizer N recommendations for grassland than has been formulated to date. It is quite clear that putting together fertilizer N recommendations that do not take account of the soil supply of background-N is futile. Recommendations need to be based on the relationship between the requirement for soil N and stocking rate as presented in Figure 10. Soil N requirement consists of background-N + applied fertilizer N. This relationship is as follows:

$$\text{Soil N req.} = (\text{SR} \times 300) - 300$$

SR is stocking rate in cows/ha.

This relationship is intermediate between Solohead and Gately (1994) presented in Figure 10 and is selected for its obvious simplicity. The requirement for fertilizer N can be estimated from the following equation:

$$\text{Fertilizer N req.} = (\text{SR} \times 300) - (300 + \text{background-N})$$

This equation is relevant to stocking rates between 1.7 and 2.8 cows/ha and is probably reliable for soils with background-N supplying capacities of between 60 and 250 kg/ha.

The big problem with this equation is to determine background-N at different sites around the country. It is apparent that an average value of 219 kg N/ha was taken from Ryan (1976) and used in the 1994-Teagasc recommendations. The validity of this value is questionable. It is based on N off-take from unfertilised grassland plots at 26 sites around the country over four growing seasons (1967 to 1970). However, the white clover contents of these swards averaged 310 g/kg DM in 1967, 290 g/kg DM in 1968 and 100 g/kg in 1970. Measurements of clover contents were not carried out during 1969. It is likely that the availability of background N based on these results is an overestimate. It can be seen in Table 13 of the present experiment that clover contents of approximately 240 g/kg made substantial quantities of N available in the soil during 2001 and 2002.

Recent on-going work in Ireland indicates that background-N under permanent grassland amounts to between 60 and 250 kg N/ha/year; average quantities are approximately 130 kg N/ha/year (Kay O'Connell, pers. comm.), although this is based on limited data. In the UK the range is between 50 and 250 kg N/ha with an average of around 110 kg N/ha/year (Richards, 1977; Hopkins *et al*., 1990; Gill *et al*., 1995). In the Netherlands the range is between 45 and 235 kg N/ha with mean values of around 135 kg N/ha/year (Hassink, 1995). Low values are generally associated with (1) soils in arable rotation, (2) shallow sandy soils or (3) upland soils of marginal agricultural value. These data are useful in that they provide an indication of the range of values that can be expected. Low values in Ireland are associated with disadvantaged sites, in terms of soil depth, drainage status etc. that tend to be located in the west and northwest of the country. High values are associated with deep fertile soils particularly in the northeast of the country.

Implications for farmers

The importance of such information becomes clear when three issues are considered: (1) Water Quality, (2) The Nitrates Directive and (3) REPS. No derogation on the stocking rate limits imposed under the Nitrates Directive will be allowed in the long term unless there is an improvement in water quality nationally. Accurate recommendations are essential to maintain productivity with least fertilizer input. Under the Nitrates Directive fertilizer N recommendations will become statutory. Penalties will be imposed if farmers fail to abide by what were originally designed to be recommendations. It is clear that for any stocking rate one recommendation cannot be applicable to a diverse range of soil and climatic conditions.

Table 15. Fertilizer N requirements at different sites around Ireland

Stocking rate (cows/ha)	**Site**	**Background N** (kg/ha)	**Data Source**	**Fertilizer Req.** (kg/ha)
2.1	Kilmaley	60	O'Connell, pers comm.	270
2.1	Drumlins Cavan/Leitrim	90	O'Connell, Ryan, 1976	240
2.1	Solohead/Moorepark	120	O'Connell *et al.*, 2003	210
2.1	National Average	130	O'Connell, pers comm.	200
2.1	Grange/Ballyhaise	220 - 250	O'Connell, pers comm.	110 - 80

In Table 15, fertilizer N requirements at different sites are presented based on the above equation and recorded background-N at each site. A moderate stocking rate of 2.1 cows/ha is selected because this stocking rate can be carried at each of these sites. It is clear that far more fertilizer N is required at the less productive sites to achieve the same level of output. Under a mandatory set of recommendations that does not take account of differences between soils, farmers operating on less fertile soils, mainly in the west of the country, will be placed in a very disadvantaged position. On the other hand, farmers on fertile soils in the east of the country will have much greater capacity to apply fertilizer N perhaps more than is actually required to meet their objectives. This same problem arises in the case of REPS. Farmers on less fertile soils are at a clear disadvantage under REPS.

The magnitude of the differences in fertilizer N requirements at the different sites highlights the importance of this question for research. There is more than a three-fold difference in fertilizer N requirements between poor soils in the west (Kilmaley) and fertile sites in the northeast (Grange & Ballyhaise) to achieve the same level of output. Furthermore, at moderately fertile sites such as Moorepark or Solohead background N is able to supply around one-third of total N requirement at a stocking rate of 2.1 cows/ha. On average capacity in Ireland background-N is sufficient to supply around 45% of total soil N requirements at this stocking rate. This is certainly a source of N that cannot be ignored.

Upper limits to fertilizer N use

Under the Intensive system at Solohead both silage and pasture output responded linearly to soil N availability amounting to 350 kg fertilizer N + 120 kg background N = 470 kg available soil N/ha/year. It is generally accepted that grassland swards are highly responsive to soil N availability of up to around 450 kg N/ha/year (Richards, 1977; Prins, 1983; Hopkins *et al*., 1990; Hassink, 1995; Verbruggen *et al*., 2003). At levels of soil N availability greater than 450 kg N/ha, responsiveness begins to diminish, particularly at supply greater than 500 kg/ha. Hence, the relationship in Figure 10 extends as far as a soil N supply of 480 kg N/ha or a stocking rate of 2.8 cows/ha. This corresponds to an application rate of fertilizer N input of 410 kg/ha for an average soil in Ireland supplying 130 kg background-N/ha during the growing season. Very few farmers in Ireland are operating at this level of intensity. On poorer soils stocking rates exceeding 2.2 cows/ha are unlikely because of problems of soil traffic-ability etc. and hence on the poorest of soils fertilizer N requirements are unlikely to exceed 300 kg N/ha/year.

Fertilizer N application in the spring

It was pointed out above that on Intensive there was scope to lower fertilizer N inputs during the early spring from 58 kg/ha to 29 kg/ha. O’Donovan *et al* (2004) showed very high production responses in terms of grass production on 18 March to fertilizer N input of 90 kg N/ha under conditions at Moorepark. It is reasonable to assume that grass growth during the spring is around three weeks later at Solohead than Moorepark because of (1) differences in soil type and (2) soil temperatures during January, February and March and (3) differences in the growth studies at both sites (Fig 11). Therefore to achieve the same levels of production response at Solohead during the spring as that outlined by O’Donovan *et al*. (2004) it would be necessary to apply 90 kg N/ha during early to mid February. Applying 90 kg N/ha all in one go in February at Solohead carries the risk of substantial losses via denitrification as well as by leaching and run-off taking into account the high rates of surplus rainfall during February and the soil-type at Solohead (Fig. 12). Therefore it seems to be prudent to split this 90 kg N/ha into two applications: (1) 30 kg N/ha applied around mid-February and (2) 60 kg N/ha applied around mid-March, depending on ambient weather and ground conditions on these application dates. The proportion in each split being in concurrence with expected increases in grass growth rates (Fig. 11). This will lower risk of losses and increase the possibility of capturing more of this N in the growing crop later in the growing season.

For example, where O’Donovan *et al*., applied 90 kg N/ha in mid January at Moorepark, recovery amounted to around 49% of applied fertilizer (or 44 kg N/ha). Furthermore, there was no further recovery of the applied fertilizer N when the grass was again harvested in 8 April. This indicates that 51% of applied fertilizer N or 46 kg N/ha was lost from the soil. If all of this N was lost as nitrate leached from the soil then the nitrate-N concentration of water draining from the soil during this period would be 23 mg/litre or around twice the MAC of 11.3 mg/litre. However, it is highly unlikely that all of the N lost from the soil will be lost as leached nitrate except on sandy shallow soils. On the other hand, it is important to bear these risks in mind when making recommendations. These losses also constitute a waste of money.

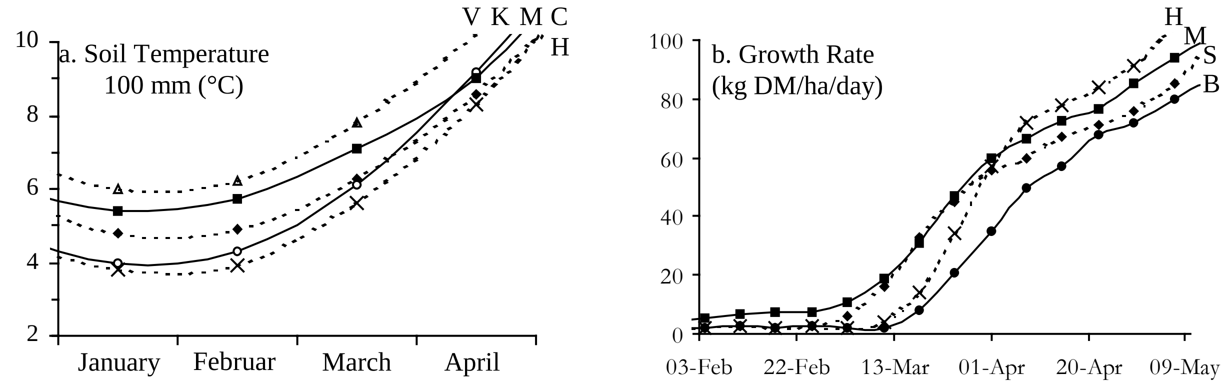


Figure 11. (a) Soil temperatures during the late-winter and spring at a range of sites in Ireland from the south west to north (V = Valencia △, Co. Kerry; C = Cork airport ◆, south Co. Cork; M = Moorepark ▪, north Co. Cork; K = Kilkenny °, in the midlands & H = Clones ×, Co. Monaghan in the north) and (b) grass growth rates during the spring at a range of sites in Ireland from south to north: (M = Moorepark ▪, Co. Cork; S = Solohead ◆, Co. Tipperary; H = Ballyhaise ×, Co. Cavan & B = Ballinamore •, Co. Leitrim).

It can be seen in Fig. 12 that there are large surpluses of rainfall during January and February and that there are substantially lower surpluses during March and April. Surplus rainfall plays an obvious role in nitrate leaching and also plays a key role in the process of denitrification; the wetter the soil the greater the risk of denitrification. Delaying the greater part of fertilizer N applications until March will help to lower losses and increase N-use efficiency giving better value for money. It is well known that response rates to applied fertilizer N increase substantially from March onwards (Murphy, 1977). Hence, the validity of splitting applications during the early springtime.

This objective can be achieved by a planned approach to fertilizer N application during the spring based on calendar dates. At Solohead, around 30 kg N/ha was applied in mid-February, 60 kg N/ha in mid-March and 60 kg N/ha in early to mid-April. This latter application was to coincide with closing up of the silage ground, concentrating stocking rate on the grazing area and in anticipation of the surge in grass growth that normally occurs during late April and early May. These applications were bulk-spread over the whole of the experimental area at each date except to where cows would be grazing during the following few days (ranging between 2 and 7 days). Under such circumstances, when the grazing rotation is as long as 70 days, ensuring the sufficient fertilizer is applied during March and early April is facilitated by a blanket approach to fertilizer N application. To achieve efficient use of applied fertilizer N and high sward productivity around 150 kg N/ha needs to be applied in three applications in the period between mid-February and mid-April at Solohead. At sites with earlier growth such as Moorepark fertilizer N needs to be applied around three-weeks earlier on average, for example mid January, late February/early March and early to mid April. At later sites these dates are late February, late March and mid April. It can be seen if Figure 11 that, while early spring growth is prevented by low soil temperatures at more northern locations, there is little difference in the production capacity of different sites by the middle of April.

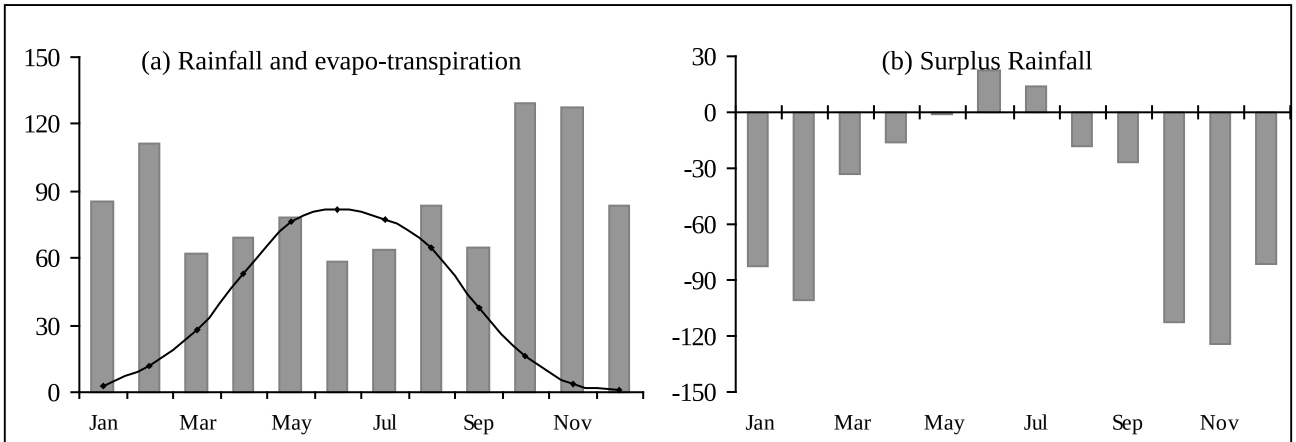


Figure 12. (a) Average monthly rainfall (bars) and potential evapotranspiration (lines) (mm/month) at Solohead between 2000 and 2002 and (b) Surplus rainfall (mm/month)

There can be considerable variation in growing conditions between one spring and another. However, when it comes to making recommendations on when to commence fertilizer N applications during the spring the best research can offer at the moment is to make recommendations based on calendar dates under Irish conditions (for review of this subject see Humphreys *et al*., 2003). A clear planned approach to spring fertilizer N application puts the farmer in control of fertilizer N use on the farm and avoids wasteful, inefficient and potentially environmentally damaging fertilizer N application practices.

It can be seen in Figure 5 that most of the N available in the top-soil (>200mm at Solohead) during late November and early February is in the form of ammonium. Available ammonium in the soil is rapidly nitrified to nitrate unless it is otherwise taken up by the sward (Whitehead, 1995) and, hence, ammonium usually does not accumulate in soil. The presence of ammonium in the topsoil is indicative of net mineralization during the winter period. Estimation of rates of mineralization during the winter (early November to mid-February) at Solohead range between 200 and 300 g N/ha/day. Similar rates were recorded by Gill *et al*. (1995) in the south-west of England. Under the zero-fertilizer N-input at Moorepark, O'Donovan *et al*., (2004) recorded N uptake of around 43 kg/ha during the period between 10 October and 18 March. This equates to soil N availability of around 270 g N/ha/day and only the available N recovered by the sward was recorded in this case. This level of soil N availability is able to sustain growth rates of between 6 to 10 kg DM/ha/day. It can also be seen in Fig. 5 that around 10 kg N/ha was immediately available in the soil in early

February. This is probably enough N to sustain the growth of over 300 kg pasture DM. While there are clear benefits associated with the application of fertilizer N during the spring it should be borne in mind that the likelihood of N deficiency during January and February is buffered against by this background supply of N. It is only when sustained (not intermittent) growth rates of greater than 5.0 kg DM/ha/day are being recorded during the spring that the requirement for fertilizer N becomes urgent.

Fertilizer N application during the autumn

Under Intensive, total mineral N availability in late September was 111 kg/ha in 2000, 113 kg/ha in 2001 and 40 kg/ha during 2002. It is likely that the lower N availability during 2002 was due to the exceptionally wet conditions experienced during the grazing season. These wet conditions probably contributed to high losses via denitrification during the warm summer months as outlined above. Losses of N from the soil during the early winter from Intensive were estimated at 88 kg/ha during 2000/01, 100 kg/ha during 2001/02 and 32 kg/ha during 2002/03. Even with the inclusion of the exceptional 2002 there were large losses of N from Intensive during the autumn and early winter. This indicates that there is a strong case for avoiding heavy applications of fertilizer N during the late autumn.

The N available in the soil can go a long way towards meeting the requirements of the sward during the autumn. The application of fertilizer N in September is not recommended by MAFF (2000) or by Murphy (1977). Both recommend final applications in mid to late August. Highest rates of nitrate leaching are usually recorded during the autumn and early winter period when drainage recommences after the summer (Fig. 12). Therefore ceasing fertilizer N application before the end of August is good agricultural practice from an environmental perspective. On the other hand, because grazed grass is a very cost-competitive feed, there is a clear incentive to extend the grazing season into the late autumn and winter (Binnie *et al*., 2001). An application of fertilizer N in early September will promote growth during this period at milder sites where there is potential to utilize this pasture during the late autumn and winter (Casey & Brereton, 1996). A more detailed description of fertilizer N application strategies is provided in the end of project report no. 4984 entitled “Environmentally sustainable fertilizer nitrogen management practices for pasture production”.

White Clover

One of the big surprises was the extent of the increase in productivity of the white clover swards during the experiment both by supplying N from N-fixation and by improving sward nutritive value under low fertilizer N input. It resulted in large surpluses in silage production during 2001 and 2002, which clearly indicated that Minimal has a much greater stock carrying capacity than that imposed during this experiment. The stock carrying capacity of white clover swards is being examined further at Solohead in project no. 5150. The results of the experiment presented in this report have shown the viability of this approach to white clover introduction into swards using low-cost techniques. They also indicate that white clover can potentially make an important contribution to low-cost production on the majority of dairy and beef farms in Ireland. Although white clover contributed to slightly higher nitrate losses during the winter period concentrations of nitrate N were low and well below the EPA guide concentration of 5.56 mg/litre. Furthermore, from the perspectives of National Emissions Ceilings Directive and the National Climate Change Strategy white clover contributes to lower ammonia and nitrous oxide emissions and requires lower fossil fuel consumption (for manufacture, transport and application of fertilizer) than fertilizer N. White clover also has the potential to contribute to relatively productive grassland-based farming systems while remaining within the total N limits required by REPS. Payments associated with REPS potentially can contribute to the future viability of medium-sized average-cost diary producers where the amount of quota available per ha is medium to low (Dillon *et al*., 2003; Donworth & Maher, 2003).

Organic N loads and nitrate-N leaching losses

The organic N loads/ha based on standard value of 85 kg/cow (DAFF, 1996) are presented in Table 2 and again in Table 16 where they are compared with actual estimates of organic N loads. These estimates are based on the components of the diets (grazed-grass, grass-silage and concentrates) of the cows and the CP concentrations of these components recorded during this experiment.

The basis for the requirements for silage per cow is presented in Table 4. It is assumed that around 7% or 0.1 t of silage DM/cow is wasted during feeding out and as a consequence of rejection (O’Kiely pers. comm.). All treatments but Moderate more-or-less met this silage requirement and therefore in Table 16 additional concentrate is supplied to make up the deficit in the feed budget. The CP concentrations of the silage presented in Table 16 are taken from Table 9 and are the same across treatments because there were no significant differences between treatments. The quantity of grazed grass consumed is estimated from the energy requirements of the cows. The CP concentration in the grazed grass is based on the estimates presented in Table 12. The level of concentrate fed is the average fed during the three years of this experiment except on Moderate for reasons outlined above. Total estimated DM intake was on average 13.9 kg DM/cow/day averaged on an annual basis. If it is estimated that each cow ate approximately 10.0 kg DM/day for each day of an average non-lactating period of 78 days, then DM consumption was 14.9 kg DM/cow for each day of 287 days of lactation.

Table 16. Stocking rate, fertilizer N input and organic N loading per ha, estimated intake and the crude protein (CP) concentrations in the components of Intake, N in intake, output, excretion and deposition, and organic N loads per ha and surplus N/ha in comparison to nitrate-N concentrations in drainage water during the winter.

	Minimal	**Extensive**	**Moderate**	**Intensive**	**Source**
Fertilizer N (kg/ha/year)	80	175	250	350	
Stocking Rate (cows/ha/year)	1.75	2.10	2.50	2.50	
Organic N load (kg/ha/year)	149	178	210	210	Standard 85 kg/cow
		DM intake and CP in DM intake			
Silage Consumed (t DM/cow)	1.30	1.30	1.12	1.30	120 days (Table 4)
CP in silage (g/kg)	144	144	144	144	(Table 9)
Grazed Grass (t DM/cow)	3.25	3.25	3.25	3.25	365 – 120 = 245 days
CP in consumed grass (g/kg)	201	215	232	242	(Table 12)
Concentrate (t DM/cow)	0.51	0.51	0.69*	0.51	*compensate for silage
CP in concentrate (g/kg)	175	175	175	175	
Total Intake (t DM/cow)	**5.06**	**5.06**	**5.06**	**5.06**	13.9 kg/cow/day
		Nitrogen Intake (kg/cow/year)			
Silage	30.0	30.0	25.8	30.0	
Grazed Grass	104.5	111.8	120.6	125.8	
Concentrate	14.3	14.3	19.3	14.3	
Total N intake	**148.8**	**156.0**	**165.8**	**170.1**	
		Nitrogen in output (kg/cow/year)			
Milk (224.5 kg CP/cow at 63.9 g N/kg CP)	35.1	35.1	35.1	35.1	(Tables 6 & 14)
Meat (cull cows & calves)	2.3	2.3	2.3	2.3	(Table 14)
Total N output	**37.4**	**37.4**	**37.4**	**37.4**	
Organic N excretion (kg/cow)	111	119	128	133	
Organic N deposition (kg/cow)	100	107	116	120	
Organic N load (kg/ha)	**175**	**224**	**289**	**299**	
Surplus N (kg N/ha)	88	133	200	300	(Table 14)
Losses of Mineral N (kg/ha)	18	12	27	66	(Fig. 5)
		Nitrate-N in drainage water			
Nitrate-N (kg/ha)	**11.0**	**5.0**	**5.0**	**13.3**	
Nitrate-N (mg/litre)	2.0	0.9	0.9	2.4	(Fig. 6)

On this basis, annual intake of N ranged between 149 kg/cow on Minimal to 170 kg/cow on Intensive. There was no significant difference in milk protein output per cow (Table 6) and therefore an average value across treatments is used in Table 16. Output of N in cull cows and calves was estimated at 2.3 kg N/cow/year and similar across treatments. Therefore organic N excretion ranged between 111 and 133 kg/cow. It is assumed that 10% of this excreted N is lost as gaseous ammonia losses to give organic N deposition/cow. Organic N deposition/cow is multiplied by stocking rate to give organic N load/ha. These ranged between 175 and 299 kg/ha and increased with increasing stocking rate and fertilizer N input. They are considerably higher than the standard values, however, the level of milk output per cow in this experiment was well above the national average of around 4650 kg/cow, which accounts for this difference.

While the calculated organic N loads/ha are closely related to surplus N on each of the treatments they are less closely related to losses of mineral N during the winter months and not related to the levels of nitrate N lost in the drainage water during the winter. It is clear that under the conditions at Solohead that a substantial proportion of N losses took place as a consequence of denitrification of nitrate in the soil.

For denitrification to occur (1) nitrate needs to be present in the soil, (2) anaerobic conditions in the soil, (3) soil temperatures >5.0°C (4) a suitable source of carbon (C), and (5) soil pH > 6.0. All of these criteria were met at Solohead during this experiment. There were large amounts of nitrate present in the soil in late September under the higher N input treatments. The soil at Solohead is classified as being medium-wet heavy textured soil (Walsh, 1984) with a high bulk density that increases with depth and prone to waterlogging under persistent rainfall leading to anaerobic conditions in the soil. Furthermore during the winter period, average monthly soil temperatures generally remain >5.0°C during the months of October, November and December. This coincides with the largest losses of nitrate from the soil (Fig. 5). The soil at Solohead has above-average organic matter contents and hence an abundant source of C at all depths (Table 1) and soil pH at Solohead during the experimental period was around 6.5.

It seems most likely that nitrate being leached from the topsoil into more dense heavy textured subsoil encountered anaerobic conditions under conditions of high rainfall, which caused the leaching in the first place. Most of the nitrate was denitrified and lost as N_2 or N_2O gasses. Only a relatively small proportion of the nitrate available to be lost survived to reach the water draining from the soil. Solohead is representative of 18% of the agricultural area of Ireland. These results question the validity of limiting organic N loading on such soils as a means of preventing nitrate leaching to water under the Nitrates Directive.

Conclusions

- Lowering fertilizer N inputs had no detectable impact on milk output per cow in this experiment.

- There was relationship between requirement for fertiliser N and stocking rate along the line:

  Fertilizer N req. = (SR x 300) – (300 + background-N)

  Where SR is stocking rate in cows per ha and background N is the release of N from net mineralization of soil organic matter N. The average value for background-N is around 130 kg/ha.
- Very high levels of productivity from grass + white clover swards receiving 80 kg N/ha/year. These swards had around 80% of the carrying capacity of the Intensive treatment. *Rhizobium* bacteria in symbiotic association in white clover supplied available soil N contributing to grassland productivity and also improving the nutritive value of the sward under low fertilizer N inputs. White clover is potentially very useful for farmers farming under REPS where both stocking rates and fertilizer N inputs are limited.
- Very low losses of nitrate-N in drainage water under organic N loads of up to 300 kg/ha were recorded in this experiment. Losses of nitrate-N in drainage water accounted for less than 5% of N losses. It is likely that denitrification and losses of di-nitrogen (N_2) and nitrous oxide (N_2O) gasses were the main pathways for loss. This is consistent with the heavy wet imperfectly drained soils, high rainfall, intermittent soil saturation and the mild conditions experienced at Solohead.

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