Final Report

Improved Canopy and Nitrogen Management for the UK Potato Crop

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1. SUMMARY

The CUF N model relies on assumptions that tuber and total N uptake vary predictably in relation to the quantity of radiation absorbed by the potato crop. A test of these assumptions using 1467 plots of N uptake data taken over many seasons and locations with contrasting varieties and agronomies showed that absorption of radiation by the potato crop was a key determinant of N uptake and redistribution. When analysed in relation to radiation absorbed by the potato crop, tuber and total N uptake were adequately described by linear and exponential relationships, respectively. Collectively, this analysis showed that the principles underpinning the CUF N model were valid.

Collaborative work with Cygnet-PB has allowed the development of robust protocols that will enable plant breeders, grower groups and other stake-holders to understand the physiology of uptake and redistribution of N within new varieties and quickly work out their probable N requirement in relation to season length and yield. These new protocols should largely obviate the need for extensive and expensive empirical N-response experiments and will allow the agronomy of new varieties to be optimised rapidly. The collaborative study with Cygnet in 2010 also provided useful information on the effects of variety, N supply and time of sampling on amino acid concentrations in potato tubers. Similar studies at CUF have tested the effects of varying N applications (0 to 375 kg N/ha) on N uptake, canopy persistence and yield of contrasting varieties. These studies have consistently shown that differences in yield response to N by determinate and indeterminate varieties are largely explicable by reference to the rate of tuber N uptake in relation to total N. This information underpins current N recommendations (e.g. Fertilizer Manual RB209) and will be critical in the development of more precise N recommendation systems in the future.

Collaborative work with Spearhead International used the CUF N and yield models to identify factors that may be limiting the yields of processing crops. The study involved monitoring and sampling of commercial crops and the analysis of experiments within fields of Lady Rosetta and Courage in 2008-2010. An initial analysis showed that tuber yields were consistent with canopy persistence and the absorption of incident radiation and thus factors such as water stress or disease were relatively unimportant. Measurements also showed that canopy persistence was related to total N uptake and therefore, in principle, canopy persistence and yield would be increased if N uptake could be increased. However, N-response experiments consistently showed that the current commercial rates of N application were excessive and thus yields were not limited by the amount of N applied. Measurements of N uptake, soil mineral N, soil penetration resistance and estimates of root length density suggested that N fertilizer falling into wheelings was not used efficiently by the crop. This information has been used by the grower to reduce the total amount of N applied (with no effect on yield) and to modify the method of N application to minimise loss of N into the wheeling.

A series of experiments attempted to quantify the effects of contrasting soil conditions (achieved by cultivating soils at varying soil moisture contents) on crop growth and yield. When compared with the effects of irrigation or N supply, the effect of cultivating soils at different soil moisture contents on tuber yield was relatively small.

Whilst poor soil conditions exacerbated the effects of insufficient N on tuber yield, there was little evidence that yields of crops grown in poor soil conditions would be increased by applying more N. In all cases, the effects of soil conditions, irrigation and N application rate on canopy longevity and yield were explicable in terms of these treatments on total N uptake and the rate of transfer of N from haulm to tubers.

A series of experiments at CUF tested the effects of shading (c. 46 % reduction in radiation intensity), N application rate (0 or 200 kg N/ha) and, in 2009 and 2010, water supply on the N nutrition, growth and yield of Estima (2008 and 2009) and Desiree (2010). Tuber populations were generally reduced in shaded crops and this was consistent with previous studies. Whilst shading reduced total DM and tuber FW yield, the reduction was not as great as the reduction in incident radiation and this was attributed to the shaded crops having greater radiation use efficiencies. Although shading modified the relationship between N uptake, N redistribution and radiation absorption, the effects of the treatments on canopy persistence and yield were still explicable in relation to total and tuber N uptake.

Nitrogen response experiments on a silt-textured soil at Holbeach Hurn, showed that for potato crops following peas, the amount of N needed for Maris Piper to achieve a yield of c. 60 t/ha was c. 130 kg N/ha and for Marfona, c. 100 kg N/ha was need for a yield of 50 t/ha. These experiments showed that respectable yields can be achieved with modest inputs of N fertilizer and provided data supporting the CUF model.

2. INTRODUCTION AND OBJECTIVES

The current project (R405) was developed from an earlier BPC-funded project (R273). The earlier project developed a practical N management system that originated from research over many years at Cambridge University Farm (CUF). This system describes total (haulm and tuber) N uptake and the redistribution of N from the haulm to the tubers as a function of the quantity of radiation absorbed by the crop. Project R273 clearly showed that:

1. The majority of a crop's N is taken up in a relatively short period (50–60 DAE).
2. Growth subsequent to 50–60 DAE is mainly concerned with the redistribution of N from the haulm to the tubers leading, ultimately, to canopy senescence. In consequence, for much of the growing season, increases in tuber yield are independent of total N uptake.
3. There was usually a direct correlation between canopy longevity and the amount of N taken up early in the season when based on radiation absorption.
4. The amount of N taken up was poorly related to the amount of N applied.
5. The patterns of N uptake and distribution explain the observed differences in varietal response to N fertilizer and the determinacy grouping used in current fertilizer recommendations.
6. Estimates of dates of canopy senescence can be disrupted by pathological or environmental factors that disrupt the orderly transfer of N from haulm to the tubers.

The new Potato Council funded project (R405) had five main objectives and these are summarised below:

1. To provide a robust test of the N management system.
2. To investigate those factors that limit N uptake early in the season and thus limit canopy potential and yield.
3. To investigate those factors that may impair canopy function late in the season and thus result in a failure to achieve potential.
4. To characterise existing and new varieties in relation to their N nutrition and thereby help select varieties that are more efficient in their use of N.
5. To develop recommendations that maximise the efficiency of fertilizer N use by the potato crop.

The relationship between the experimental program and the objectives are summarised in Table 1. There are linkages between this program and other Potato Council funded work including: Improving Water Use Efficiency through Understanding Soil and Plant Water Balance (R406) and Potato Council-CUF Grower Collaboration Project (R295).

Experiment	Objective				
	1 System test	2 Early limit	3 Late limit	4 Variety test	5 N use eff'cy
Babraham (Varieties) 2008	+			+	+
Babraham (Varieties × N) 2009	+			+	+
Babraham (Varieties × N) 2010	+			+	+
CUF (Varieties × N) 2008	+			+	+
CUF (Varieties × N) 2009a	+			+	+
CUF (Varieties × N) 2009b	+			+	+
CUF (Varieties × N) 2010	+			+	+
Spearhead Int. (Lady Rosetta & Courage) 2008	+	+	+		+
Spearhead Int. (Lady Rosetta) 2009	+	+	+		+
Spearhead Int. (Lady Rosetta) 2010	+	+	+		+
CUF (Soil conditions, Maris Piper) 2008	+	+	+		+
CUF (Soil conditions, Maris Piper) 2009	+	+	+		+
CUF (Soil conditions, Lady Rosetta & Maris Piper) 2010	+	+	+		+
CUF (Shading, Estima) 2008	+	+	+		
CUF (Shading, Estima) 2009	+	+	+		
CUF (Shading, Desiree) 2010	+	+	+		
Holbeach (N, Maris Piper) 2008					+
Holbeach (N, Maris Piper) 2009					+
Holbeach (N, Marfona) 2010					+
CUF (Split N Estima) 2008	+	+			+

TABLE 1. RELATIONSHIP BETWEEN PROJECT OBJECTIVES AND EXPERIMENT LISTED IN THIS REPORT

3. MATERIALS AND METHODS COMMON TO ALL EXPERIMENTS

3.1.1. Harvesting and sample processing

The number of above-ground stems was recorded and all tubers > 10 mm were collected. At each sampling, the total fresh weight of the haulm was recorded and a representative sub-sample of haulm (c. 1 kg) was taken. The tubers were graded in 10 mm increments and the number and weight of tubers in each 10 mm grade was recorded. A sub-sample of tubers (c. 1 kg) was taken from the 50-60 mm grade, washed, chipped and dried, for 48 h (i.e. to constant weight) at 90 °C together with the haulm sub-sample. The dried haulm and tuber sub-samples were sent to a commercial laboratory for measurement of total N concentration.

3.1.2. Estimation of radiation absorption and radiation use efficiency

Radiation absorption was calculated on a daily basis as the product of daily estimates of ground cover and daily incident radiation. Radiation use efficiency (RUE) was calculated for each plot by linear regression of total dry matter (DM) yield against radiation absorption. The regression line was constrained to pass through the origin and estimates of the slope of the relationship (i.e. t DM/TJ) were then tested by analysis of variance. The RUE for tuber DM production was calculated in a similar way except that the regression line was not constrained to pass through the origin. The intercept of the fitted line with the x-axis gives an indication (as TJ/ha) of the onset of tuber bulking. This intercept was converted to DAE since the pattern of radiation absorption against time was known.

3.1.3. Estimation of parameters of N uptake and redistribution

The rate of tuber N uptake (kg N/TJ) was analysed in a similar way using an unconstrained linear relationship. Total (i.e. haulm and tuber) N uptake was analysed by fitting an exponential curve, constrained to pass through the origin, to values of total N uptake against radiation absorption. The constrained curve assumes that total N uptake is negligible at the time or emergence. Maximum total N uptake was assumed to be equivalent to the asymptotic values of these fits.

3.1.4. Varietal differences in N nutrition

3.1.4.1. Introduction to work with Cygnet PB

Ongoing Potato Council-funded work at Cambridge University Farm has consistently shown that canopy persistence and yield potential is linked to N uptake and the rate of N redistribution from the canopy to the tubers. This work has also shown these characteristics are associated with a variety's determinacy and can, therefore, be used to help formulate N fertilizer recommendations. In principal, using these characteristics to guide N application rates will reduce the need for empirical N-response experiments and may also help plant breeders, growers and agronomists rapidly optimise the agronomy of new varieties. These experiments were done at Babraham, Cambridgeshire in collaboration with Cygnet PB who planted and managed the trial, measured plant emergence and ground cover and assisted with crop sampling whilst CUF staff did the crop sampling and processing, data analysis and interpretation.

4. MATERIALS AND METHODS

Details specific to each collaborative experiment with Cygnet PB are shown in Table 2 and details of sampling, sample processing and data analysis are shown on page 12.

4.1. Collaborative work with Cygnet PB 2008

	2008	2009	2010
Location	Home Farm, Babraham	Home Farm, Babraham	Home Farm, Babraham
Grid reference	TL500505	TL503504	TL510498
Number of varieties	5	6	8
N rates tested (kg N/ha)	200	200	100 or 200
Design	Varieties allocated at random to three blocks	Varieties allocated at random to four blocks	Varieties and N rates in factorial combination and allocated at random to four blocks
Average row width (cm)	91.4	91.4	91.4
Plot dimensions	4 rows × 5 m	4 rows × 7.5 m	4 rows × 9.3 m
Plant date	16 April	14 April	19 April
Within row spacing (cm)	33.3	33.3	33.3
Plant population (no./ha)	32 800	32 800	32 800
Varieties	Bonnie Cabaret Estima Maris Piper Saxon	Bonnie Casablanca Chicago Estima Lionheart Maris Piper	Cabaret Casablanca Chicago Estima Hermes Lady Rosetta Maris Piper Markies
1st N application (Date)	100 kg N/ha (16 April)	100 kg N/ha (14 April)	100 kg N/ha (24 March)
2nd N application (Date)	100 kg N/ha (12 June)	100 kg N/ha (14 June)	100 kg N/ha (7 June) to treatments
Irrigation (mm)	c. 50	45	158
Harvest 1	8 July	24 June	23 June
Harvest 2	17 September	9 July	13 July
Harvest 3		26 August (Estima & Casablanca)	9 August
Harvest 4		30 September (Bonnie, Maris Piper Chicago & Lionheart	16 September
Harvest areas (m2)	3.05	3.05	2.41

TABLE 2. TREATMENT DETAILS FOR COLLABORATIVE EXPERIMENT WITH CYGNET PB IN 2008-2010

4.2. Results and Discussion

4.2.1. Emergence, ground cover and radiation absorption

The average date of 50 % plant emergence was 16 May and ranged from 13 May (Maris Piper) to 18 May (Saxon). All varieties achieved complete emergence. The patterns of ground cover development for the five varieties are shown in Figure 1 and Figure 2. Initial ground cover expansion in all varieties was rapid, however a hail storm in mid-June destroyed some canopy. Both Bonnie and Maris Piper achieved near-complete (100 %) ground cover whereas Saxon had a maximum ground cover of 87 %. The canopies of Cabaret, Estima and Saxon were less persistent than those of Bonnie and Maris Piper. At the first sampling on 8 July, the average integrated ground cover for all varieties was 2718 % days and the crops had absorbed 5.01 TJ/ha of radiation and differences between the varieties were relatively small and not statistically significant (Table 3). At the second sampling on 17 September, the average integrated ground cover and radiation absorption had increased to 7891 % days and 12.24 TJ/ha, respectively. Due to their early senescence, the integrated ground covers and radiation absorptions of Cabaret, Estima and Saxon were smaller than those of Bonnie and Maris Piper.

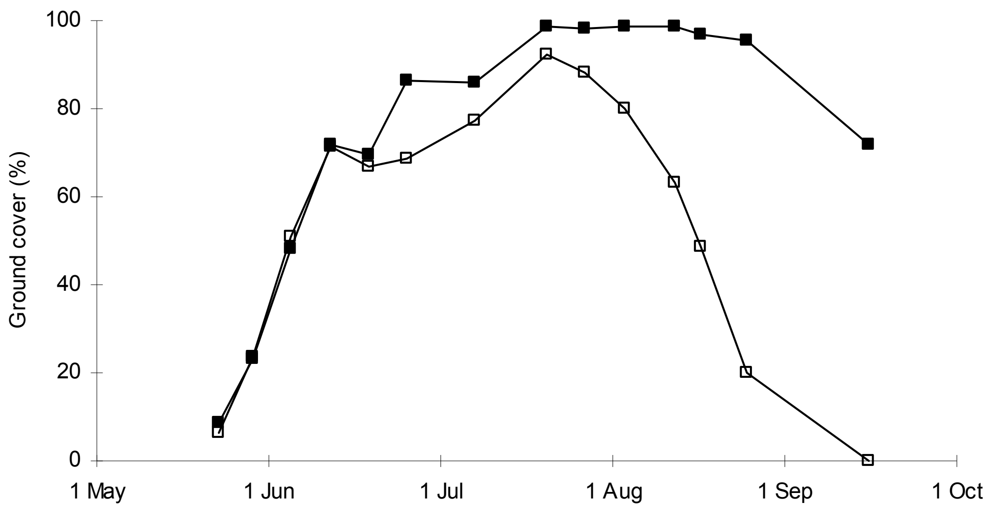


FIGURE 1. GROUND COVER DEVELOPMENT IN ESTIMA (□) AND MARIS PIPER (■).

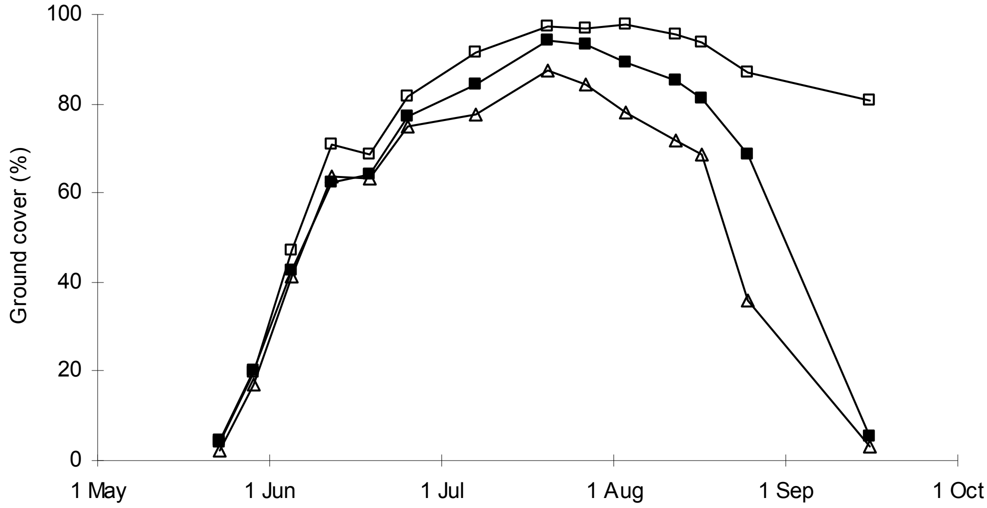


FIGURE 2. GROUND COVER DEVELOPMENT IN BONNIE (□), CABARET (■) AND SAXON (△).

Variety	8 July		17 September	
	Integrated ground cover (% days)	**Radiation absorption (TJ/ha)**	**Integrated ground cover (% days)**	**Radiation absorption (TJ/ha)**
Bonnie	2833	5.25	9327	13.89
Cabaret	2622	4.85	7652	12.01
Estima	2691	4.91	6395	10.50
Maris Piper	2930	5.40	9483	14.14
Saxon	2515	4.67	6597	10.66
Mean	2718	5.01	7891	12.24
S.E. (8 D.F.)	116.9	0.230	183.2	0.328

TABLE 3. VARIETAL DIFFERENCE IN INTEGRATED GROUND COVER AND RADIATION ABSORPTION AT TWO HARVEST DATES

4.2.2. Components of yield and N uptake on 8 July

At the first sampling on 8 July, the average number of mainstems and tubers > 10 mm was 131 000 and 479 000/ha, respectively (Table 4). Maris Piper had most mainstems and tubers whilst Saxon and Bonnie had the least. Average tuber FW yields were 25.2 t/ha and yield differences between varieties were relatively small and not statistically significant. However, as a consequence of producing relatively few tubers, Bonnie had the largest mean tuber size whilst Maris Piper (which produced the most tubers) had the smallest mean tuber size. The mean total dry weight yield for all five varieties was 6.30 t/ha and, in agreement with values for integrated ground cover and radiation absorption, there were no statistically significant differences between varieties. When averaged over all varieties, the total N uptake was 147 kg N/ha.

4.2.3. Components of yield and N uptake on 17 September

The final harvest was taken on 17 September. The average number of mainstems and tubers > 10 mm was 126 000 and 432 000/ha, respectively (Table 5 5). Overall, these values are similar to those measured at the earlier harvest but for some varieties (i.e. Estima and Saxon) the number of tubers at the second sampling was substantially smaller. Tuber FW yields ranged from 56-57 t/ha (Cabaret, Estima and Saxon) to 83 t/ha (Bonnie). The large tuber FW yield of Bonnie was due, in part, to a low tuber DM concentration (18.9 %) compared with Maris Piper (24.5 %). As a consequence of the largest tuber FW yield and the smallest tuber population, Bonnie had a very large value for mean tuber size. However, Bonnie is marketed as an early baker with a season length less than 120 days and, in practice, if large yields were anticipated, seed rates would be increased to reduce the proportion of oversize tubers. Differences in total dry weight yields were explicable in terms of canopy persistence and radiation absorption and the average value for all five varieties was 15.1 t/ha. Total N uptake averaged 224 kg N/ha and ranged from 182 kg N/ha (Estima) to 276 kg N/ha (Bonnie).

	Number of mainstems (000/ha)	Number of tubers (000/ha)	Tuber FW yield > 10 mm (t/ha)	Mean tuber size (mm)	Coefficient of variation (%)	Total DW yield (t/ha)	Total N uptake (kg N/ha)
Bonnie	116	398	26.2	50.0	19.4	5.92	154
Cabaret	134	484	22.3	40.9	14.7	5.95	140
Estima	132	528	28.4	43.6	16.5	6.75	147
Maris Piper	172	578	23.6	38.8	13.9	6.88	163
Saxon	101	409	25.4	45.7	14.9	6.02	130
Mean	131	479	25.2	43.8	15.9	6.30	147
S.E. (8 D.F.)	10.2	16.9	1.27	0.54	0.65	0.278	9.3

TABLE 4. COMPONENT OF YIELDS, TUBER SIZE DISTRIBUTION AND TOTAL N UPTAKE ON 8 JULY

	Number of mainstems (000/ha)	Number of tubers (000/ha)	Tuber FW yield > 10 mm (t/ha)	Mean tuber size (mm)	Coefficient of variation (%)	Total DW yield (t/ha)	Total N uptake (kg N/ha)
Bonnie	109	376	83.0	74.2	20.2	17.86	276
Cabaret	137	440	57.7	54.7	16.9	14.79	208
Estima	111	428	56.2	56.7	18.2	11.25	182
Maris Piper	166	567	68.3	55.8	18.5	18.87	249
Saxon	105	350	56.6	61.0	18.6	12.53	206
Mean	126	432	64.4	60.5	18.5	15.06	224
S.E. (8 D.F.)	14.8	33.1	2.24	1.12	0.99	0.462	10.7

TABLE 5. COMPONENT OF YIELDS, TUBER SIZE DISTRIBUTION AND TOTAL N UPTAKE ON 17 SEPTEMBER

4.2.4. Modelling of yield, canopy persistence and likely N requirement

Canopy persistence and yield potential are related to total N uptake and the rate of N transfer between haulm and tubers. Determinate varieties have smaller total N uptakes and faster N transfer rates than indeterminate varieties when grown under similar conditions. The first stage of the analysis uses the CUF yield model to confirm that the varieties under test are behaving in a normal manner i.e. their yields can be explained on the basis of radiation absorption and standard parameters for RUE and that the crop was not unduly stressed by disease or water stress. The relationship between predicted and observed yield for the five varieties is shown in Figure 3. The model predicted the yield at final harvest reasonably well with the possible exception of Estima and Saxon where the model overestimated final yield. However, this overestimate may have been due, in part, to poor estimates of ground cover as a result of the partial defoliation early in the season or competition from volunteer oil seed rape plants that were problematic toward the end of the season.

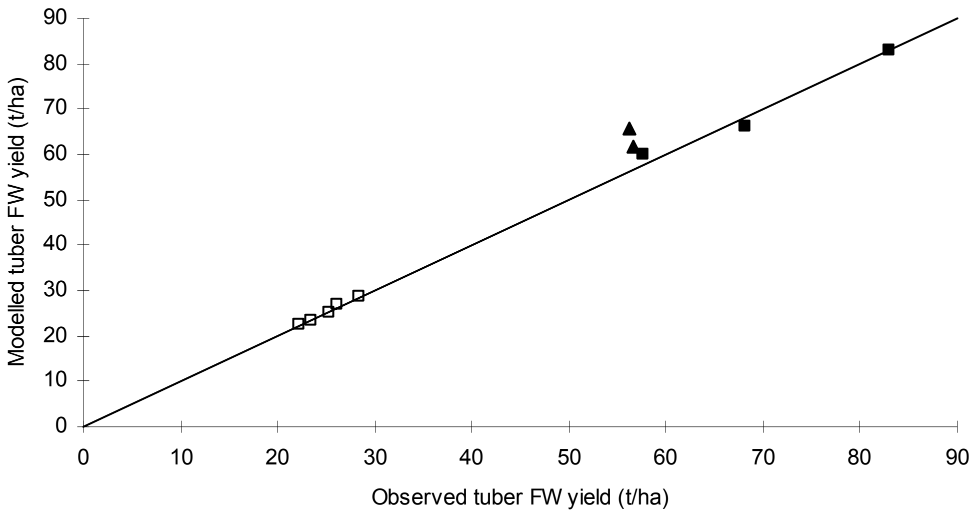


FIGURE 3. RELATIONSHIP BETWEEN MODELLED AND OBSERVED TUBER FW YIELD. THE MODEL WAS PARAMETERISED USING DATA FROM THE HARVEST ON 8 JULY (□) AND THEN USED TO FORECAST YIELD FOR THE HARVEST ON 17 SEPTEMBER (■). SAXON AND ESTIMA ARE REPRESENTED BY (▲). THE STRAIGHT LINE IS A 1 : 1 RELATIONSHIP.

Values for tuber and total N uptake (shown in Table 4 and Table 5) were regressed against radiation absorption to estimate the rates of tuber N uptake and the asymptotic value for total N uptake. The rates of tuber N uptake are shown in Table 6 and whilst differences in these values were not statistically significant, Maris Piper (Determinacy Group 3) had a numerically slower rate than either Estima or Saxon (Determinacy Group 1). In contrast, Maris Piper and Bonnie had the largest values for total N uptake, suggesting that these varieties are more efficient in taking up N and perhaps have a longer period of N uptake than the other, more determinate varieties. The ratio of haulm N (which represents a pool of N that is depleted by the developing tubers) and the rate of tuber N uptake may be used to rank varieties according to their probable determinacy. In this experiment, Saxon and Estima had the smallest ratios showing that small canopy N reserves were coupled with fast rates of N uptake. Conversely, Maris Piper and Bonnie had a very similar ratio and this suggests that the

N requirement of Bonnie should be broadly similar to that of Maris Piper. Cabaret had the largest ratio and this implies that its N requirement may be somewhat less than that of Maris Piper.

Variety	Rate of tuber N uptake (kg N/TJ)	Tuber N uptake at 6 TJ/ha (kg N/ha)	Asymptotic value of total N uptake (kg N/ha)	Ratio of haulm N uptake to rate of tuber N uptake
Bonnie	17.7	83	309	6.2
Cabaret	16.6	82	205	8.6
Estima	17.1	93	194	4.5
Maris Piper	15.9	77	277	6.1
Saxon	18.4	98	261	3.1
Mean	17.1	87	249	5.7
S.E. (8 D.F.)	1.13	4.0	16.5	1.05

Table 6. Parameters of tuber and total N uptake for five varieties. Indeterminate varieties are associated with slow rate of tuber N uptake, large asymptotic values for total N uptake and large ratios of haulm N uptake to rate of tuber N uptake

4.3. Conclusions

The purpose of this experiment was to demonstrate some principles in ranking varieties according to their likely N requirements. In retrospect, it would have been useful to increase the replication and to have an additional sampling between 50 and 124 DAE since this would have allowed a more precise characterisation of N uptake and redistribution. However, the system suggests that Saxon is as determinate or possibly more determinate than Estima, Bonnie is similar to Maris Piper, whilst Cabaret is as indeterminate as Maris Piper or possibly more so.

5. Collaborative work with Cygnet PB 2009

5.1. Results and Discussion

5.1.1. Emergence, ground cover development and radiation absorption

The average date of 50 % plant emergence was 12 May and ranged from 11 May (Maris Piper) to 16 May (Chicago). All varieties achieved complete emergence. The pattern of ground cover development for all six varieties is shown in Figure 4 and Figure 5. Initial ground cover expansion in all varieties was rapid and all varieties achieved complete ground cover. The canopies of Estima and Casablanca were the least persistent whilst those of Bonnie and Maris Piper were the most persistent. By final harvest, due to more persistent canopies, Bonnie, Maris Piper and Lionheart had absorbed the largest amount of solar radiation whilst Estima had absorbed the least (Table 7).

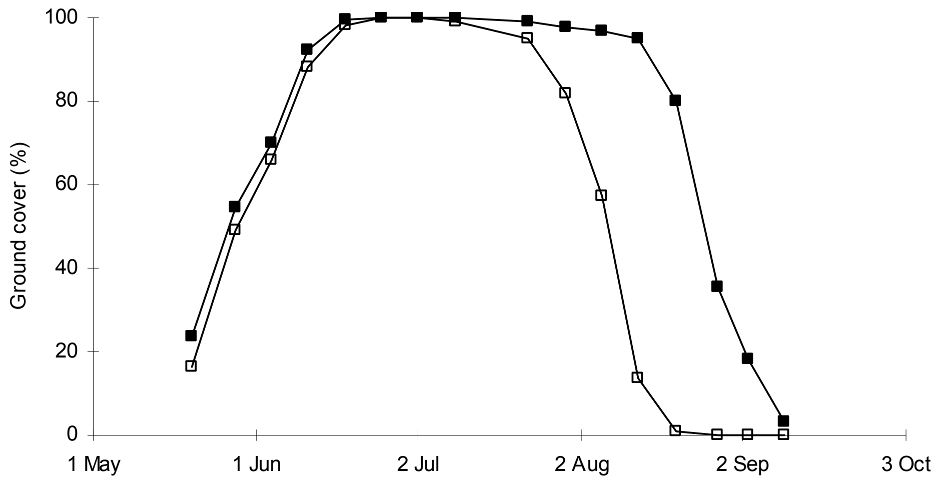


FIGURE 4. GROUND COVER DEVELOPMENT IN ESTIMA, □ AND MARIS PIPER, ■.

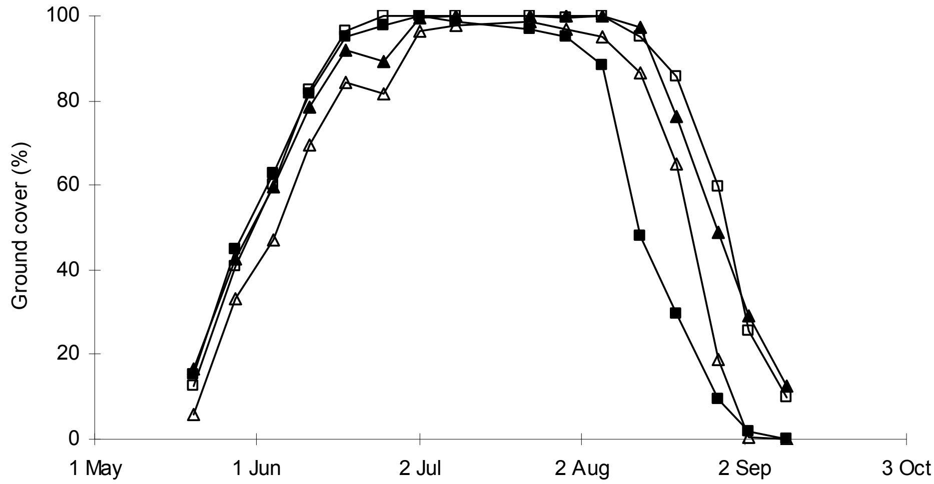


FIGURE 5. GROUND COVER DEVELOPMENT IN BONNIE, □; CASABLANCA, ■; CHICAGO, △ AND LIONHEART, ▲.

	24 June		9 July		26 August / 30 September	
Variety	**Ground cover (% days)**	**Radiation absorbed (TJ/ha)**	**Ground cover (% days)**	**Radiation absorbed (TJ/ha)**	**Ground cover (% days)**	**Radiation absorbed (TJ/ha)**
Bonnie	2348	4.53	3848	7.47	8965	14.96
Casablanca	2407	4.64	3892	7.55	7408	12.79
Estima	2541	4.90	4036	7.83	6754	12.03
Maris Piper	2732	5.26	4232	8.20	8952	15.08
Chicago	1897	3.67	3291	6.39	7538	12.58
Lionheart	2319	4.47	3772	7.31	8814	14.66
S.E. (15 D.F.)	32.0	0.062	35.6	0.069	85.4	0.126
Mean	2374	4.58	3845	7.46	8072	13.68

TABLE 7. VARIETAL DIFFERENCES IN INTEGRATED GROUND COVER AND RADIATION ABSORPTION AT THREE HARVEST DATES

5.1.2. First sampling (c. 43 DAE)

At the first sampling (Table 8), Bonnie had the smallest tuber population (298 000/ha) and Casablanca had the largest (480 000/ha). Tuber FW yields ranged from 10.9 t/ha (Chicago) to 24.9 t/ha (Estima) with an average tuber FW yield of 18.5 t/ha. Total (haulm and tuber) DM yield averaged 5.50 t/ha and varietal differences in total DM yield were broadly consistent with estimates of radiation absorption. When averaged over all varieties, total N uptake was 155 kg N/ha.

5.1.3. Second sampling (c. 58 DAE)

Varietal differences in stem and tuber population were similar to those found at the earlier harvest. Between the two harvests, average tuber yields increased from 18.5 t/ha to 32.1 t/ha, equivalent to an average tuber bulking rate of *c.* 0.9 t/ha/day (Table 8). Total DM yields ranged from 8.0 t/ha (Chicago) to 10.6 t/ha (Casablanca) and, again, varietal differences in total DM yield were explicable by radiation absorption. Total N uptake ranged from 153 kg N/ha (Estima) to 177 kg N/ha (Maris Piper).

5.1.4. Final sampling (c. 106 or 141 DAE)

All varieties were sampled at complete or near-complete senescence and tuber FW yields > 10 mm ranged from c. 60 t/ha (Estima, Chicago and Lionheart) to 87 t/ha (Bonnie) with Casablanca and Maris Piper producing yields of c. 70 t/ha (Table 8). Estima had the smallest total DM yield (13.0 t/ha) and Maris Piper the largest (19.8 t/ha) and these difference are consistent with the observed differences in canopy persistence and radiation absorption. Total N uptake ranged from 178 kg N/ha (Estima) to 246 kg N/ha (Maris Piper).

	Number of mainstems (000/ha)	Number of tubers > 10 mm (000/ha)	Tuber FW yield > 10 mm (t/ha)	Tuber DM concentration (%)	Total DM yield (t/ha)	Total N uptake (kg N/ha)
24 June						
Bonnie	84.5	298	16.6	13.4	4.86	143
Casablanca	143.3	480	23.6	15.7	5.98	147
Estima	113.5	456	24.9	14.9	6.30	162
Maris Piper	153.2	449	19.6	15.6	6.23	179
Chicago	77.9	336	10.9	17.4	4.48	144
Lionheart	105.2	396	15.2	14.4	5.17	155
S.E. (15 D.F.)	7.18	22.7	0.83	0.46	0.27	9.4
Mean	113.0	402	18.5	15.2	5.50	155
9 July						
Bonnie	90.2	302	36.0	15.7	9.17	167
Casablanca	138.9	494	40.7	19.6	10.64	168
Estima	111.0	437	37.0	18.9	9.66	153
Maris Piper	165.7	495	30.4	19.6	9.62	177
Chicago	90.3	361	22.2	21.5	7.95	158
Lionheart	105.2	409	26.2	19.4	8.55	156
S.E. (15 D.F.)	4.79	27.2	1.62	0.25	0.405	8.7
Mean	116.8	416	32.1	19.1	9.26	163
26 August or 30 September						
Bonnie	87.0	294	86.8	19.8	19.5	223
Casablanca	137.6	466	71.5	21.5	16.9	211
Estima	116.8	415	59.7	19.8	13.0	178
Maris Piper	156.6	464	67.3	25.8	19.8	246
Chicago	106.9	332	56.4	27.9	17.7	230
Lionheart	101.1	376	60.7	26.8	18.4	222
S.E. (15 D.F.)	8.22	24.4	3.49	0.42	0.95	11.2
Mean	117.6	391	67.1	23.6	17.5	218

TABLE 8. COMPONENTS OF YIELD AND NITROGEN UPTAKE ON THREE DATES

5.1.5. Modelling of yield, canopy persistence and N requirement

Canopy persistence and yield potential are related to total N uptake and the rate at which N is transferred from the haulm to the tubers (which leads to canopy senescence). Determinate varieties such as Estima have smaller total N uptakes and faster rate of N transfer than indeterminate varieties grown under similar conditions. The first stage of analysis was to examine if crop growth was largely explicable in terms of radiation absorption, RUE and the partitioning of DM between haulm and tubers according to the CUF yield model. The relationship between predicted and observed tuber FW yield for the six varieties grown at Babraham is shown in Figure 6. The yield model performed well and, with the exception of an early sampled-Estima crop, the majority of predicted tuber FW yields were within ± 10 % of the observed tuber FW yields. This suggests that the yield potential of these crops were not unduly limited by factors such as water stress or disease and should therefore be explicable in terms of N uptake and redistribution.

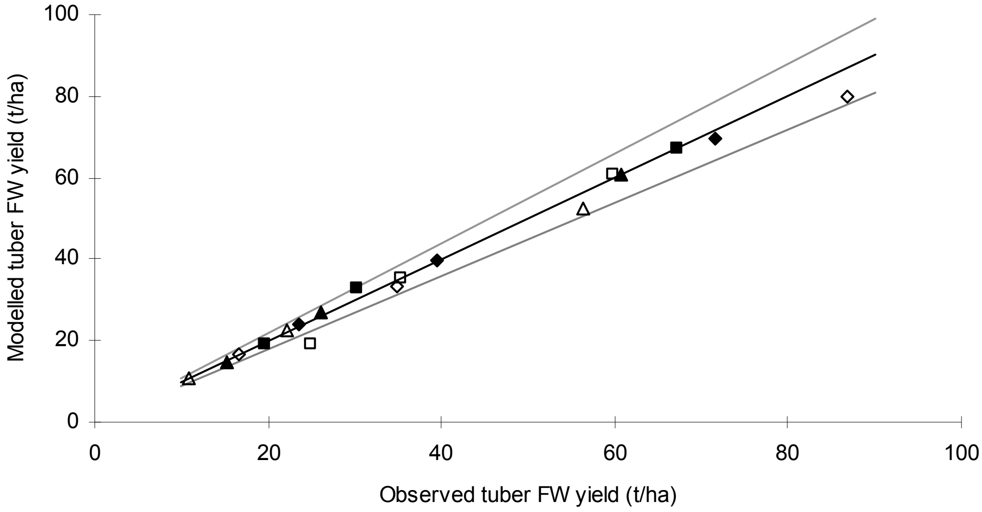


FIGURE 6. RELATIONSHIP BETWEEN MODELLED AND OBSERVED TUBER FW YIELD. THE MODEL WAS PARAMETERISED USING DATA FROM THE HARVEST ON 24 JUNE. ESTIMA, □; MARIS PIPER, ■; BONNIE, ◊; CASABLANCA, ♦; CHICAGO, △ AND LIONHEART, ▲. THE STRAIGHT LINES ARE 1 : 1 (± 10 %) RELATIONSHIPS.

Varietal differences in RUE were relatively small (Table 9) and broadly similar to values calculated for experiments at CUF. Rates of tuber N uptake ranged from 14.6 (Estima) to 20.2 kg N/TJ (Chicago) and averaged 16.9 kg N/TJ (Table 9). Casablanca and Estima had the smallest value for maximum haulm uptake whilst Maris Piper had the largest. The ratio of maximum haulm N uptake to the rate of tuber N uptake gives an indication of canopy persistence, determinacy and N requirement. Unfortunately, relatively large standard errors and a probable under-estimate of the rate of tuber N uptake for Estima (due to an aberrant plot) have complicated the interpretation of these data. However, the experimental evidence suggests that Bonnie and Lionheart should be managed in a similar way to Maris Piper. For Bonnie, this conclusion is supported by a similar experiment at Babraham in 2008 and an experiment at CUF in 2009 (see p. 52). The data also suggest that Casablanca and 99C-051-002 will have a larger N requirement than Maris Piper and should be managed in a similar way to Estima.

Variety	Radiation use efficiency (t/TJ)	Rate of tuber N uptake (kg N/TJ)	Maximum haulm N uptake (kg N/ha)	Asymptotic value of total N uptake (kg N/ha)	Ratio of haulm N uptake to rate of tuber N uptake
Bonnie	1.27	15.6	109	240	7.1
Casablanca	1.34	16.7	91	223	5.5
Estima	1.14	14.6	93	174	6.5
Maris Piper	1.27	18.3	145	230	8.7
Chicago	1.36	20.2	106	244	5.3
Lionheart	1.23	15.8	108	237	7.1
S.E. (15 D.F.)	0.044	1.22	5.3	19.4	0.72
Mean	1.27	16.9	109	225	6.7

TABLE 9. PARAMETERS OF TUBER AND TOTAL N UPTAKE FOR SIX VARIETIES. INDETERMINATE VARIETIES ARE ASSOCIATED LARGE RATIOS OF HAULM N UPTAKE COMPARED WITH RATE OF TUBER N UPTAKE

5.2. Conclusions

The purpose of this experiment was to further develop a system to rank varieties according to their determinacy and expected N fertilizer requirements. The usefulness of a similar experiment in 2008 was limited due to insufficient replication and insufficient sampling occasions. These problems were rectified in 2009 and the data were more robust. However, three sampling occasion should be considered the minimum and ideally there should be more than a two-week interval between the first and second sampling so that a better estimate of the shape of the total N uptake curve can be obtained.

6. COLLABORATIVE WORK WITH CYGNET PB 2010

6.1. Results and Discussion

6.1.1. Emergence, ground cover development and radiation absorption

The average date of 50 % plant emergence was 24 May (35 DAP), the date was not affected by either N application rate or variety and all treatment combinations achieved complete or near-complete plant emergence. There was a significant effect of variety on initial ground cover expansion so that at 25 DAE the ground cover of Chicago was smaller than that of either Estima or Hermes (Table 10). This may have been a consequence of different canopy architecture since the stem populations for these three varieties were similar. Nitrogen application rate had no effect on ground cover at 25 DAE. Maximum ground cover was affected by both variety and N application rate and only Hermes given 200 kg N/ha achieved 100 % ground cover. Values for season-long integrated ground cover and radiation absorption are shown in Table 11.

	Ground cover at 25 DAE (%)		**Maximum ground cover**			
Variety	**100 kg N/ha**	**200 kg N/ha**	**100 kg N/ha**		**200 kg N/ha**	
Cabaret	59	60	97	(83)	96	(82)
Casablanca	63	60	96	(81)	96	(80)
Chicago	56	56	87	(69)	98	(84)
Estima	69	71	94	(77)	99	(85
Hermes	79	79	99	(87)	100	(90)
Lady Rosetta	63	65	90	(72)	98	(84)
Maris Piper	68	68	100	(88)	99	(87)
Markies	66	70	95	(80)	100	(88)
Mean for N	65	66	95	(79)	98	(85)
Grand mean	66		96 (82)			
S.E. (45 D.F.)	108.0 (N); 305.5 (Variety*N)		N, 0.6 (0.2); Variety*N 1.7 (0.4)			

TABLE 10. EFFECT OF VARIETY AND N APPLICATION RATE ON ESTIMATE OF GROUND COVER AT 25 DAE (%) AND MAXIMUM GROUND COVER (%, AND (ANGULAR TRANSFORMED))

	Integrated ground cover (% days)		**Radiation absorbed (TJ/ha)**	
Variety	**100 kg N/ha**	**200 kg N/ha**	**100 kg N/ha**	**200 kg N/ha**
Cabaret	5580	6342	9.66	10.74
Casablanca	5142	5538	9.12	9.61
Chicago	5610	6833	9.57	11.24
Estima	4110	4904	7.73	9.04
Hermes	5676	7019	10.20	12.00
Lady Rosetta	4933	6816	8.87	11.54
Maris Piper	7245	8253	12.13	13.45
Markies	7153	8417	11.80	13.67
Mean for N	5681	6765	9.88	11.41
Grand mean	6223		10.65	
S.E. (45 D.F.)	108.0 (N); 305.5 (Variety*N)		0.156 (N); 0.442 (Variety*N)	

TABLE 11. EFFECT OF VARIETY AND N APPLICATION RATE ON WHOLE SEASON INTEGRATED GROUND COVER AND RADIATION ABSORPTION

When averaged over all treatment combinations, the mean integrated ground cover in 2010 was 6223 % days. In a similar experiment in 2009, the integrated ground covers of Estima and Maris Piper given 200 kg N/ha were 6754 and 8952 % days, respectively. The corresponding values in 2010 were 4904 and 8253 % days. These data show that ground covers were less persistent in 2010 with determinate varieties such as Estima being most affected. The cause for the poor ground covers is not known but may be a consequence of poor seed-beds or inadequate water supply. On average, increasing the N application rate from 100 to 200 kg N/ha increased ground cover persistence by c. 1100 % days (equivalent to an extra 11 days at complete ground cover). The pattern of ground cover development for each treatment combination is shown in Figure 7.

6.1.2. Stems and tuber populations

The experiment was sampled four times during the season. When compared over the four samplings mean stem populations were reasonably consistent and averaged 111 000/ha (Table 12). Lady Rosetta tended to have the smallest stem population whilst Maris Piper and Cabaret had the largest. On average, tuber populations at the final sampling were smaller than at earlier ones and, on average, Lady Rosetta had the smallest tuber population and Maris Piper the largest. Increasing the N application rate from 100 to 200 kg N/ha had no effect on either stem or tuber population > 10 mm at any harvest.

	23 June		**13 July**		**9 August**		**16 September**	
Variety	**Stems**	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**
Cabaret	128.4	445	126.8	486	129.5	469	141.4	472
Casablanca	117.6	465	106.7	472	109.3	476	108.7	433
Chicago	99.4	540	104.1	573	111.8	618	108.7	455
Estima	108.2	485	116.5	503	107.7	484	117.0	487
Hermes	101.5	557	99.9	526	104.6	583	101.5	525
Lady Rosetta	81.8	401	75.1	402	84.9	434	81.8	366
Maris Piper	132.5	635	140.3	649	128.9	620	134.1	545
Markies	116.0	394	116.0	470	109.8	473	109.8	468
S.E. (45 D.F.)	7.45	27.8	5.16	27.0	6.25	28.3	4.98	24.0
Grand mean	110.7	490	110.7	510	110.8	520	112.9	469

TABLE 12. MAIN EFFECT OF VARIETY ON TOTAL STEM POPULATION AND TUBER POPULATION > 10 MM (000/HA) ON FOUR OCCASIONS

(a)

(b)

(c)

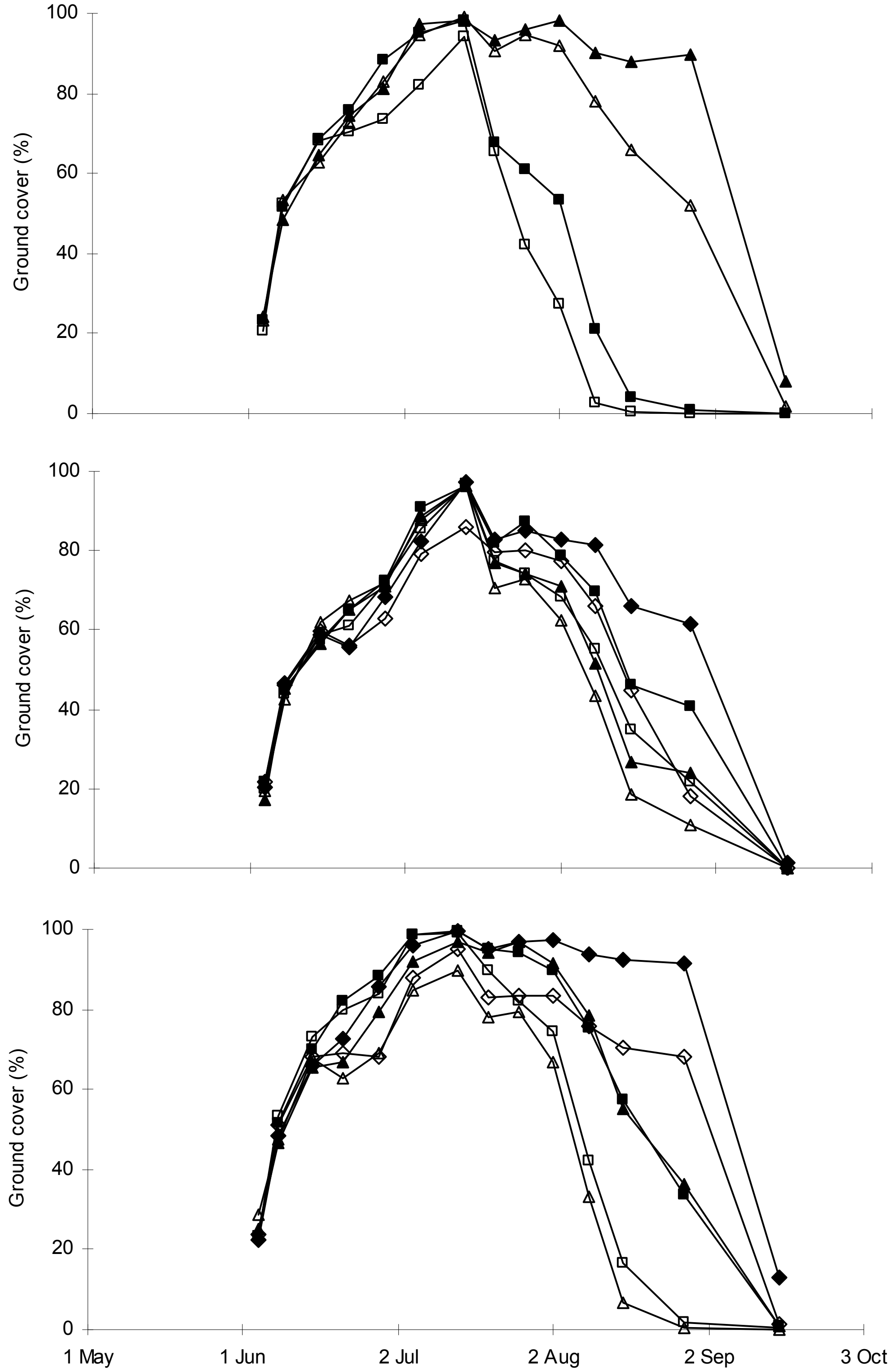


FIGURE 7. GROUND COVER DEVELOPMENTS IN (A) ESTIMA, ■ AND MARIS PIPER, ▲; (B) CABARET, ■; CASABLANCA, ▲ AND CHICAGO ♦; (C) HERMES, ■; LADY ROSETTA, ▲ AND MARKIES ♦. OPEN SYMBOLS, 100 KG N/HA AND CLOSED SYMBOLS 200 KG N/HA.

6.1.3. First sampling (30 DAE)

At the first sampling, mean tuber FW yield averaged 4.6 /ha and was not affected by N application rate but tuber yields ranged from 2.7 t/ha in Markies to 6.2 t/ha in Estima (Table 13). Total DM production averaged 2.3 t/ha and varietal differences in total DM production were small. Whilst Lady Rosetta had the largest tuber N uptake and Markies the smallest, tuber N uptake was not significantly affected by N application rate. At 30 DAE, total N uptake averaged 86 DAE and, when averaged over the eight varieties was increased from 82 to 91 kg N/ha when the N application rate was increased from 100 to 200 kg N/ha.

	kg N/ha	Tuber FW (t/ha)	Tuber DM (%)	Total DM (t/ha)	Tuber N (kg N/ha)	Total N (kg N/ha)
Cabaret	100	3.9	12.7	2.03	8.9	75
	200	4.0	12.6	2.05	9.5	82
Casablanca	100	4.9	14.0	1.91	11.6	69
	200	5.9	13.8	2.20	13.5	81
Chicago	100	5.0	14.7	2.46	14.0	90
	200	4.6	14.8	2.34	14.2	96
Estima	100	5.8	12.9	2.35	12.1	83
	200	6.6	12.5	2.35	15.2	88
Hermes	100	3.5	13.1	2.39	10.3	91
	200	3.5	12.8	2.22	10.3	94
Lady Rosetta	100	6.5	16.0	2.58	17.5	82
	200	5.4	15.4	2.41	17.6	91
Maris Piper	100	4.2	12.7	2.18	9.2	80
	200	4.8	12.6	2.46	12.0	99
Markies	100	2.9	13.3	2.18	8.6	83
	200	2.6	12.3	2.11	9.5	97
S.E. (45 D.F.)		0.53	0.17	0.190	1.45	5.8
Grand mean		4.6	13.5	2.26	12.1	86

TABLE 13. EFFECTS OF VARIETY AND N APPLICATION RATE ON COMPONENTS OF YIELD AND NITROGEN UPTAKE ON 23 JUNE

6.1.4. Second sampling (50 DAE)

The second crop sampling was taken at c. 50 DAE when the average tuber FW yield was 23 t/ha (Table 14). At this stage of the season, N application rate had no significant effect on tuber yield but yields were largest in Casablanca (28 t/ha) and smallest in Chicago and Markies (c. 20 t/ha). Total DW yields averaged 7.0 t/ha and effects of variety and N application rate were small and non-significant. Tuber N uptake averaged 66 kg N/ha and was increased from an average of 61 kg N/ha when 100 kg N/ha had been applied to 71 kg N/ha when 200 kg N/ha was applied. Lady Rosetta had the largest tuber N uptake (80 kg N/ha) and Maris Piper the smallest (57 kg N/ha). Total N uptake was 152 kg N/ha when averaged over all treatment combinations. Total N uptake was increased from 133 to 172 kg N/ha when the amount of N applied was increased from 100 to 200 kg N/ha. On average, Estima had the smallest total N uptake (141 kg N/ha) and Lady Rosetta and Markies the largest (167 kg N/ha).

	kg N/ha	Tuber FW (t/ha)	Tuber DM (%)	Total DM (t/ha)	Tuber N (kg N/ha)	Total N (kg N/ha)
Cabaret	100	22.8	18.3	6.55	55	126
	200	22.6	18.5	6.62	64	165
Casablanca	100	26.8	19.3	7.08	66	126
	200	29.4	18.2	7.38	81	160
Chicago	100	19.0	21.6	6.47	54	136
	200	19.9	21.5	6.71	69	163
Estima	100	26.0	17.8	6.74	63	120
	200	24.7	18.1	6.94	70	162
Hermes	100	22.7	21.2	7.27	62	144
	200	22.1	19.4	7.00	71	168
Lady Rosetta	100	22.5	24.2	7.68	79	149
	200	23.7	22.3	7.88	81	186
Maris Piper	100	22.2	19.6	6.83	52	129
	200	22.1	19.2	7.25	62	172
Markies	100	18.7	19.5	6.29	56	134
	200	22.5	17.6	7.46	74	201
S.E. (45 D.F.)		1.68	0.44	0.422	5.4	8.8
Grand mean		23.0	19.8	7.01	66	152

TABLE 14. EFFECTS OF VARIETY AND N APPLICATION RATE ON COMPONENTS OF YIELD AND NITROGEN UPTAKE ON 13 JULY

6.1.5. Third sampling (77 DAE)

At the third sampling increasing the amount of N applied from 100 to 200 kg N/ha increased tuber FW yield from 38 to 42 t/ha (Table 15). When averaged over both N treatments, Markies had the smallest yield (34 t/ha) and Hermes the largest (44 t/ha). Total DM yields ranged from 10.1 t/ha in Estima to 12.7 t/ha in Hermes. Increasing the N application rate, increased total DM yields from 10.7 to 12.1 t/ha. On average, tuber N uptake was 112 kg N/ha with 100 kg N/ha and 139 kg N/ha with 200 kg N/ha and average tuber N uptake in Markies was 109 kg N/ha compared with 156 kg N/ha in Lady Rosetta. Increasing the N application rate from 100 to 200 kg N/ha increased average total N uptake from 149 to 204 kg N/ha. As found at the second sampling, Estima had the smallest total N uptake (155 kg N/ha) and Lady Rosetta the largest (196 kg N/ha).

	kg N/ha	Tuber FW (t/ha)	Tuber DM (%)	Total DM (t/ha)	Tuber N (kg N/ha)	Total N (kg N/ha)
Cabaret	100	36.5	22.0	10.06	103	146
	200	41.6	21.7	11.22	127	194
Casablanca	100	35.0	21.2	8.75	101	128
	200	46.8	21.1	11.62	136	181
Chicago	100	40.9	25.3	12.57	121	171
	200	37.8	24.5	11.87	130	206
Estima	100	39.1	20.2	9.19	107	128
	200	43.6	21.7	11.00	143	182
Hermes	100	42.8	23.8	11.87	131	163
	200	45.3	24.6	13.50	148	202
Lady Rosetta	100	36.3	25.9	10.98	132	158
	200	45.7	25.5	13.69	181	233
Maris Piper	100	40.7	23.1	11.72	105	147
	200	43.0	22.5	12.91	127	214
Markies	100	35.0	23.3	10.60	95	148
	200	34.6	21.3	10.90	122	220
S.E. (45 D.F.)		2.59	0.61	0.691	11.9	12.2
Grand mean		40.3	23.0	11.41	126	176

TABLE 15. EFFECTS OF VARIETY AND N APPLICATION RATE ON COMPONENTS OF YIELD AND NITROGEN UPTAKE ON 9 AUGUST

6.1.6. Final sampling (115 DAE)

The final sampling was on 16 September when all the canopies were at complete or near-complete senescence. Tuber FW yields averaged 50 t/ha (
Table 16). In 2009, the yields of Estima and Maris Piper given 200 kg N/ha were 59.7 and 67.3 t/ha, respectively, whereas in this experiment the corresponding yields were 50.3 and 54.8 t/ha. The overall response to increasing the N application rate was to increase tuber FW yields from 46 to 53 t/ha. When averaged over both N treatments, Maris Piper had the largest tuber yield (53.6 t/ha) and Chicago the smallest (44.4 t/ha). On average, tuber DM concentrations were smallest in Estima (19.7 %) and largest in Chicago (25.7). On average, tuber DM concentrations were slightly increased (from 23.2 to 23.6 %) by increasing the N application rate. Total DM yields averaged 12.6 t/ha and the response to an extra application of 100 kg N/ha was to increase total DM yield from 11.5 to 13.7 t/ha. In 2010, the total DW yields of Estima and Maris Piper given 200 kg N/ha were 10.3 and 15.5 t/ha, respectively. For comparison, in 2009, the yields of the same treatments were 13.0 and 19.8 t/ha and these reductions in yield are consistent with the reduction in ground cover persistence and radiation absorption. Between the third and final samplings, average tuber N uptake increased from 126 to 149 kg N/ha. For Estima and Lady Rosetta, there was little or no increase in tuber N uptake between the third and final harvest whereas for other varieties the average increase was up to c. 50 kg N/ha. When 100 kg N/ha had been applied the average tuber N uptake was 125 kg N/ha and this was increased to 173 kg N/ha in response to a further application of 100 kg N/ha. The average total N uptake at the final harvest was 161 kg N/ha which was *c.* 16 kg N/ha less than found at the penultimate harvest. The difference may be due to loss of N in senesced leaves not recovered at the final harvest. The average increase in total N uptake in response to increasing the amount of N applied was from 134 to 188 kg N/ha.

Averaged over N application rates, the smallest total N uptake was Estima (130 kg N/ha) and the greatest Markies (193 kg N/ha).

	kg N/ha	Tuber FW (t/ha)	Tuber DM (%)	Total DM (t/ha)	Tuber N (kg N/ha)	Total N (kg N/ha)
Cabaret	100	50.7	21.7	11.93	123	131
	200	56.0	22.9	13.89	172	183
Casablanca	100	46.4	21.4	10.31	113	117
	200	54.0	21.5	12.19	162	168
Chicago	100	40.9	25.4	11.35	124	134
	200	47.9	26.1	13.83	173	189
Estima	100	41.9	19.7	8.52	105	108
	200	50.3	19.7	10.29	149	153
Hermes	100	47.2	23.8	11.87	129	135
	200	54.3	23.0	13.23	181	190
Lady Rosetta	100	40.7	24.9	10.55	128	132
	200	50.8	26.1	14.11	183	194
Maris Piper	100	52.3	24.0	14.06	135	154
	200	54.8	24.7	15.51	172	199
Markies	100	46.6	24.5	13.08	143	161
	200	57.7	24.7	16.73	194	224
S.E. (45 D.F.)		2.71	0.30	0.713	8.6	9.0
Grand mean		49.5	23.4	12.59	149	161

TABLE 16. EFFECTS OF VARIETY AND N APPLICATION RATE ON COMPONENTS OF YIELD AND NITROGEN UPTAKE ON 16 SEPTEMBER

6.1.7. Radiation use efficiency, onset of tuber bulking, modelling of tuber yield, canopy persistence and N requirements

The efficiency with which absorbed solar radiation is converted to total DM yield is a key step in yield production. When averaged over both N application rates the average RUE was 1.20 t DM/TJ (
Table 17 and Figure 8a). On average Chicago had larger RUE than Hermes or Estima (1.29 compared with 1.17 and 1.15 t DM/TJ, respectively). Increasing the N application rate from 100 to 200 kg N/ha was associated with a small, numeric increase in total RUE but this was not significant.

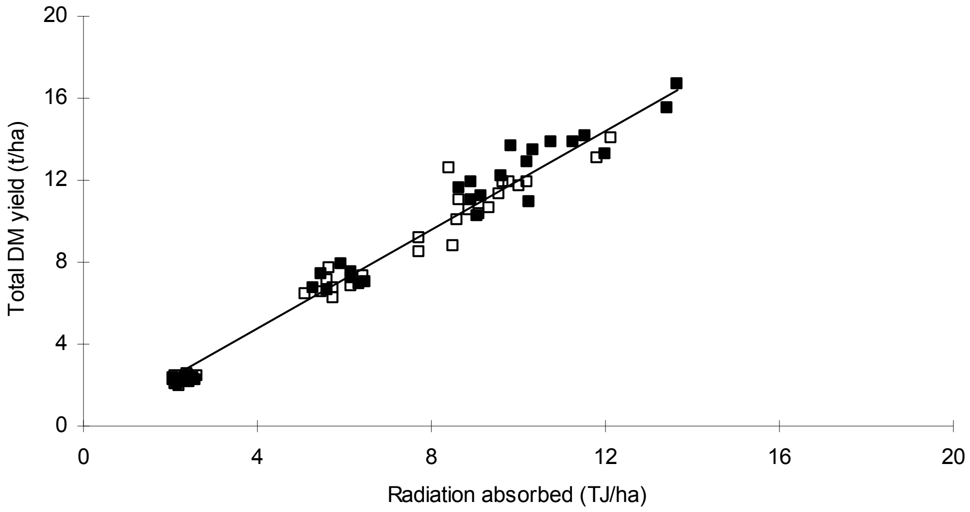
Variety	Total RUE (t DM/TJ) 100 kg N/ha	200 kg N/ha
Cabaret	1.20	1.24
Casablanca	1.11	1.31
Chicago	1.30	1.27
Estima	1.15	1.16
Hermes	1.17	1.17
Lady Rosetta	1.24	1.30
Maris Piper	1.15	1.19
Markies	1.12	1.17
Mean for N	1.18	1.23
Grand mean	1.20	
S.E. (45 D.F.)	0.035 (N); 0.050 (Variety*N)	

TABLE 17. EFFECT OF VARIETY AND N APPLICATION RATE ON RADIATION USE EFFICIENCY (RUE)

Analysis of crop growth using the CUF yield model showed that, in general, there was good agreement between modelled yields at the third and final harvests and those observed (Figure 8b). For samplings on 9 August and 16 September, the average observed and modelled tuber FW yields were 44.8 and 44.7 t/ha, respectively and with the exception of some yields from the penultimate sampling, the majority of modelled tuber FW yield were within ± 10 % of the observed tuber FW yields. This suggests that yields of these crops were largely explicable in terms of ground cover persistence and radiation absorption and factors such as pests, diseases and environmental stresses were relatively unimportant.

On average, the onset of tuber bulking occurred c. 28 DAE (Table 18) and increasing the N application rate from 100 to 200 kg N/ha delayed the onset of bulking by c. 1 day. Bulking occurred earliest in Lady Rosetta (26 DAE) and latest in Cabaret and Markies (30 DAE). Rates of tuber N uptake averaged 16.8 kg N/TJ and the effect of increased N was to increase the rate of tuber N uptake from 15.5 to 18.0 kg N/TJ. When averaged over the N application rates, Estima had the fastest rate of tuber N uptake (19.3 kg N/TJ) and Maris Piper the slowest (13.8 kg N/ha). Maximum total N uptake averaged 182 kg N/ha and was increased from 149 to 214 kg N/ha by increasing the N application rate from 100 to 200 kg N/ha. Markies had the largest value for total N uptake (204 kg N/ha) and Estima the smallest (155 kg N/ha). Similarly, maximum haulm N uptake was, on average, 78 kg N/ha when 100 kg N/ha had been applied and 98 kg N/ha when the N application rate was increased to 200 kg N/ha. Of the eight varieties tested, Casablanca had the smallest haulm N uptake (averaging 72 kg N/ha) and Markies the largest (101 kg N/ha). The effect of N application rate on maximum haulm N uptake differed between varieties. In Markies, haulm N uptake increased by 36 kg N/ha in response to 100 kg N/ha but for Estima and Chicago the increase was c. 11 kg N/ha.

(a)



(b)

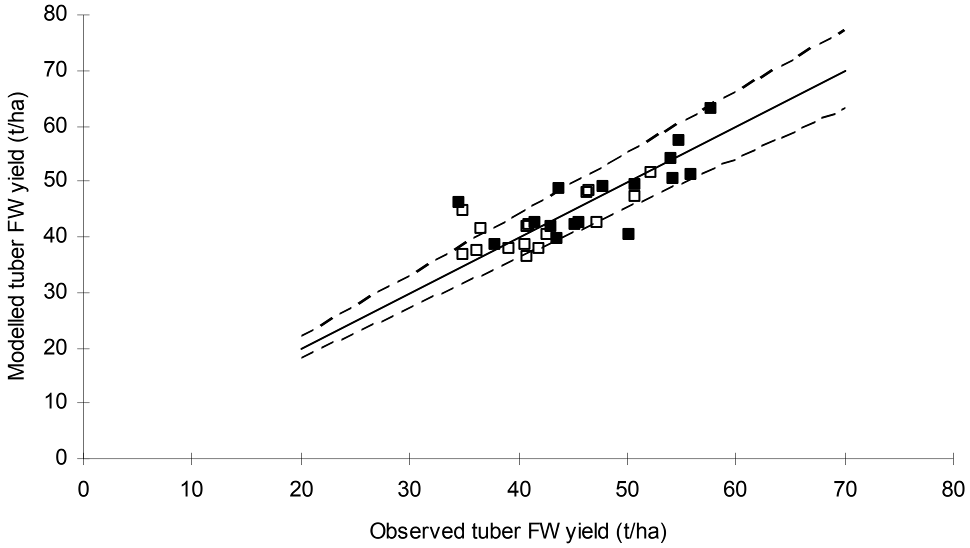


FIGURE 8. (A) RELATIONSHIP BETWEEN TOTAL DRY MATTER YIELD AND RADIATION ABSORPTION FOR EIGHT VARIETIES GROWN AT BABRAHAM. LINE IS FITTED RELATIONSHIP CONSTRAINED TO PASS THROUGH THE ORIGIN. (B) COMPARISON OF YIELDS PREDICTED BY THE CUF YIELD MODEL AND OBSERVED YIELDS AND AT THIRD AND FOURTH HARVESTS. SOLID LINE IS 1 : 1 RELATIONSHIP; DASHED LINES ARE ± 10 %. 100 KG N/HA, □ AND 180 KG N/HA, ■.

Variety	kg N/ha	Onset of tuber bulking (DAE)	Rate of tuber N uptake (kg N/TJ)	Tuber N uptake at 6 TJ (kg N/ha)	Asymptotic value of total N uptake (kg N/ha)	Maximum haulm N uptake (kg N/ha)
Cabaret	100	29.6	15.3	67	146	75
	200	30.2	18.5	75	213	93
Casablanca	100	25.6	14.3	68	133	63
	200	26.6	19.4	90	190	81
Chicago	100	27.1	15.7	73	155	86
	200	27.2	17.2	81	213	97
Estima	100	27.6	17.9	74	123	75
	200	29.0	20.8	81	187	87
Hermes	100	29.0	16.5	63	156	89
	200	29.6	18.4	69	215	98
Lady Rosetta	100	24.9	17.3	81	157	73
	200	27.5	19.5	88	230	97
Maris Piper	100	29.0	13.0	54	161	80
	200	29.1	14.7	63	225	109
Markies	100	29.6	14.1	58	164	83
	200	31.2	15.8	66	243	119
S.E. (45 D.F.)		0.92	1.29	4.2	11.8	4.0
Grand mean		28.3	16.8	72	182	88

TABLE 18. EFFECT OF VARIETY AND N APPLICATION RATE ON PARAMETERS OF TUBER, HAULM AND TOTAL N UPTAKE

The N requirement of a particular variety to maximise yield is dependent upon its capacity to take up and store N and the rate at which these reserves of N are then transferred to the tubers as they bulk. Thus, determinate varieties such as Estima are characterised by a limited capacity to store N in the haulm and a rapid rate of transfer whilst indeterminate varieties such as Maris Piper and Russet Burbank are characterised by large haulm N uptakes and relatively slow rates of transfer. The ratio of maximum haulm N : rate of tuber N uptake can be used to help rank varieties into determinacy groups and help estimate the amount N fertilizer needed to achieve an intended canopy persistence and yield. Table 19 summarises ratio data for several varieties grown at CUF and Babraham in 2009 and 2010. The absolute value of the ratios varies from site-to-site and season-to-season and thus this value is not solely under varietal control. However, in general and once the standard error associated with the ratios are taken into account, the ordering of the ratios for well-researched varieties such as Estima, Maris Piper and Russet Burbank correspond to their determinacy groups. Varieties such as Lady Rosetta and Hermes have intermediate ratios, whilst very indeterminate varieties such Vales Sovereign and Markies have ratios somewhat larger than those of Maris Piper or Russet Burbank.

Year Site	Variety group†	2010 Babraham	2010 CUF	2009 Babraham	2009 CUF	2009 CUF
Bonnie	-			7.1	8.3	
Brooke	-					11.3
Cabaret	3	5.1				
Casablanca	-	4.2		5.5		
Chicago	-	5.7		5.3		
Chopin	-				5.3	
Crisps4all	-		8.2		6.7	
Estima	1	4.2	6.2	6.5	5.5	6.6
Hermes	3	5.5				
Lady Rosetta	2	5.0				
Maris Piper	3	7.4		8.7	7.9	
Markies	4	7.7			8.1	
Russet Burbank	3		10.1			8.9
Vales Sovereign	4				9.9	
S.E.		0.50	0.85	0.72	0.60	0.78

† from Potato Council, 2009 'Crop Nutrition for Potatoes'

TABLE 19. SUMMARY SHOWING RATIOS OF HAULM N TO RATE OF TUBER N UPTAKE FOR CONTRASTING VARIETIES GROWN AT BABRAHAM AND CUF 2010 AND 2009. RATIOS CALCULATED FOR CROPS RECEIVING 200-250 KG N/HA

6.2. Conclusions

The purpose of this experiment was to further develop a methodology that would enable new varieties to be ranked according to their determinacy and probable N requirements. The 2010 experiment generated more useful data than one in 2009 due to increased replication and more frequent sampling which allowed for a more accurate description of N uptake and redistribution. The methodology is now reasonably robust and despite poor canopy longevity and yields in 2010, the varietal rankings were broadly similar to those found in 2009. It is probable that some of the site/seasonal variation in the ratios could be removed by applying more N fertilizer than was used in this experiment so that the effects of variable soil N supply could be minimised.

7. INTRODUCTION TO VARIETY AND N WORK AT CUF

This experiment was similar in design and scope to those done in previous seasons. The principal objective of the experiment was to provide data to validate modules with the CUF N management and yield forecasting models. Subsidiary objectives included investigation of factors that limit crop yield potential and causes for seasonal variation in yield.

7.1. Materials and Methods

Details specific to each variety and N experiment at CUF are shown in Table 20 and details of sampling, sample processing and data analysis are shown on page 13. All the experiments were planted manually with dibbers. For each experiment, average row spacing was 76.2 cm and within-row plant spacing was 25 cm giving an intended plant population of 52 493 /ha. Each treatment combination was replicated four times and allocated at random to blocks. Plant emergence was measured every 3 or 4 days from first emergence until plant emergence ceased and ground covers were measured by grid weekly. Irrigation was applied by boom and hose reel combination and agrochemicals were applied according to standard farm practice. Harvests were taken from rows two and three of each four row plot. A minimum of a two-plant (0.5 m) discard was left between adjacent harvests area or plot ends.

	2008	2009a	2009b	2010
Field	Osier	Dry Field	Dry Field	Cage Field
N rates tested (kg N/ha)	0, 125, 250 & 375	0, 125, 250 & 375	0 & 180	0, 125, 250 & 375
Plot dimensions	4 rows × 10 m	4 rows × 10 m	4 rows × 7.5 m	4 rows × 10 m
Planting date	16 April	17 April	20 April	14 April
Varieties (average seed weight, g)	Estima (25.0)	Brooke (21.1)	Bonnie (26.5)	Crisps4all (68.3)
	Russet Burbank (25.4)	Estima (24.2)	Chopin (18.6)	Estima (26.2)
		Russet Burbank (29.0)	Crisps4all (48.3)	Russet Burbank 23.6)
			Estima (24.2)	
			Maris Piper (39.3)	
			Markies (27.3)	
			Vales Sovereign (43.1)	
Date of N application	16 April, after planting	16 April	20 April, after planting	13 April
Total irrigation (mm)	144	160	186	181
Harvest 1	5 June	8 June	12 June	14 June
Harvest 2	13 June	6 July	9 July	12 July
Harvest 3	10 July	24 July	29 July	27 July
Harvest 4	11 August	13 August	24 September (0kg N/ha)	16 August
Harvest 5	17 September (Estima)	1 October	1 October (180 kg N/ha)	7 October
Harvest 6	29 September (R. Burbank)			
Harvest areas (m2)	1.91	1.91	1.91	1.91

TABLE 20. TREATMENT DETAILS FOR VARIETY AND N EXPERIMENTS AT CUF 2008-2010

8. CUF 2008

8.1. Results and Discussion

8.1.1. Emergence, ground cover development and radiation absorption

The average date of 50 % emergence for Estima and Russet Burbank was 18 May (32 DAP) and 16 May (30 DAP), respectively. Increasing the N application rate from 0 to 375 kg N/ha delayed the mean date of 50 % plant emergence from 15 May to 19 May. The effects of applying no N or 375 kg N/ha on plant emergence in Estima is shown in Figure 9. For Estima, the date of 90 % emergence was 16 May when no N had been applied and 27 May when 375 kg N/ha had been applied. Nitrogen application had a similar effect on the pattern of emergence of Russet Burbank. The protracted emergence caused by large N application will also result in protracted tuber initiation and this will make scab control more difficult. Furthermore, as the interval between emergence of the first and final 10 % of plant increases so will the probability that these plants will initiate tubers in different radiation environments resulting in stems that set a variable number of tubers. Thus, protracted emergence is likely to result in increased variability in number of tubers and tuber size distribution.

With the exception of the Estima that received no N, all crops achieved complete ground cover (Figure 10). Increasing the rate of N application had relatively little effect on the initial expansion of the crop canopy but canopy persistence was increased as the N application rate increased. The effects of N application rate on canopy persistence (as integrated ground cover) and season-long radiation absorption are shown in Table 21 and Table 22, respectively. The mean canopy persistence was 7557 % days compared with 5927 % days found in a similar experiment in 2007. For Estima, increasing the N application rate from 0 to 250 or 375 kg N/ha increased ground cover by c. 1100 % days. For Russet Burbank, ground cover persistence was increased by c. 2400 % days when the N application rate was increased from 0 to 375 kg N/ha. When averaged over the N treatments, Russet Burbank absorbed c. 3.4 TJ/ha more energy than Estima. For Estima the amount of radiation absorbed was maximised by N application of c. 250 kg N/ha whereas for Russet Burbank most radiation was absorbed when 375 kg N/ha had been applied.

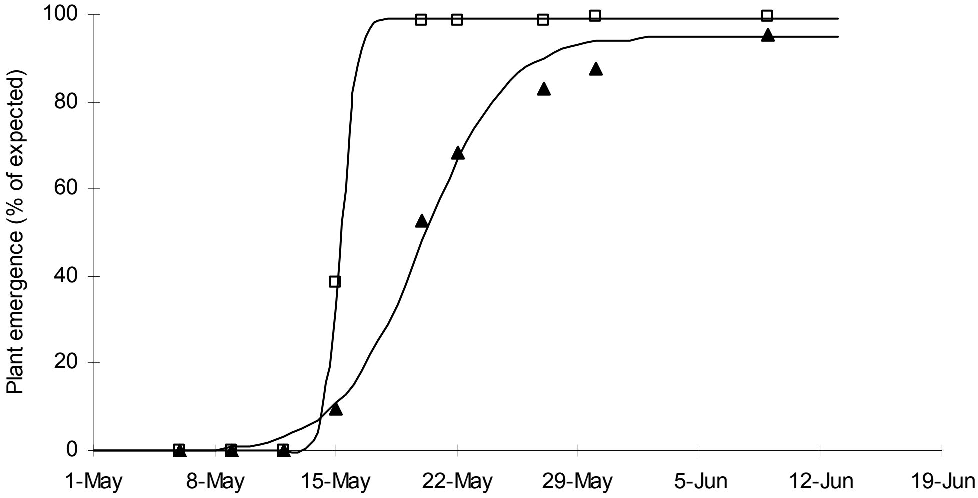


FIGURE 9. EFFECT OF N APPLICATION RATE ON EMERGENCE IN ESTIMA GIVEN 0, □ OR 375 ▲ KG N/HA. LINES ARE DERIVED FROM A LOGISTIC MODEL.

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Estima	5554	6031	6430	6625	6160
Russet Burbank	7844	8623	9071	10280	8954
Mean	6699	7327	7750	8453	7557

S.E. (21 D.F.) Variety, 119.6; N rate, 169.1; Variety and N rate 239.1

TABLE 21. EFFECT OF VARIETY AND N APPLICATION RATE ON SEASON-LONG INTEGRATED GROUND COVER (% DAYS)

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Estima	9.65	10.50	11.06	11.29	10.62
Russet Burbank	12.78	13.75	14.16	15.26	13.99
Mean	11.21	12.13	12.61	13.27	12.31

S.E. (21 D.F.) Variety, 0.145; N rate, 0.205; Variety and N rate 0.290

TABLE 22. EFFECT OF VARIETY AND N APPLICATION RATE ON SEASON-LONG RADIATION ABSORPTION (TJ/HA)

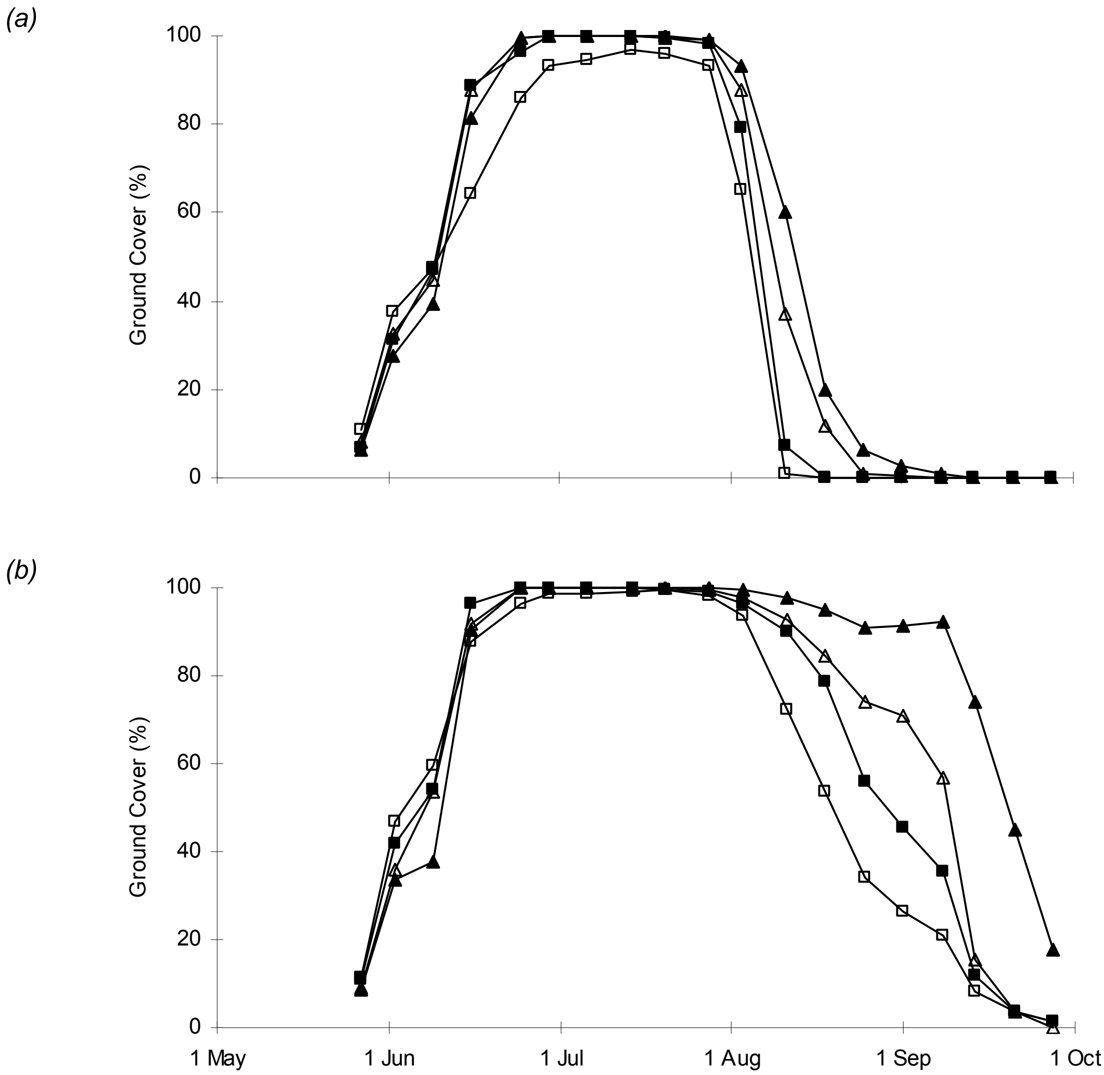


FIGURE 10. GROUND COVER DEVELOPMENT IN (A) ESTIMA AND (B) RUSSET BURBANK GIVEN 0, □; 125, ■; 250, △ OR 375, ▲ KG N/HA.

8.1.2. Yield at final harvest

For Estima, a final yield assessment was made on 17 September (c. 122 DAE) and for Russet Burbank the final yield assessment was made on 29 September (c. 136 DAE). At final harvest, with the exception of the Russet Burbank that received 375 kg N/ha, all the canopies had completely senesced. The effects of variety and N application rate on the number of above-ground stems are shown in Table 23. Russet Burbank had a larger stem population than Estima and for both varieties increasing the N application rate from 0 to 375 kg N/ha caused a statistically significant decrease in tuber population. This effect of N on the stem population is unusual and there are few plausible mechanisms that can explain this effect. However, since large N applications delayed emergence it is possible that the late emerging plants were preferentially grazed by rabbits or since the later emerging plants may have been weaker their stems were more prone to loss by disease.

	Nitrogen application rate (kg N/ha)				
	0	125	250	375	Mean
Estima	91	89	79	68	82
Russet Burbank	131	84	93	92	100
Mean	111	87	86	80	91

S.E. (21 D.F.) Variety, 2.8; N rate, 4.0; Variety and N rate 5.6

TABLE 23. EFFECT OF VARIETY AND N APPLICATION RATE ON ABOVE-GROUND STEM POPULATION (000/HA)

For both varieties, increasing the N application rate from 0 to 375 kg N/ha significantly increased the number of tubers per stem from c. 5.0 to 6.5. In consequence, N fertilizer rate had no statistically significant effect on tuber populations (Table 24). When averaged over all treatment combinations, the average tuber FW yield was 68.7 t/ha (Table 25). The average yield in a similar experiment in 2007 was 47.9 t/ha and in 2006 the average yield was 51.8 t/ha. When averaged over N application rates, tuber FW yields were similar for both varieties. Once the standard error of the means are taken into account the optimum for both varieties was probably between 125 and 250 kg N/ha.

	Nitrogen application rate (kg N/ha)				
	0	125	250	375	Mean
Estima	429	491	475	449	461
Russet Burbank	680	680	581	615	639
Mean	554	585	528	532	550

S.E. (21 D.F.) Variety, 18.4; N rate, 26.1; Variety and N rate 36.9

TABLE 24. EFFECT OF VARIETY AND N APPLICATION RATE ON TUBER POPULATION > 10 MM (000/HA)

	Nitrogen application rate (kg N/ha)				
	0	125	250	375	Mean
Estima	55.2	70.9	75.7	79.2	70.3
Russet Burbank	56.7	64.7	69.1	77.8	67.1
Mean	56.0	67.8	72.4	78.5	68.7

S.E. (21 D.F.) Variety, 1.78; N rate, 2.52; Variety and N rate 3.56

TABLE 25. EFFECT OF VARIETY AND N APPLICATION RATE ON TUBER FW YIELD > 10 MM (T/HA)

8.1.3. Efficiency of total and tuber dry matter production

The efficiency with which a crop converts absorbed radiation into total DM is a key step in yield production. Using data from each harvest, values of total (i.e. tuber and haulm) DM yield were regressed against radiation absorption on a plot-by plot basis. These data were analysed by linear regression and the fitted line was constrained to pass through the origin. The fitted parameter was then subject to analysis of variance. The slope of this relationship is an estimate of season-long RUE. The average RUE for all treatment combination was 1.29 t DM/TJ (Table 26) and was reasonably consistent to values found in previous seasons at CUF (i.e. 1.30 t DM/TJ in 2007 and 1.19 t DM/TJ in 2006). Differences in RUE between varieties, whilst statistically significant, were relatively small and N application rate had no effect.

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Estima	1.26	1.32	1.38	1.39	1.33
Russet Burbank	1.15	1.25	1.32	1.27	1.25
Mean	1.21	1.28	1.35	1.33	1.29

S.E. (21 D.F.) Variety, 0.028; N rate, 0.040; Variety and N rate 0.057

TABLE 26. EFFECT OF VARIETY AND N APPLICATION RATE ON SEASON-LONG RADIATION USE EFFICIENCY (T DM/TJ)

A similar analysis investigated the relationship between tuber DM yield and radiation absorption. As in the previous analysis, data from all five harvests were used but the straight line was not constrained to pass through the origin. The average efficiency of tuber DM production for all treatment combinations was 1.25 t DM/TJ. Nitrogen application rate had no statistically significant effect on the efficiency of DM production, however Estima was more efficient than Russet Burbank (1.30 compared with 1.19 TJ/ha). The intercept of the fitted line with the x-axis gives an indication of the apparent start of tuber bulking. On average, Estima started the linear phase of bulking once it had absorbed 1.07 TJ/ha of solar radiation compared with 1.85 TJ/ha for Russet Burbank. These values for energy absorption were converted to DAE and are shown in Table 27. The onset of bulking was earlier in Estima than in Russet Burbank and, for Estima, the onset of bulking occurred shortly after tuber initiation. For both varieties, the apparent start of tuber bulking was earliest when no N had been applied. In 2007, the mean values for Estima and Russet Burbank were 19.6 and 23.4 DAE, respectively. This variation in the delay in bulking represents variation in potential season length and whilst varietal differences in onset of tuber bulking were relatively consistent, there were large seasonal variations in the absolute values.

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Estima	24.0	26.3	26.3	25.8	25.6
Russet Burbank	28.5	30.3	31.5	33.8	31.0
Mean	26.3	28.3	28.9	29.8	28.3

S.E. (21 D.F.) Variety, 0.63; N rate, 0.89; Variety and N rate 1.26

TABLE 27. EFFECT OF VARIETY AND N APPLICATION RATE ON APPARENT ONSET OF TUBER BULKING (DAE)

8.1.4. Nitrogen uptake and redistribution in relation to radiation absorption

The rate of tuber N uptake, in relation to radiation absorption, is a key component of the CUF N model since it represents the rate at which N reserves within the canopy are depleted and this is a factor controlling canopy persistence. Tuber N uptake data from all five harvests were regressed against absorbed radiation as described in the previous section and the slope of this line is the rate of tuber N uptake (as kg N/TJ). On average, Estima had a faster rate of tuber N uptake than Russet Burbank (Table 28). The relative difference in varieties is consistent from season to season and explains many of the differences in canopy persistence between determinate (Estima) and indeterminate (Russet Burbank) varieties. For both varieties, the rate of tuber N uptake nearly doubled as the N application rate was increased from 0 to 375 kg N/ha.

The CUF N model also relies on an estimate of the maximum, total N uptake by the crop. This was estimated by fitting an exponential curve to total N uptake in relation to the quantity of radiation absorbed by the crop. The curve was constrained to pass through the origin and this assumes that total N uptake is negligible at the time of crop emergence. For the purposes of this analysis, estimate of asymptotic total N uptake was assumed to be equivalent to the maximum total N uptake. When averaged over all treatments, the mean maximum total N uptake was 202 kg N/ha (Table 29) and this was about 40 kg N/ha larger than that found in 2007. Varietal differences in total N uptake were relatively small and not statistically significant, however increasing the N application from 0 to 375 kg N/h increased the maximum total N uptake from 127 to 260 kg N/ha.

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Estima	11.7	15.0	18.7	20.8	16.5
Russet Burbank	10.6	13.1	15.7	19.0	14.6
Mean	11.2	14.0	17.2	19.9	15.6

S.E. (21 D.F.) Variety, 0.53; N rate, 0.75; Variety and N rate 1.06

TABLE 28. EFFECT OF VARIETY AND N APPLICATION RATE ON RATE OF TUBER N UPTAKE IN RELATION TO RADIATION ABSORPTION (KG N/TJ)

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Estima	122	177	227	271	199
Russet Burbank	133	194	244	248	205
Mean	127	186	235	260	202

S.E. (21 D.F.) Variety, 6.7; N rate, 9.4; Variety and N rate 13.4

TABLE 29. EFFECT OF VARIETY AND N APPLICATION RATE ON ESTIMATED MAXIMUM TOTAL N UPTAKE (KG N/HA)

Examination of a collation of Estima (479 plots) and Russet Burbank (89 plots) data collected over several season and locations suggested an association between maximum total N uptake (as estimated from a fitted exponential curve) and the rate of tuber N uptake (as estimated from a fitted straight line). Further analysis of these data showed a statistically significant relationship between the rate of tuber N uptake and the maximum total N uptake (Figure 11). The regression showed that c. 69 % of the variation in tuber N uptake rate could be explained by total N uptake and whether the variety was Estima or Russet Burbank. Thus for a maximum total N uptake of 200 kg N/ha (c. the mean of the data set), the predicted rate of tuber N uptake for Estima would be 16.5 (±0.10) kg N/TJ compared with 13.7 (±0.23) for Russet Burbank. Thus, due to the faster rate of tuber N uptake Estima would deplete reserves of N faster than Russet Burbank and thus for a similar total N uptake, the canopy persistence of Estima would be expected to be less than that of Russet Burbank. Similarly, a doubling of total N uptake (i.e. due to a large application of N fertilizer) would not double canopy persistence due to the increase in tuber N uptake rate.

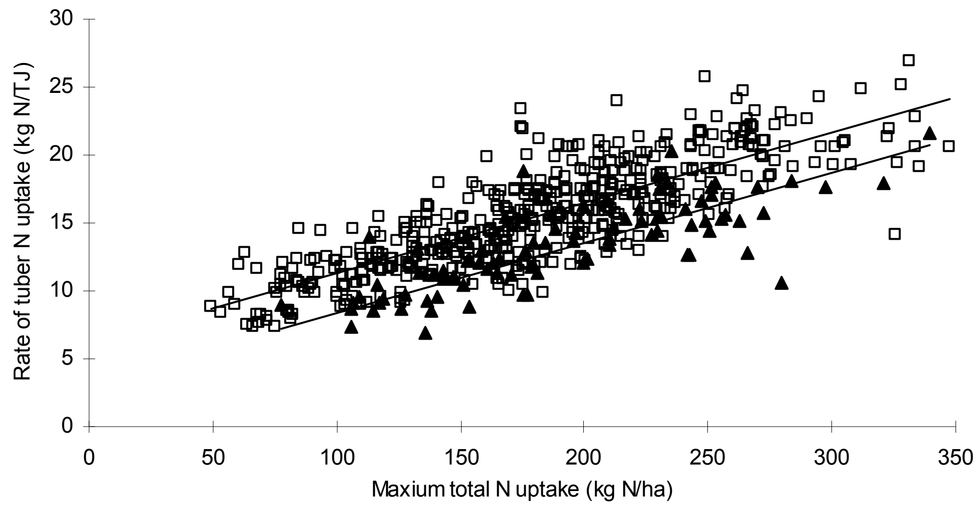


FIGURE 11. RELATIONSHIP BETWEEN RATE OF TUBER N UPTAKE AND MAXIMUM TOTAL N UPTAKE FOR ESTIMA (□) AND RUSSET BURBANK (▲). FITTED LINE FOR ESTIMA IS RATE = 6.16 (±0.292) + 0.052 (± 0.0015) × N UPTAKE. FITTED LINE FOR RUSSET BURBANK IS 3.34 (± 0.250) + 0.052 (±0.0015) × N UPTAKE.

8.2. Conclusions

The relationships between rate of total N uptake and maximum total N uptake are important because they explain some of the difference in varietal response to fertilizer. Furthermore, these data will be useful in modelling the relationship between canopy persistence, total N uptake and, in principal, N applied. It may be possible therefore to devise fertilizer recommendation on the basis of a crop's physiological response to N rather than many empirical N response studies.

9. CUF 2009A

9.1. Results and Discussion

9.1.1. Emergence, ground cover development and radiation absorption

When averaged over N treatments, the mean date of 50 % emergence for Brooke, Estima and Russet Burbank was 21, 22 and 17 May (34, 35 and 30 DAP), respectively. Increasing the N application rate from 0 to 375 kg N/ha had no statistically significant effect on the date of 50 % plant emergence in any variety. In 2008, increasing the N application from 0 to 375 kg N/ha resulted in delays in emergence and in some cases failure to achieve 100 % plant emergence. The difference between the two seasons may be a consequence of applying the N before planting in 2009 compared with application immediately after planting in 2008. With the exception of Estima that received no N, all crops achieved complete ground cover (Figure 12). Increasing the rate of N application had relatively little effect on the initial expansion of the crop canopy but canopy persistence was increased as the N application rate increased. The effects of N application rate on canopy persistence (estimated as integrated ground cover) and season-long radiation absorption are shown in Table 30 and Table 31 respectively. The mean canopy persistence was

8568 % days compared with 7557 and 5927 % days found in similar experiments in 2008 and 2007, respectively. For Estima and Russet Burbank, increasing the N application rate from 0 to 250 or 375 kg N/ha increased ground cover by 1700-1800 % days. For Brooke, ground cover persistence was increased by c. 2900 % days when the N application rate was increased from 0 to 375 kg N/ha. When averaged over all treatment combinations, c. 14 TJ/ha of solar energy was absorbed during the course of the season, with Brooke and Russet Burbank absorbing c. 3.4 TJ/ha more solar energy than Estima. For all three varieties the amount of radiation absorbed was maximised by N application of between 250 and 375 kg N/ha.

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Brooke	7515	9124	9748	10219	9195
Estima	6091	7260	7785	7623	7190
Russet Burbank	8361	9037	9661	10219	9320
Mean	7322	8474	9065	9412	8568

S.E. (33 D.F.) Variety, 123.8; N rate, 142.9; Variety and N rate 247.6

TABLE 30. EFFECT OF VARIETY AND N APPLICATION RATE ON SEASON-LONG INTEGRATED GROUND COVER (% DAYS)

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Brooke	12.59	14.82	15.36	16.24	14.75
Estima	10.29	12.09	13.02	12.74	12.04
Russet Burbank	13.86	14.84	15.66	16.22	15.15
Mean	12.25	13.92	14.68	15.07	13.98

S.E. (33 D.F.) Variety, 0.156; N rate, 0.180; Variety and N rate 0.311

TABLE 31. EFFECT OF VARIETY AND N APPLICATION RATE ON SEASON-LONG RADIATION ABSORPTION (TJ/HA)

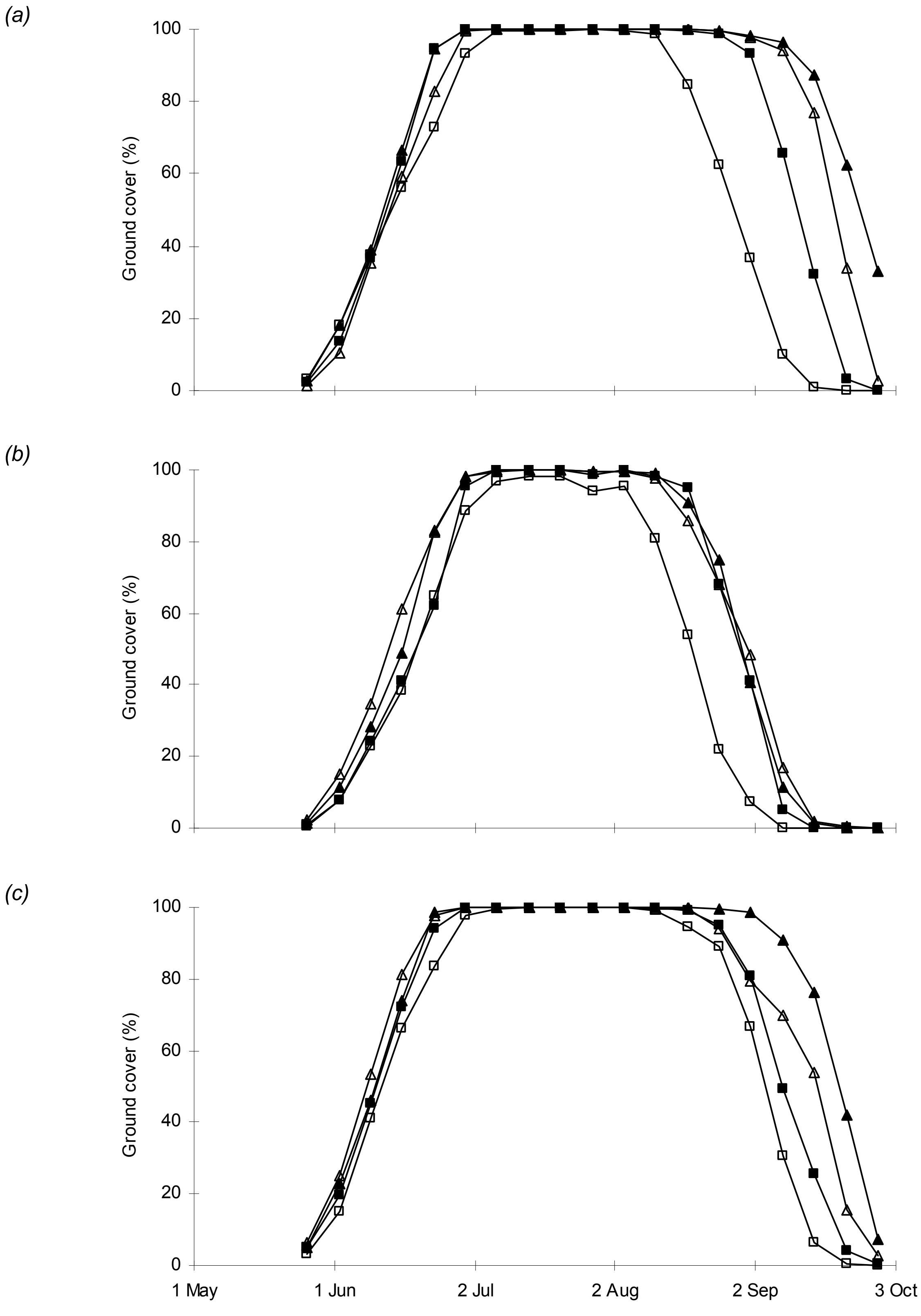


FIGURE 12. GROUND COVER DEVELOPMENT IN (A) BROOKE, (B) ESTIMA AND (C) RUSSET BURBANK. NITROGEN APPLIED (KG N/HA) 0, □; 125, ■; 250, △ OR 375, ▲.

9.1.2. Yields at final harvest

A final yield assessment was made at c. 134 DAE and with the exception of the Brooke and Russet Burbank that had received 375 kg N/ha, all canopies had completely senesced by this stage. The average mainstem population for Brooke, Estima and Russet Burbank was 75, 67 and 91 000/ha, respectively and tuber populations > 10 mm for Brooke, Estima and Russet Burbank averaged 485, 381 and 362 000/ha, respectively. Neither stem nor tuber population was significantly affected by N application rate. At final harvest, average tuber DM concentrations ranged from 19.9 % in Estima to 25.0 % in Brooke. On average, increasing the N application rate from 0 to 375 kg N/ha decreased tuber DM concentration from 24.2 to 22.2 % and this effect was larger in Brooke and Russet Burbank than it was in Estima. In 2009, the overall average tuber DM concentration was 22.8 % compared with 21.0 % in 2008. When averaged over all treatment combinations, the average tuber FW yield was 64.9 t/ha (Table 32). The average yield in a similar experiment in 2008 was 70.0 t/ha and 46.5 t/ha in 2007. Once the standard errors of the means are taken into account, the optimum N application rate for both Estima and Russet Burbank was estimated as between 125 and 250 kg N/ha but closer to 125 kg N/ha for Brooke.

	Nitrogen application rate (kg N/ha)				
	0	125	250	375	Mean
Brooke	55.6	58.7	59.4	64.6	59.6
Estima	58.0	74.5	82.4	70.7	71.4
Russet Burbank	56.3	57.2	68.5	72.4	63.6
Mean	56.6	63.5	70.1	69.2	64.9

S.E. (33 D.F.) Variety, 2.49; N rate, 2.88; Variety and N rate 4.99

TABLE 32. EFFECT OF VARIETY AND N APPLICATION RATE ON TUBER FW YIELD > 10 MM (T/HA)

9.1.3. Efficiency of total and tuber dry matter production

The efficiency with which crops convert absorbed solar radiation into total DM yield is a key step in yield production. The average RUE for all treatment combinations was 1.34 t DM/TJ (Table 33) and this was reasonably consistent with values found in previous seasons at CUF. Differences in RUE between varieties, whilst statistically significant, were relatively small and increasing the N application rate from 0 to 375 kg N/ha had no significant effect on RUE.

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Brooke	1.40	1.28	1.24	1.37	1.32
Estima	1.47	1.50	1.47	1.41	1.46
Russet Burbank	1.28	1.15	1.26	1.29	1.24
Mean	1.38	1.31	1.33	1.35	1.34

S.E. (33 D.F.) Variety, 0.027; N rate, 0.031; Variety and N rate 0.054

TABLE 33. EFFECT OF VARIETY AND N APPLICATION RATE ON SEASON-LONG RADIATION USE EFFICIENCY (T DM/TJ)

The average efficiency of tuber DM production for all treatment combinations was 1.27 t DM/TJ. Nitrogen application rate had no statistically significant effect on the efficiency of DM production but Estima was more efficient than either Brooke or Russet Burbank (1.40 compared with 1.29 and 1.11 t DM/TJ, respectively). The onset of bulking was earliest in Estima, and latest in Brooke (Table 34). For Estima, increasing the N application rate had relatively little effect on the apparent onset of tuber bulking. However for Brooke and Russet Burbank the apparent start of tuber bulking was earliest when no N had been applied and increasing the N application rate to 375 kg N/ha delayed the onset of bulking by c. 9 days in Brooke and 6 days in Russet Burbank.

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Brooke	29.5	35.8	34.5	38.3	34.5
Estima	26.8	27.0	25.5	26.0	26.3
Russet Burbank	27.3	28.3	30.5	32.8	29.7
Mean	27.8	30.3	30.2	32.3	30.2

S.E. (33 D.F.) Variety, 1.51; N rate, 1.74; Variety and N rate 3.01

TABLE 34. EFFECT OF VARIETY AND N APPLICATION RATE ON APPARENT ONSET OF TUBER BULKING (DAE)

9.1.4. Nitrogen uptake and redistribution in relation to radiation absorption

The rate of tuber N uptake, in relation to radiation absorption, is a key component of the CUF N model since it represents the rate at which N reserves within the canopy are depleted and this is a factor controlling canopy persistence. On average, Brooke and Estima had a faster rate of tuber N uptake than Russet Burbank (Table 35). For all three varieties, the rate of tuber N uptake increased by c. 50 % as the N application rate was increased from 0 to 375 kg N/ha.

	Nitrogen application rate (kg N/ha)				
	0	125	250	375	Mean
Brooke	12.9	17.8	20.5	20.1	17.8
Estima	13.5	18.2	18.6	18.2	17.1
Russet Burbank	11.5	13.8	16.1	18.5	15.0
Mean	12.6	16.6	18.4	18.9	16.6

S.E. (33 D.F.) Variety, 0.66; N rate, 0.76; Variety and N rate 1.31

TABLE 35. EFFECT OF VARIETY AND N APPLICATION RATE ON RATE OF TUBER N UPTAKE IN RELATION TO RADIATION ABSORPTION (KG N/TJ)

Estimates of maximum total and maximum haulm N uptake are shown in Table 36 and Table 37, respectively. When averaged over all treatments, the mean maximum total N uptake was 256 kg N/ha (Table 36) and larger was than found in 2008 and 2007. Increasing the N application rate from 0 to 375 kg N/ha increased average total N uptake from 176 to 330 kg N/ha. As the N application rate was increased, total N uptake was increased to a larger extent in Brooke and Russet Burbank than in Estima and when 375 kg N/ha had been applied the difference in total N uptake was nearly

100 kg N/ha. Similar varietal differences and effects of N application rate were evident in the effects of treatments on estimates of maximum haulm N uptake as for maximum total N uptake.

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Brooke	179	238	303	358	270
Estima	171	237	265	270	236
Russet Burbank	177	223	289	364	263
Mean	176	233	286	330	256

S.E. (33 D.F.) Variety, 6.9; N rate, 7.9; Variety and N rate 13.8

TABLE 36. EFFECT OF VARIETY AND N APPLICATION RATE ON ESTIMATED MAXIMUM TOTAL N UPTAKE (KG N/HA), CUF 2009

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Brooke	73	160	223	231	172
Estima	70	109	121	142	111
Russet Burbank	79	132	141	177	132
Mean	74	134	162	184	138

S.E. (33 D.F.) Variety, 4.6; N rate, 5.3; Variety and N rate 9.1

TABLE 37. EFFECT OF VARIETY AND N APPLICATION RATE ON ESTIMATED MAXIMUM HAULM N UPTAKE (KG N/HA)

When no N was applied, varietal differences in maximum total and maximum haulm N uptake were small and not statistically significant but a key difference between varieties appears to be the response to N when it is in plentiful supply. Table 38 summarises estimates of maximum total N uptake for Estima and Russet Burbank in several experiments where N application varied from 0 to 200 or 375 kg N/ha. When no N was applied, the average maximum total N uptake was similar in both Estima and Russet Burbank. These data also show that Estima and Russet Burbank have a similar capacity to 'scavenge' N from the soil and thus varietal differences in N requirement does not appear to be related to how well they exploit the soil N supply (SNS). When large amounts of N fertilizer were applied, the average total N uptake of Estima increased to 248 kg N/ha whist that of Russet Burbank increased to 272 kg N/ha. For Estima, in the presence of large amounts of N (from SNS + fertilizer), total N uptake did not exceed 275 kg N/ha in any year whilst for Russet Burbank it increased to more than 325 kg N/ha in 2009. Whilst this is a relatively limited data set, it suggests that a key difference between varieties is their capacity to take up N relatively early in the season for use at a later point. A key question is why, when plenty of N was available, the total N uptake of Estima and Russet Burbank was so variable between seasons.

	Estima		Russet Burbank		
	0 kg N/ha	Nmax	0 kg N/ha	Nmax	S.E.
2004	147	275	152	277	15.3
2005	107	181	114	194	9.5
2006	168	257	162	317	14.0
2007	63	233	127	230	14.1
2008	122	271	133	248	13.4
2009	171	270	177	364	13.8
Mean	130	248	144	272	-

TABLE 38. COMPARISON OF ESTIMATES OF MAXIMUM TOTAL N UPTAKE (NMAX) IN ESTIMA AND RUSSET BURBANK GROWN AT CUF 2004-2009. IN 2004 AND 2005 NMAX WAS 200 KG N/HA WHILST IN OTHER YEARS IT WAS 375 KG N/HA

9.2. Conclusions

This experiment has provided further evidence for some of the varietal differences in N accumulation and N redistribution. These relationships, between rate of total N uptake and maximum total N uptake, are important because they explain some of the differences in varietal response to fertilizer. Furthermore, these data will be useful in modelling the relationship between canopy persistence, total N uptake and, in principal, N applied. Using these data, it should be may be possible to devise fertilizer recommendation on the basis of a crop’s physiological response to N rather than many empirical N response studies.

10. CUF 2009B

10.1. Results and Discussion

10.1.1. Emergence, ground cover development and radiation absorption

When averaged over all treatments, the date of 50 % plant emergence was 20 May, 30 days after planting. Increasing the N application rate from 0 to 180 kg N/ha had no significant effect on the date of 50 % plant emergence, however the date of emergence was earliest in Maris Piper (19 May) and latest in Markies (22 May).

When no N was applied, most varieties achieved complete (100 %) ground cover and all varieties achieved ground covers in excess of 95 % (Figure 13). When the N application rate was increased to 180 kg N/ha, all varieties achieved complete ground cover and canopy persistence was also increased. The effects of variety and N application rate on integrated ground cover and radiation absorption are shown in Table 39. Averaged over N application rates, Chopin had the least persistent canopy (5890 % days) and Maris Piper had the most persistent (8481 % days). On average, increasing the N application rate from 0 to 180 kg N/ha increased canopy persistence from 6736 to 7663 % days, however the increase in canopy persistence was much larger in some varieties than in others. For example, in Markies the increase was 1447 % days compared with 211 % days for Maris Piper. The average amount of radiation absorbed by the crops was 12.72 TJ/ha and the amount of radiation absorbed increased from 11.87 to 13.57 TJ/ha when the amount of N applied was increased from 0 to 180 kg N/ha. Varietal differences in radiation absorption were closely related to differences in ground cover persistence.

Variety	Integrated ground cover (% days) 0 kg N/ha	180 kg N/ha	Radiation absorbed (TJ/ha) 0 kg N/ha	180 kg N/ha
Bonnie	7054	8205	12.20	14.57
Chopin	5460	6320	9.60	11.02
Crisps4all	6188	7479	10.83	12.93
Estima	5674	6400	9.96	11.10
Maris Piper	8376	8587	14.91	15.47
Markies	6833	8280	12.40	15.21
Vales Sovereign	7565	8368	13.16	14.70
Mean for N	6736	7663	11.87	13.57
Grand mean	7199		12.72	
S.E. (39 D.F.)	65.1 (N); 172.1 (Variety*N)		0.114 (N); 0.301 (Variety*N)	

TABLE 39. EFFECT OF VARIETY AND N APPLICATION RATE ON SEASON-LONG INTEGRATED GROUND COVER AND RADIATION ABSORPTION

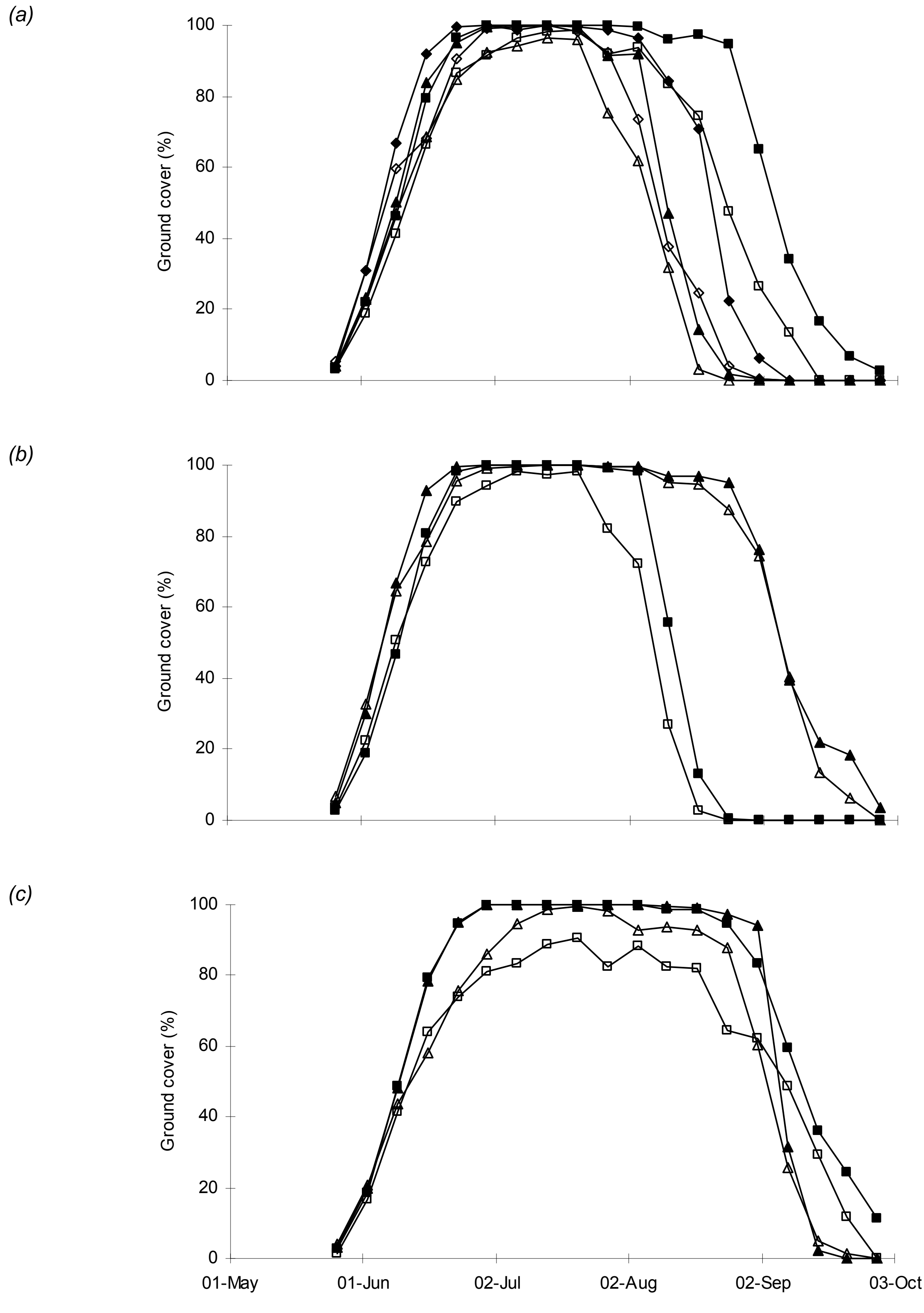


FIGURE 13. GROUND COVER DEVELOPMENT IN (A) BONNIE, □; CHOPIN, △ AND CRISPS4ALL, ◊; (B) ESTIMA, □ AND MARIS PIPER, △; (C), MARKIES, □ AND VALES SOVEREIGN (△). OPEN SYMBOLS, 0 KG N/HA AND CLOSED SYMBOLS, 180 KG N/HA.

10.1.2. Stem and tuber populations

The main effects of variety on total stem and tuber population at each harvest are shown in Table 40. Stem populations were not significantly affected by N application rate and were reasonably consistent between harvests. Bonnie produced the fewest stems (c. 82 000/ha) whilst Crisps4all produced the most (c. 250 000/ha). The first harvest was taken too early (23 DAE) to obtain a useful estimate of the tuber population > 10 mm. At the second, third and final harvest tuber populations were not affected by N application rate and averaged 577 000/ha. Bonnie consistently had the smallest tuber population (averaging 372 000/ha) whilst Crisps4all tended to have the largest (765 000/ha).

	12 June		9 July		29 July		24 September & 1 October	
Variety	**Stems**	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**
Bonnie	81.3	-	88.6	397	73.0	342	85.9	378
Chopin	111.5	-	107.6	587	106.3	574	108.3	610
Crisps4all	240.4	-	271.2	815	246.7	685	240.8	794
Estima	107.6	-	105.6	541	109.6	534	106.9	533
Maris Piper	173.9	-	173.9	744	171.2	705	184.4	724
Markies	101.0	-	100.4	490	109.6	511	94.5	471
Vales Sovereign	192.2	-	179.1	568	187.7	575	185.7	529
S.E. (39 D.F.)	6.49	-	6.01	27.9	6.16	24.2	5.07	21.7
Grand mean	144.0	-	146.6	592	143.4	561	143.8	577

TABLE 40. MAIN EFFECT OF VARIETY ON TOTAL STEM POPULATION (000/HA) AND TUBER POPULATION > 10 MM (000/HA) AT EACH HARVEST

10.1.3. Yields and N uptake 12 June (c. 23 days after emergence)

At the first crop sampling the overall, average total (i.e. haulm and tuber) DW yield was 1.20 t/ha (Table 41). When averaged over all varieties, increasing the N application rate from 0 to 180 kg N/ha increased total DW yield by c. 0.1 t/ha. Bonnie had the smallest total DW yield (1.0 t/ha) and Maris Piper the largest (1.5 t/ha). Tuber FW yields averaged 0.62 t/ha and ranged from 0.08 t/ha (Markies) to 1.74 t/ha (Chopin). Due to effects on DM partitioning, increasing the N application rate from 0 to 180 kg N/ha reduced average tuber FW yields from 0.71 to 0.52 t/ha. Total N uptake averaged 56 kg N/ha and was increased from 47 to 65 kg N/ha by increasing the N application rate. On average, Markies had the smallest total N uptake (46 kg N/ha) and Maris Piper the largest (68 kg N/ha) but these differences were probably associated with the later emergence in Markies than Maris Piper.

Variety	kg N/ha	Tuber FW (t/ha)	Tuber DM (%)	Total DM (t/ha)	Tuber N (kg N/ha)	Total N (kg N/ha)
Bonnie	0	0.46	11.7	0.92	1.31	43
	180	0.44	11.5	1.08	1.44	53
Chopin	0	1.85	13.0	1.17	5.56	49
	180	1.64	11.9	1.22	4.92	60
Crisps4all	0	0.31	13.4	1.39	1.09	50
	180	0.25	15.7	1.63	1.08	81
Estima	0	0.80	12.4	1.13	2.22	49
	180	0.47	11.6	1.04	1.45	55
Maris Piper	0	1.00	12.5	1.38	2.83	54
	180	0.69	12.2	1.65	2.30	81
Markies	0	0.07	9.8	0.94	0.29	39
	180	0.08	10.5	1.06	0.32	53
Vales Sovereign	0	0.47	13.1	1.08	1.48	46
	180	0.10	11.7	1.17	0.41	70
S.E. (39 D.F.)		0.116	1.06	0.094	0.368	5.3
Mean		0.62	12.2	1.20	1.91	56

TABLE 41. EFFECT OF VARIETY AND N APPLICATION RATE ON COMPONENTS OF YIELD AND N UPTAKE ON 12 JUNE

10.1.4. Yields and N uptake 9 July (c. 50 days after emergence)

At the second sampling the average total DM yield was 8.1 t/ha (Table 42). When averaged over varieties, total DM yield was 7.6 t/ha when no N had been applied compared with 8.5 t/ha when 180 kg N/ha had been applied. Markies had the smallest total DM yield (6.4 t/ha) and Maris Piper the largest (8.9 t/ha). At c. 50 DAE, the mean tuber FW yield was 30 t/ha and, assuming TI occurred at c. 20 DAE, this implies an average bulking rate of c. 1 t FW/ha/day. Nitrogen application rate had no statistically significant effect on tuber FW yield. When averaged over both N application rates Estima had the largest tuber FW yield (37 t/ha) and Markies the smallest (22 t/ha). Total N uptake averaged 157 kg N/ha and was 113 kg N/ha when no N was applied and 201 kg N/ha when 180 kg N/ha had been applied. The increase in N uptake (88 kg N/ha), indicates an efficiency of fertilizer N use of 49 %. Varietal differences in total N uptake were not statistically significant.

Variety	kg N/ha	Tuber FW (t/ha)	Tuber DM (%)	Total DM (t/ha)	Tuber N (kg N/ha)	Total N (kg N/ha)
Bonnie	0	34.8	15.1	7.41	43	107
	180	33.8	14.4	8.19	65	189
Chopin	0	33.6	18.6	7.96	64	122
	180	36.3	17.0	9.06	95	213
Crisps4all	0	26.5	22.2	8.34	55	110
	180	24.5	20.7	8.98	75	198
Estima	0	35.5	18.0	8.15	62	121
	180	38.2	16.2	9.10	83	180
Maris Piper	0	30.5	19.2	9.01	53	133
	180	28.3	17.4	8.76	79	220
Markies	0	20.8	17.6	5.69	40	94
	180	22.2	15.9	7.10	64	196
Vales Sovereign	0	27.1	17.0	6.76	40	108
	180	28.8	15.6	8.54	60	208
S.E. (39 D.F.)		1.71	0.42	0.471	4.4	13.6
Mean		30.1	17.5	8.08	63	157

TABLE 42. EFFECT OF VARIETY AND N APPLICATION RATE ON COMPONENTS OF YIELD AND N UPTAKE ON 9 JULY

10.1.5. Yields and N uptake 29 July (c. 70 days after emergence)

At the third harvest the average total DW yield had increased to 13.0 t/ha (Table 43). Total DW yields were 11.7 t/ha when no N had been applied and 14.3 t/ha when 180 kg N/ha had been applied as a consequence of a more extensive ground cover. Bonnie had the largest total DM yield and Markies the smallest (14.2 and 10.9 t/ha, respectively). The average tuber FW yield was 51.5 t/ha. On average, tuber FW yields were c. 10 t/ha larger when 180 kg N/ha had been applied when compared with no N. However, the tuber FW yield response to N fertilizer was much larger in some varieties than in others. For example, the response to 180 kg N/ha was 21 t/ha in Estima compared with 3 t/ha in Maris Piper and 4 t/ha in Vales Sovereign. Total N uptake averaged 204 kg N/ha and differences in total N uptake between varieties were not statistically significant. In the absence of N fertilizer, total N uptakes averaged 145 kg N/ha and this was increased to 262 kg N/ha when 180 kg N/ha had been applied.

Variety	kg N/ha	Tuber FW (t/ha)	Tuber DM (%)	Total DM (t/ha)	Tuber N (kg N/ha)	Total N (kg N/ha)
Bonnie	0	58.7	16.8	12.5	101	162
	180	77.4	14.8	16.0	143	301
Chopin	0	48.7	21.4	12.0	108	143
	180	61.3	18.9	14.4	167	248
Crisps4all	0	37.2	24.5	11.6	90	136
	180	42.2	22.4	13.7	138	250
Estima	0	49.5	19.3	11.3	99	134
	180	70.3	18.1	15.7	187	273
Maris Piper	0	46.7	20.9	12.9	97	161
	180	50.1	18.6	13.9	130	241
Markies	0	34.4	21.4	9.4	74	121
	180	40.5	18.0	12.4	115	254
Vales Sovereign	0	49.9	19.0	12.1	85	161
	180	54.1	16.8	13.7	120	273
S.E. (39 D.F.)		2.62	0.27	0.63	8.8	15.4
Mean		51.5	19.3	13.0	118	204

TABLE 43. EFFECT OF VARIETY AND N APPLICATION RATE ON COMPONENTS OF YIELD AND N UPTAKE ON 29 JULY

10.1.6. Yields and N uptake at final harvest

Total dry weight yields averaged 16.9 t/ha (Table 44) and total DW yields were 14.6 t/ha when no N had been applied and 19.2 t/ha when 180 kg N/ha had been applied. In the absence of N fertilizer, Chopin, Crisp4all and Estima had the smallest total DW yield (c. 12.5 t/ha) whilst Maris Piper and Vales Sovereign had the largest total DW yield (c. 17.7 t/ha). When N had been applied, Estima had the smallest total DW yield (13.8 t/ha) whilst the total DW yields of Bonnie, Maris Piper and Markies were in excess of 20 t/ha. The mean tuber FW yield was 67 t/ha and when averaged over all seven varieties the increase in tuber FW yield in response to N was c. 19 t/ha. When no N was applied, both Bonnie and Vales Sovereign had tuber FW yields in excess of 70 t/ha and when 180 kg N/ha had been applied Bonnie, Maris Piper and Vales Sovereign had yields between 80 and 90 t/ha. At the final sampling the overall, average total N uptake was 206 kg N/ha which implies there was little new N uptake in the 50–60 days between the third and final samplings. This is consistent with the hypothesis that most N is taken up in the first half of the season. When no N was applied the mean total N uptake was 152 kg N/ha and when N had been applied it was increased to 259 kg N/ha. There were large varietal differences in total N uptake particularly where N had been applied. For example, when 180 kg N/ha had been applied the total N uptake of Estima was 196 kg N/ha compared with 285 kg N/ha in Maris Piper and 302 kg N/ha in Markies.

Variety	kg N/ha	Tuber FW (t/ha)	Tuber DM (%)	Total DM (t/ha)	Tuber N (kg N/ha)	Total N (kg N/ha)
Bonnie	0	70.2	19.2	15.2	132	157
	180	90.5	19.0	20.2	222	271
Chopin	0	53.4	22.4	12.9	125	140
	180	72.2	21.0	16.6	221	243
Crisps4all	0	41.4	26.2	12.2	122	142
	180	64.2	25.6	19.3	224	264
Estima	0	55.7	20.4	12.3	117	136
	180	69.4	18.5	13.8	182	196
Maris Piper	0	62.3	25.3	17.9	143	168
	180	82.3	24.6	23.2	250	285
Markies	0	46.5	26.3	14.0	128	148
	180	70.5	25.0	21.9	249	302
Vales Sovereign	0	71.7	22.1	17.6	150	175
	180	84.4	19.7	19.5	208	253
S.E. (39 D.F.)		2.60	0.57	0.89	9.8	11.9
Mean		66.8	22.5	16.9	177	206

TABLE 44. EFFECT OF VARIETY AND N APPLICATION RATE ON COMPONENTS OF YIELD AND N UPTAKE AT FINAL HARVEST

10.1.7. Radiation use efficiency, onset of tuber bulking, modelling of yield, canopy persistence and N requirements

Canopy persistence and therefore yield potential are related to total N uptake and the rate at which N is accumulated in the tubers. There is now a considerable body of evidence to show that determinate varieties such as Estima have a limited capacity to take up N and have a comparatively rapid rate of transfer of N from haulm to tubers when compared with indeterminate varieties grown under similar conditions. In order to compare varieties in terms of the their N uptake and redistribution characteristics it is first necessary to ensure that their growth and yield are explicable by considering the amount of radiation these have absorbed and the efficiency with which the radiation had converted to DM yield. Figure 14a shows that, for this experiment, the relationship between total DM yield and radiation absorption is closely represented by a linear relationship constrained to pass through the origin. Subsequent analysis showed that the slope of the line (an estimate of RUE) was 1.37 t/TJ. This average value is typical for potato crops grown under temperate, UK conditions. There was some evidence that there were some varietal differences in RUE but these were relatively small. For example, when averaged over both N application rates the RUE for Markies was 1.29 t/TJ compared with 1.46 t/TJ for Chopin. The effects of N application rate on RUE whilst statistically significant were also relatively small – when no N was applied the average RUE was 1.29 t/TJ compared with 1.46 t/TJ when the N application rate was increased to 180 kg N/ha. These apparent varietal and nutritional differences in RUE may be at least partly due to overestimates of ground cover particularly in those crops with sparse canopies grown without fertilizer and towards the end of the season when canopies may have lodged or were senescing. The CUF yield model was parameterised using data collected at the second sampling (c. 50 DAE) and was then used to model yields at the third and final harvests. In general the model performed well and most predictions were within ± 10 % of the observed values Figure 14b.

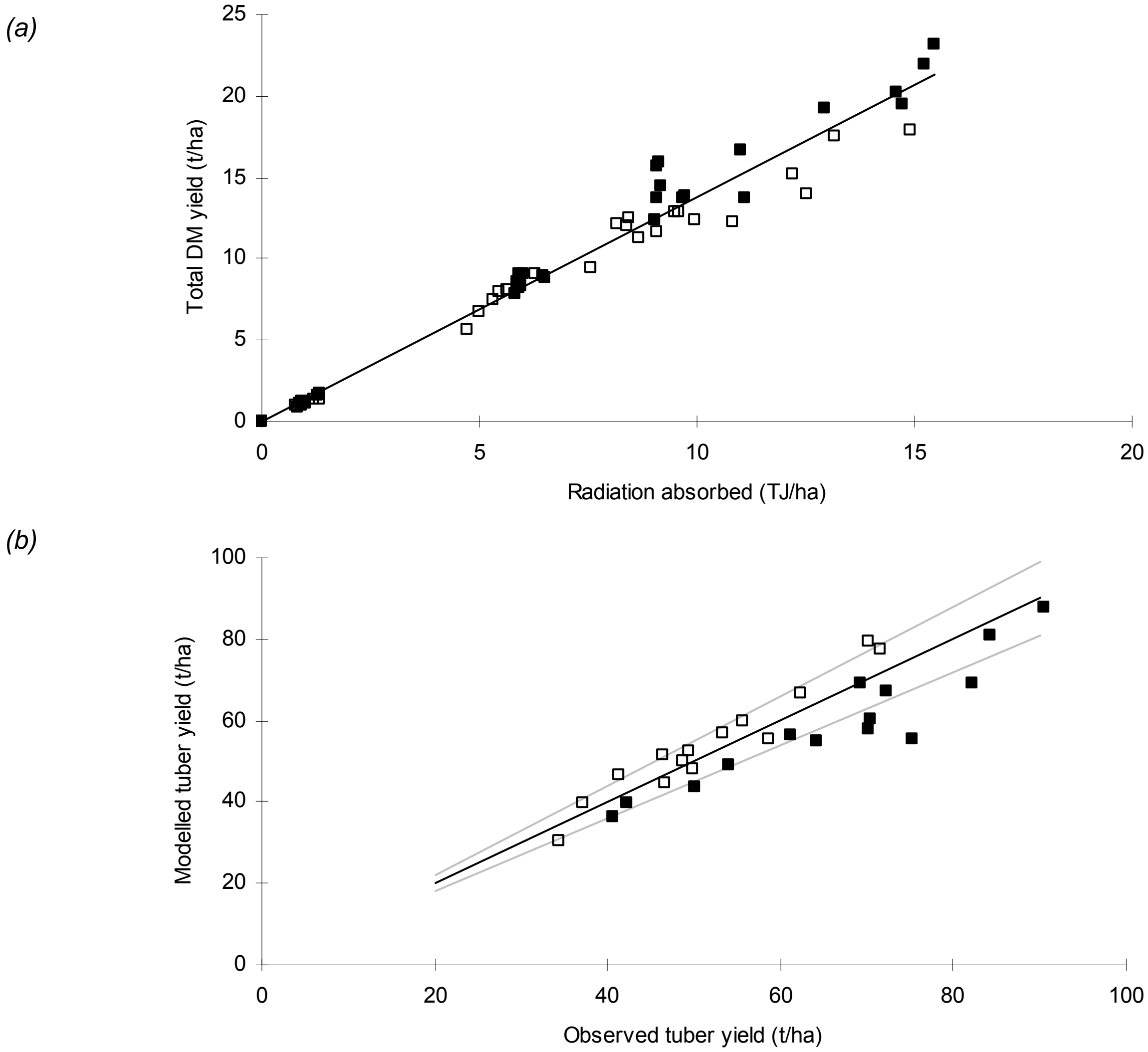


FIGURE 14. (A) RELATIONSHIP BETWEEN TOTAL DRY MATTER (DM) YIELD AND RADIATION ABSORPTION FOR SEVEN VARIETIES GROWN AT CUF. LINE IS FITTED RELATIONSHIP CONSTRAINED TO PASS THROUGH THE ORIGIN. (B) COMPARISON OF YIELD PREDICTED BY THE CUF YIELD MODEL AND OBSERVED YIELD FOR THE THIRD AND FINAL HARVEST. BLACK LINE IS 1 : 1 RELATIONSHIP; GREY LINES ARE ± 10 %. 0 KG N/HA, □ AND 180 KG N/HA, ■.

Where no N was applied, the model tended to overestimate yield in some varieties and this may have been due to the model overestimating the amount of radiation absorbed by the 0N crops. Conversely, when 180 kg N/ha was applied the model tended to underestimate yield. These underestimates are not easily explained but may be a consequence of inadequate modelling of DM partitioning between haulm and tuber (i.e. the harvest index), of tuber DM concentration or a poor estimate of yield at the one of the samplings. The reasonably close relationship between modelled and observed yield suggests that yield formation was closely related to canopy persistence and radiation absorption and was not significantly affected by factors such as water or heat stress or disease.

When averaged over all treatment combinations, the apparent onset of tuber bulking occurred c. 24 DAE (Table 45). When averaged over varieties, increasing the N application rate from 0 to 180 kg N/ha delayed bulking by c. 5 days. For some varieties (i.e. Bonnie, Estima and Vales Sovereign) the effects of increasing the N application rate were less than 2 days but for Crisps4all and Markies the effects were much larger (9 and 13 days, respectively). Therefore for varieties such Bonnie, Estima and Vales Sovereign, the onset of tuber bulking occurred very shortly after tuber initiation (assuming it was c. 19–21 DAE typical for many varieties). For other varieties, due to the effects of N on DM partitioning there was a substantial delay in the onset of tuber bulking which may only be recouped by extending the growing season.

	Apparent onset of tuber bulking (DAE)	
Variety	**0 kg N/ha**	**180 kg N/ha**
Bonnie	21.8	23.5
Chopin	22.4	25.0
Crisps4all	20.0	28.4
Estima	21.4	21.8
Maris Piper	23.3	28.5
Markies	19.4	32.6
Vales Sovereign	23.3	25.2
Mean for N	21.7	26.4
Grand mean	24.0	
S.E. (39 D.F.)	0.68 (N); 1.79 (Variety*N)	

TABLE 45. EFFECTS OF VARIETY AND N APPLICATION RATE ON APPARENT ONSET OF TUBER BULKING

Parameters of total N uptake and tuber N uptake are given in Table 46. The asymptotic value for total N uptake averaged 223 kg N/ha and was increased from 163 to 283 kg N/ha when the N application rate was increased from 0 to 180 kg N/ha. At Babraham, where the crops received 200kg N/ha, the total N uptakes of Bonnie, Estima and Maris Piper were 240, 174 and 230 kg N/ha, respectively. Comparable values at CUF (with 180 kg N/ha) were 306, 247 and 286 kg N/ha. At CUF, the mean rate of tuber N uptake was 15.1 kg N/TJ and was increased by 6 kg N/TJ by increasing the N application rate. When averaged over all treatment combinations, maximum haulm N uptake was 100 kg N/ha and increasing the N application rate from 0 to 180 kg N/h increased haulm N uptake from 70 to 130 kg N/ha. When 180 kg N/ha had been applied, haulm N uptakes in excess of 135 kg N/ha were achieved by Bonnie, Maris Piper, Markies and Vales Sovereign but maximum haulm N uptakes of Chopin and Estima were much smaller and averaged 108 kg N/ha.

Variety	kg N/ha	Rate of tuber N uptake (kg N/TJ)	Tuber N uptake at 6 TJ/ha (kg N/ha)	Asymptotic value of total N uptake (kg N/ha)	Maximum haulm N uptake (kg N/ha)
Bonnie	0	12.0	61	173	69
	180	16.6	81	306	137
Chopin	0	14.1	75	145	68
	180	21.3	105	270	112
Crisps4all	0	12.2	57	147	67
	180	18.9	80	283	126
Estima	0	12.8	66	140	71
	180	19.4	99	247	104
Maris Piper	0	10.5	53	178	82
	180	17.5	76	286	138
Markies	0	11.1	56	161	61
	180	18.0	73	321	145
Vales Sovereign	0	12.3	60	194	73
	180	15.3	72	271	151
Mean	0	12.1	61	163	70
Mean	180	18.1	84	283	130
Grand mean		15.1	72	223	100
S.E. (39 D.F.)		0.28 (N) 0.75 (V×N)	1.2 (N) 3.1 (V×N)	5.6 (N) 14.9 (V×N)	3.1 (N) 8.3 (V×N)

TABLE 46. PARAMETERS OF TUBER AND TOTAL N UPTAKE FOR SEVEN VARIETIES. INDETERMINATE VARIETIES ARE ASSOCIATED WITH LARGE RATIOS OF HAULM N UPTAKE : RATE OF TUBER N UPTAKE

The ratio of maximum haulm N uptake to the rate of tuber N uptake gives an indication of canopy persistence and determinacy. When 180 N/ha had been applied, this ratio ranged from 5.3 and 5.5 in Chopin and Estima to 9.9 in Vales Sovereign (Table 47).

	Existing determinacy group (RB 209 7th edition)	Ratio of maximum haulm N uptake to rate of tuber N uptake	Proposed determinacy group
Bonnie	-	8.3	3
Chopin	-	5.3	1
Crisps4all	-	6.7	2
Estima	1	5.5	1
Maris Piper	3	7.9	3
Markies	-	8.1	3
Vales Sovereign	-	9.9	3-4
Mean	-	7.4	-
S.E.	-	0.60	-

TABLE 47. EXISTING AND PROPOSED DETERMINACY GROUPS BASED ON RATIO BETWEEN MAXIMUM HAULM N UPTAKE AND RATE OF TUBER N UPTAKE IN CROPS GIVEN 180 KG N/HA

Using Estima (Determinacy Group 1) and Maris Piper (Determinacy Group 3) as controls, these ratios suggest that Chopin should be fertilized in a similar way to Estima, Crisp4all should be Determinacy Group 2 (i.e. fertilized in a similar way to Lady Rosetta) whilst Markies and Bonnie are similar to Maris Piper. Vales Sovereign may be more indeterminate than Group 3 varieties and may need less N than Maris Piper for a similar season length.

10.2. Conclusion

This experiment has shown that information on varietal difference in N uptake and redistribution can by used to rapidly allocate new varieties into Determinacy Groups so that N fertilizer requirements can be optimised without the need for extensive, empirical N response experiments. These initial allocations of varieties to groups can be revised using information from growers and agronomists when the varieties are grown extensively.

11. CUF 2010

11.1. Results and Discussion

11.1.1. Emergence, ground cover development and radiation absorption

When averaged over N treatments, the mean date of 50 % emergence for Crisps4all, Estima, and Russet Burbank was 22, 23 and 23 May (38, 39 and 39 DAP), respectively. Increasing the N application rate from 0 to 375 kg N/ha had no statistically significant effect on the date of 50 % plant emergence in any variety as was the case in 2009. On average, near-complete (> 98 %) plant emergence was achieved in all treatment combinations.

When no N was applied, no variety achieved complete ground cover (Figure 15). The rate of expansion was not significantly affected by variety. However, the average rate of ground cover expansion between 20 and 80 % was 2.5 %/day when no N was applied compared with 4.1 %/day when 250 kg N/ha had been applied. The effects of N application rate on canopy persistence and season-long radiation absorption are shown in Table 48. When no N had been applied, Estima had a much smaller integrated ground cover than either Crisps4all or Russet Burbank. Increasing the application rate from 0 to 375 kg N/ha, increased integrated ground cover by c. 2000 % days in Crisps4all and Estima but by a smaller amount in Russet Burbank. When averaged over the N treatments, Crisps4all absorbed c. 2.5 TJ/ha more solar energy than Estima with Russet Burbank absorbing an intermediate amount.

Ground cover	Nitrogen application rate (kg N/ha) 0	125	250	375	Mean
Crisps4all	7406	8158	8950	9449	8491
Estima	5425	6872	7195	7724	6804
Russet Burbank	7102	8212	8175	8762	8063
Mean	6644	7748	8107	8645	7786
	S.E. (33 D.F.) Variety, 124.7; N rate, 144.0; Variety and N rate 249.5				
Radiation					
Crisps4all	12.32	13.67	14.74	15.26	14.00
Estima	9.33	11.77	12.15	12.86	11.53
Russet Burbank	11.70	13.31	13.25	13.92	13.05
Mean	11.12	12.92	13.38	14.01	12.86
	S.E. (33 D.F.) Variety, 0.170; N rate, 0.196; Variety and N rate 0.339				

TABLE 48. EFFECT OF VARIETY AND N APPLICATION RATE ON SEASON-LONG INTEGRATED GROUND COVER (% DAYS) AND RADIATION ABSORPTION (TJ/HA), CUF 2010

11.2. Yields at final harvest

A final sample was taken on 7 October (137 DAE) when all crop canopies had completely senesced. The average mainstem populations for Crisps4all, Estima and Russet Burbank were 238, 109 and 72 000/ha, respectively. Tuber populations > 10 mm for Crisps4all, Estima and Russet Burbank averaged 574, 427 and 331 000/ha, respectively. Neither stem nor tuber population > 10 mm were significantly affected by N application rate. On average, Crisps4all had the greatest tuber DM concentration (25.6 %) and Estima the least (19.9 %) whilst Russet Burbank was intermediate (22.9 %). On average, increasing the N application rate from 0 to 375 kg N/ha decreased tuber DM concentration from 23.2 to 22.1 %. Once the standard error of the mean is taken into account, the optimum N application rates for FW yield for Crisps4all and Estima were probably between 125 and 250 kg N/ha whilst for Russet Burbank the optimum N application rate was c. 125 kg N/ha (Table 49).

	Nitrogen application rate (kg N/ha) 0	125	250	375	Mean
Crisps4all	45.2	56.9	63.8	64.6	57.6
Estima	51.9	68.1	74.8	73.8	67.1
Russet Burbank	48.2	59.1	53.3	56.7	54.3
Mean	48.4	61.4	64.0	65.0	59.7

S.E. (33 D.F.) Variety, 1.81; N rate, 2.09; Variety and N rate 3.61

TABLE 49. EFFECT OF VARIETY AND N APPLICATION RATE ON TUBER FW YIELD > 10 MM (T/HA)

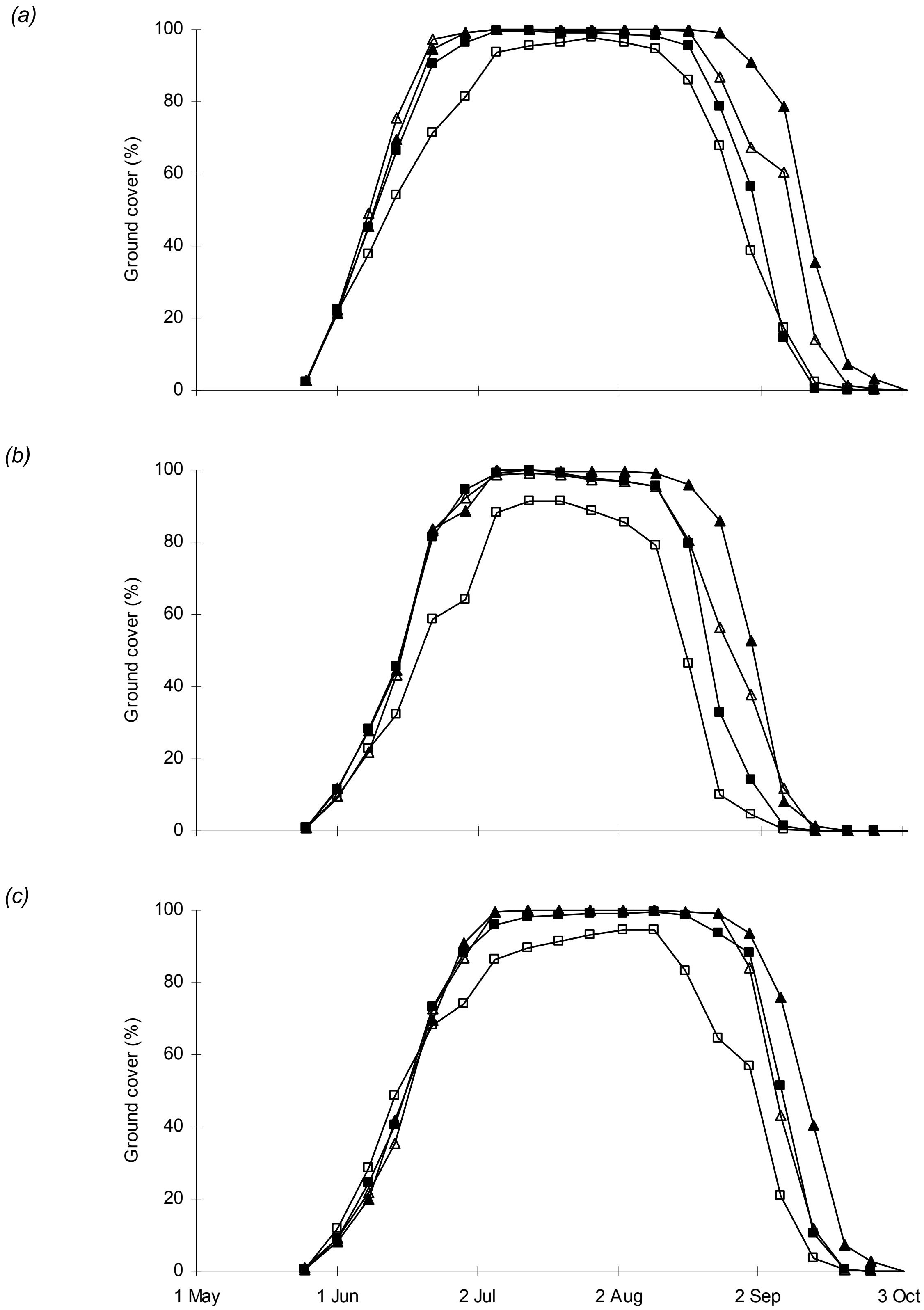


FIGURE 15. GROUND COVER DEVELOPMENT IN (A) CRISPS4ALL, (B) ESTIMA AND (C) RUSSET BURBANK. NITROGEN APPLIED (KG N/HA) 0, □; 125, ■; 250, △ OR 375, ▲.

11.2.1. Efficiency of total and tuber dry matter production

The efficiency with which crops convert absorbed solar radiation into total DM yield is a key step in yield production. The average RUE for all treatment combinations was 1.30 t DM/TJ (Table 50) and this was reasonably consistent with values found in previous seasons at CUF. Varietal differences in RUE, whilst statistically significant, were relatively small and increasing the N application rate from 0 to 375 kg N/ha had no significant effect on RUE. Nitrogen application rate had no statistically significant effect on the efficiency of tuber DM production, however Estima was more efficient than either Crisps4all or Russet Burbank (1.30 compared with 1.18 and 1.06 t DM/TJ, respectively). On average, the onset of tuber bulking was earliest in Estima and latest in Russet Burbank (Table 50). For Estima, increasing the N application rate from 0 to 125 kg N/ha delayed tuber bulking but thereafter the effects of N were small. For Crisps4all and Russet Burbank the onset of tuber bulking tended to be progressively delayed as the N rate was increased to 375 kg N/ha.

	Nitrogen application rate (kg N/ha)				
RUE	**0**	**125**	**250**	**375**	**Mean**
Crisps4all	1.14	1.33	1.32	1.30	1.27
Estima	1.30	1.39	1.40	1.40	1.37
Russet Burbank	1.26	1.32	1.24	1.16	1.25
Mean	1.24	1.35	1.32	1.29	1.30
	S.E. (33 D.F.) Variety, 0.025; N rate, 0.029; Variety and N rate 0.050				
Onset of bulking					
Crisps4all	20.0	25.5	26.6	28.2	25.1
Estima	17.9	24.2	23.8	21.5	21.9
Russet Burbank	22.2	26.3	25.7	27.0	25.3
Mean	20.0	25.3	25.4	25.6	24.1
	S.E. (33 D.F.) Variety, 1.07; N rate, 1.24; Variety and N rate 2.14				

TABLE 50. EFFECT OF VARIETY AND N APPLICATION RATE ON SEASON-LONG RADIATION USE EFFICIENCY (T DM/TJ) AND ONSET OF BULKING (DAE)

The effects of N application rate on the apparent onset of tuber bulking have been documented before and the delay of between 5 and 8 days can result in loss of yield particularly where the potential growing season is constrained (e.g. by rapidly decreasing incident radiation receipts in September). The delay in tuber bulking may also explain, in part, the effects of N application rate on tuber DM concentration. The relationship between tuber DM and days after emergence for data from 2005 to 2010 was analysed by fitting intersecting straight lines of each variety and N combination. On average, these regressions explained c. 90 % of the variation in tuber DM concentration. This showed that increasing the N application rates from 0 to 100 and 200 (in 2005) or 125 and 250 kg N/ha (in 2006-2010) slowed the rate of increase in tuber DM concentration and the final achieved tuber DM (Figure 16 and Table 51) and the effects of N on these parameters were larger in Russet Burbank than in Estima.

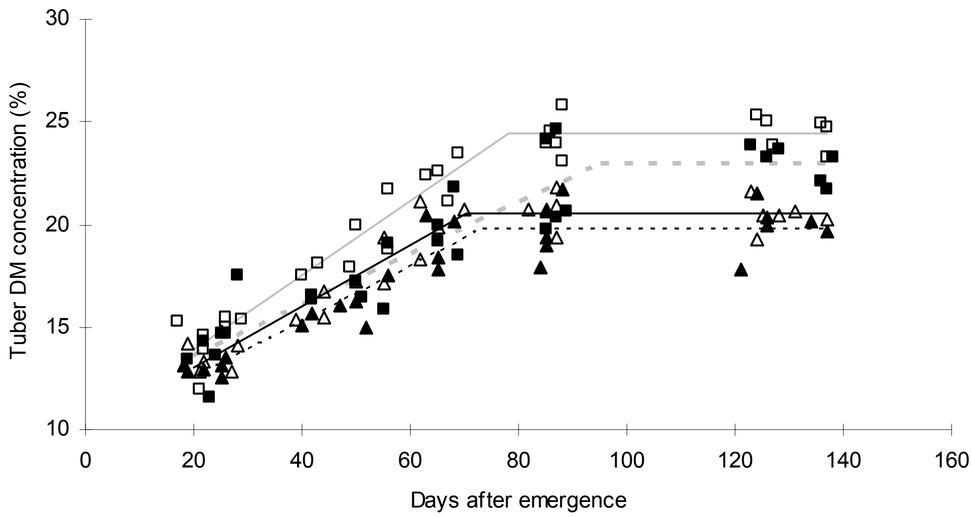


FIGURE 16. EFFECT OF VARIETY AND N APPLICATION RATE ON CHANGES IN TUBER DRY MATTER (DM) CONCENTRATION IN CROPS GROWN AT CUF IN 2005-2010. ESTIMA-N0, △ AND BLACK SOLID LINE; ESTIMA-N200/N250, ▲ AND BLACK DASHED LINE; RUSSET BURBANK-N0, □ AND GREY SOLID LINE AND RUSSET BURBANK-N200-N250, ■ AND GREY DASHED LINE.

Variety **N application rate (kg N/ha)**	**Estima** **0**	 **100-125**	 **200-250**	**Russet Burbank** **0**	 **100-125**	 **200-250**
Final tuber DM (%)	20.5 ±0.27	20.0 ±0.35	19.8 ±0.32	24.4 ±0.30	23.5 ±0.47	23.0 ±0.61
Date of achieving maximum DM (DAE)	70 ±3.4	72 ±4.5	73 ±4.5	78 ±3.4	91 ±4.8	94 ±6.8
Rate of increase in DM (%/day)	0.15 ±0.013	0.15 ±0.016	0.14 ±0.014	0.18 ±0.014	0.14 ±0.010	0.13 ±0.013
Estimate of tuber DM at 70 DAE (%)	20.5 ±0.42	19.6 ±0.53	19.4 ±0.49	22.9 ±0.45	20.5 ±0.30	19.9 ±0.39

TABLE 51. EFFECT OF VARIETY AND N APPLICATION RATE ON TUBER DRY MATTER (DM) CONCENTRATION AT CUF, 2005-2010

11.2.2. Nitrogen uptake and redistribution in relation to radiation absorption

The rate of tuber N uptake, in relation to radiation absorption, is a key component of the CUF N model since it represents the rate at which N reserves within the canopy are depleted and this is a factor controlling canopy persistence. In order to compare varieties in terms of their N uptakes and redistribution characteristics, it is first necessary to check that observed yields are largely explicable in terms of the amount of radiation absorbed by the canopies, the efficiency with which the absorbed radiation is converted to DM and the partitioning of the DM between haulm and tubers. The CUF model was parameterised using data from the second harvest 12 July (c. 50 DAE) and used to predict yields at the third, fourth and fifth samplings. In general, there was good agreement between observed and modelled yields (Figure 17). The average (n=36) observed yield was 51.8 t/ha compared with an average, modelled yield of 50.6 t/ha. Analysis indicated that most of the variation between observed and modelled yield was due to random 'error' instead of systematic bias. These data suggest that yield formation was closely related to canopy persistence and radiation absorption and was not unduly affected by factors such as water or heat stress or disease.

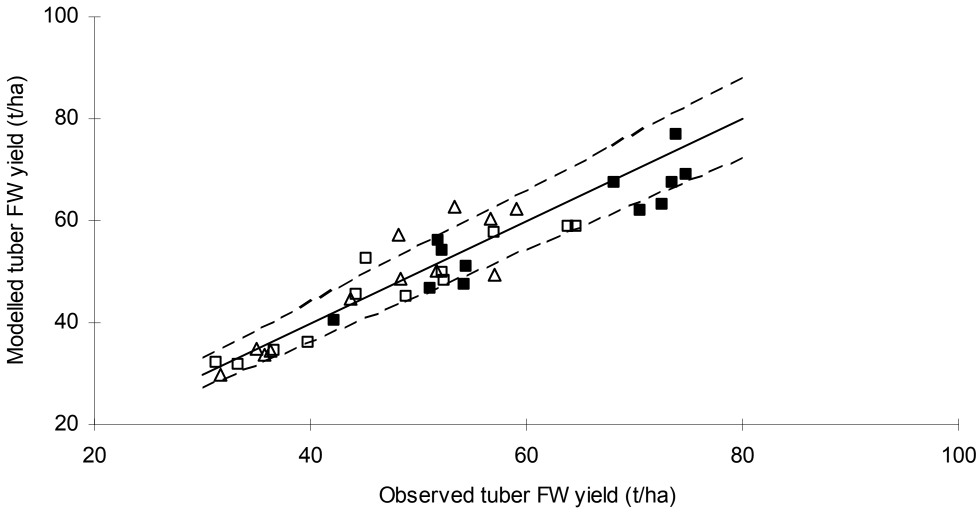


FIGURE 17. RELATIONSHIP BETWEEN MODELLED AND OBSERVED YIELD FOR CRISP4ALL (□); ESTIMA (■) AND RUSSET BURBANK (△). SOLID LINE IS 1 : 1 RELATIONSHIP AND DASHED LINES ARE ± 10 %.

On average, increasing the N application rate from 0 to 375 kg N/ha increased the rate of tuber N uptake from 12.3 to 19.3 kg N/TJ (Table 52). The rate of tuber N uptake for Crisps4all was intermediate between that of Estima and Russet Burbank. Therefore for similar haulm N uptakes, the expected sequence of canopy senescence would be Estima followed by Crisps4all and finally Russet Burbank.

	Nitrogen application rate (kg N/ha)				
	0	**125**	**250**	**375**	**Mean**
Crisps4all	11.4	17.1	19.4	20.5	17.1
Estima	13.2	19.0	20.2	19.2	17.7
Russet Burbank	11.9	15.9	16.2	18.3	15.6
Mean	12.3	17.3	18.6	19.3	16.8

S.E. (33 D.F.) Variety, 0.55; N rate, 0.64; Variety and N rate 1.11

TABLE 52. EFFECT OF VARIETY AND N APPLICATION RATE ON RATE OF TUBER N UPTAKE IN RELATION TO RADIATION ABSORPTION (KG N/TJ)

Increasing the N application rate from 0 to 375 kg N/ha increased average total N uptake from 157 to 330 kg N/ha (Table 53). As the N application rate was increased, total N uptake increased to a larger extent in Crisps4all and Russet Burbank than in Estima and when 375 kg N/ha had been applied the difference in total N uptake was 60-70 kg N/ha. Similar varietal differences and effects of N application rate were evident in the effects of treatments on estimates of maximum haulm N uptake as for maximum total N uptake (Table 53).

Total N	Nitrogen application rate (kg N/ha) 0	125	250	375	Mean
Crisps4all	155	257	316	359	272
Estima	139	249	268	289	236
Russet Burbank	179	239	270	344	258
Mean	157	248	287	330	255
	S.E. (33 D.F.) Variety, 9.8; N rate, 11.4; Variety and N rate 19.7				
Haulm N					
Crisps4all	65	125	158	190	135
Estima	61	102	118	141	106
Russet Burbank	64	108	160	166	124
Mean	63	112	146	166	122
	S.E. (33 D.F.) Variety, 3.8; N rate, 4.4; Variety and N rate 7.6				

TABLE 53. EFFECT OF VARIETY AND N APPLICATION RATE ON ESTIMATED MAXIMUM TOTAL OR HAULM N UPTAKE (KG N/HA)

When no N was applied, varietal differences in maximum total and maximum haulm N uptake were small and not statistically significant but a key difference between varieties appears to be the response to N when it is in plentiful supply. Table 54 summarises estimates of maximum total N uptake for Estima and Russet Burbank in several experiments where N application varied from 0 to 200 or 375 kg N/ha. When no N was applied, the average maximum total N uptake was similar in both Estima and Russet Burbank. These data also show that, on average, Estima and Russet Burbank have similar capacities to 'scavenge' N from the soil and thus varietal differences in N requirement do not appear to be related to how well they exploit the soil N supply (SNS). When large amounts of N fertilizer were applied, the average total N uptake of Estima increased to 254 kg N/ha whilst that of Russet Burbank increased to 282 kg N/ha. For Estima, in the presence of large amounts of N (from SNS + fertilizer), total N uptake did not exceed 290 kg N/ha in any year whilst for Russet Burbank it increased to more than 325 kg N/ha in 2009 and again in 2010. Whilst this is a relatively limited data set, it suggests that a difference between varieties may be their capacity to take up N relatively early in the season for use at a later point. A key question is why, when plenty of N was available, the total N uptake of Estima and Russet Burbank was so variable between seasons. In part, the variation in total N uptake is due to variation in the relationship between crop N uptake and the availability of N from the soil. This relationship for Estima and Russet Burbank is shown in Figure 18. The soil N supply (SNS) was assumed to be equivalent to the total N uptake of crops that received no N fertilizer. For Estima, 65 % of the variation in total N uptake was explained by variation in SNS + fertilizer N whereas for Russet Burbank 63 % of the variation was explained. For a total N supply (SNS + fertilizer N) of 300 kg N/ha, the expected N uptake in Estima would be 213 (± 7.4) kg N/ha compared with 215 (± 10.1) kg N/ha in Russet Burbank and thus at typical values of nitrogen availability, varietal difference in N uptake are small. These data also suggest that about two thirds of the variation in total N uptake (and hence yield potential) may be explicable by considering the variation in soil N supply. From 2005 to 2010, the average N uptake of unfertilized Estima was 131 (± 14.2) kg N/ha and 149 (± 9.4) kg N/ha for Russet Burbank. All these crops were grown on mineral soils at CUF, followed cereal crops and organic manures had not been applied within the rotation for many years (although soil organic matter concentrations are relatively high when compared to many arable soils). In consequence, the SNS indices for these fields were 0 or 1 and they should have supplied < 100 kg N/ha to the potato crop. Therefore, on average, the current recommendation system underestimates of SNS but the main problem remains year-to-year variation in SNS, which results in variation in total N uptake and variation in response to fertilizer. The variation in SNS may be due to variation in soil organic matter and texture, timing of cultivations and soil conditions within the ridge. Future studies will attempt to quantify the importance of these factors which will lead to improved fertilizer recommendations.

	Estima		**Russet Burbank**		
	0 kg N/ha	**Nmax**	**0 kg N/ha**	**Nmax**	**S.E.**
2004	147	275	152	277	15.3
2005	107	181	114	194	9.5
2006	168	257	162	317	14.0
2007	63	233	127	230	14.1
2008	122	271	133	248	13.4
2009	171	270	177	364	13.8
2010	139	289	179	344	19.7
Mean	131	254	149	282	

TABLE 54. COMPARISON OF ESTIMATES OF MAXIMUM TOTAL N UPTAKE IN ESTIMA AND RUSSET BURBANK GROWN AT CUF 2004-2009. IN 2004 AND 2005 THE MAXIMUM N APPLICATION RATE (NMAX) WAS 200 KG N/HA IN OTHER YEARS IT WAS 375 KG N/HA

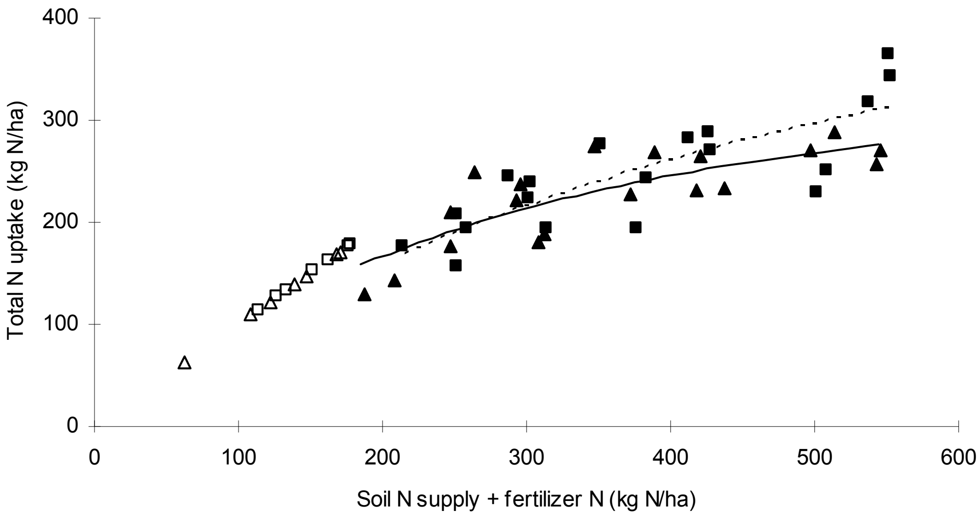


FIGURE 18. RELATIONSHIP BETWEEN MAXIMUM TOTAL N UPTAKE AND N SUPPLIED FROM SOIL AND FERTILIZER. ESTIMA WITHOUT N FERTILIZER, △; ESTIMA WITH N FERTILIZER, ▲; RUSSET BURBANK WITHOUT N FERTILIZER, □ AND RUSSET BURBANK WITH N FERTILIZER ■. SOLID LINE IS FITTED RELATIONSHIP FOR ESTIMA AND DASHED LINE IS FITTED RELATIONSHIP FOR RUSSET BURBANK.

11.3. Conclusions

This experiment has provided further information on varietal differences in N accumulation and N redistribution. These relationships, between rate of total N uptake and maximum total N uptake, are important because they explain some of the differences in varietal response to fertilizer. Furthermore, these data will be useful in modelling the relationship between canopy persistence, total N uptake and, in principal, N applied. Using these data, it should be possible to devise fertilizer recommendations on the basis of a crop's physiological response to N rather than many empirical N response studies.

12. FACTORS LIMITING YIELD PRODUCTION

12.1. Introduction

The aim of this was to establish what factors may be limiting yield formation and how resources (particularly nitrogen (N)) may be used more efficiently. The work involved a combination of monitoring of commercial crops, soil sampling to measure soil mineral N (SMN) and to identify problems (i.e. compaction), modelling of yield formation and N uptake and N response experiments. Thus the monitoring of commercial crops and experiments aims to answer the following, interlinked questions:

1. Can the commercial crops be modelled using the CUF yield model? If not, this suggests that yield formation may be limited by factors that are not explicitly accounted for within the model e.g. water and heat stress, disease and poor soil conditions.
2. Using the CUF N model, can it be established whether the crops took up sufficient N to have an adequate yield potential? If not, then N uptake may have been limited by an inadequate N supply or a failure to take up adequate N from the soil. Soil sampling for SMN and the nitrogen response experiments will provide information on whether the crops were N deficient. Penetrometer readings will help quantify locations where soil compaction may be hindering root function and, in turn, water and nutrient uptake.
3. If N uptake was adequate, was the yield potential created at the start of the season realised? If not, this suggests that yield formation was limited during the latter part of the season and this may have been due to factors such as foliage disease or water stress.
4.

12.2. Material and Methods common to studies in commercial crops

12.2.1. Commercial crop sampling

Emergence and ground cover development of the commercial crops was measured by Spearhead staff as part of the CUF irrigation scheduling system. The commercial crops were sampled, by CUF staff, on three occasions during the growing season. At each harvest four replicate areas each 3 m by one row (2.74 m2) were taken from representative areas of the commercial crop. The number of plants and stems was recorded and all tubers > 10 mm were collected. The weight of the haulm was recorded in the field using a portable electronic balance and a representative sub-sample (c. 1 kg) of haulm was retained and returned to CUF with the tubers. The tubers were graded in 10 mm increments and the number and weight of tubers in each grade was recorded. A sub-sample of tubers (c. 1 kg) was taken from the 50-60 mm grade, washed, chipped, weighed and then dried at 90 °C, together with the haulm sub-sample, to constant weight to calculate tuber and haulm DM concentration. The dried material was then sent to a commercial laboratory for total N analysis.

12.2.2. Soil sampling for soil mineral N and soil penetration resistance

Soil samples were taken from areas adjacent to where the commercial crops were sampled. To give an indication of the spatial variation in soil mineral N and penetration resistance, the soils were sampled as shown in Figure 19. Soil samples for soil mineral N were taken to a depth of 90 cm, split into 30 cm increments. The soil samples were kept cool during transit and were analysed within 48 hours of sampling by a commercial laboratory. Penetration resistance was measured using an Eijkelkamp Penetrograph recording penetrometer using a 1 cm2 cone tip.

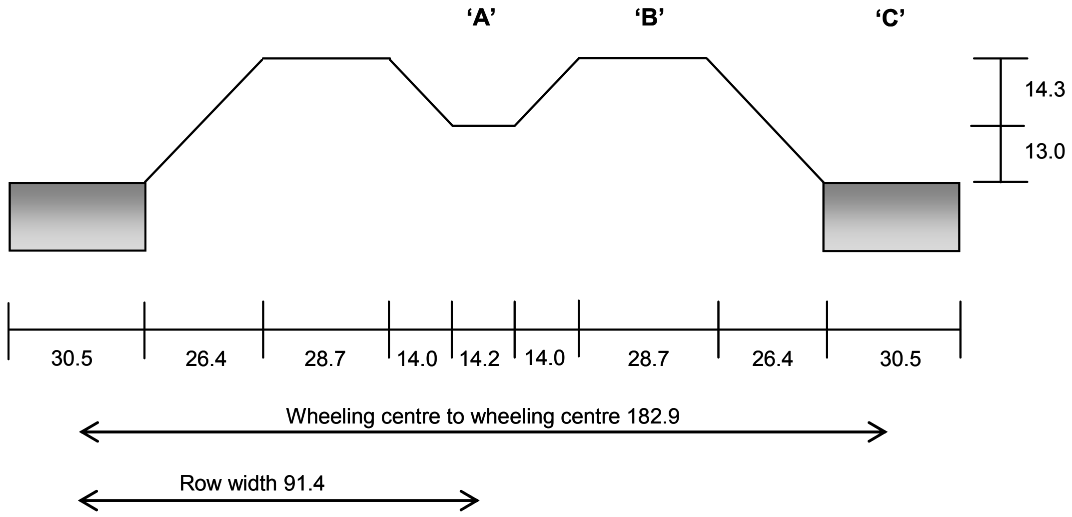


FIGURE 19. DIAGRAM SHOWING LOCATION OF SOIL SAMPLES FOR SOIL MINERAL N AND SOIL PENETRATION RESISTANCE. POSITION 'A', IN CENTRE OF BED; POSITION 'B', IN CENTRE OF RIDGE AND POSITION 'C', IN CENTRE OF WHEELING. DIMENSIONS ARE IN CM AND ARE AVERAGES FROM FIVE REPLICATE MEASUREMENTS AT TWO SITES.

12.2.3. Modelling of yield development

The CUF yield model was used to simulate tuber yield production and analysis of differences between modelled and observed yields (both hand-sampled and commercially harvested) can be used to identify possible causes of loss of yield potential. The main inputs to the CUF yield model were ground covers measured at each site and incident solar radiation. For both Lady Rosetta crops, radiation data were obtained from Broom's Barn, Higham, Suffolk. At Buchers and Knights, the final ground cover readings were taken on 11 and 18 August, respectively and, in consequence, canopy senescence was modelled.

13. SPEARHEAD 2008, LADY ROSETTA AND COURAGE

13.1. Material and Methods specific to 2008

The work was done at sites on land rented by Spearhead International Ltd of Burwell, Cambridgeshire, and was used for the production of processing crops. Some details of these two sites are given in Table 55.

Site and field	Variety	Start of planting	OS Grid	Total N applied (kg N/ha)
Buchers, Woodyard	Lady Rosetta	13 March	TL 974792	250
North Whinns	Courage	8 April	TF 863075	250

TABLE 55. SITE DETAILS FOR COMMERCIAL CROPS GROWN BY SPEARHEAD

13.1.1. Nitrogen response experiments

At each site an N-response experiment tested the effect of N application rate on tuber FW yield. Each experiment tested eight rates of N (0 to 280 kg N/ha in 40 kg N/ha increments) and each treatment was replicated four times and allocated at random to blocks. Both N-response experiments were machine planted and it was not possible to omit the pre-plant application of N from the experiment areas so the N-response experiments were superimposed on a uniform application of 130 kg N/ha at both Buchers and North Whinns. Each plot was four rows (3.66 m) wide and 7.0 m long. A single harvest was taken on 29 August (Lady Rosetta) and 12 September (Courage). The N treatments were applied, by hand, on 8 May using ammonium nitrate. At harvest, a 3 m length of row was harvested from row two of each four row plot and a discard area of c. 2 m was left at each end of the harvest area. For each plot, the number of plants and stems was recorded and tubers > 10 mm were collected and returned to CUF for grading. Samples and data were processed as described on page 13.

13.2. Results and Discussion

13.2.1. Emergence and ground covers

For the Lady Rosetta crop at Buchers, the first plants emerged on 9 May and 50 % plant emergence was achieved on 12 May. For the Courage crop at North Whinns, first emergence was recorded on 10 May and 50 % plant emergence on 12 May. Both Lady Rosetta and Courage attained complete (100 %) ground cover (Figure 20.) Despite having a similar emergence date, the initial ground cover expansion of Courage was slower than that of Lady Rosetta but it was more persistent.

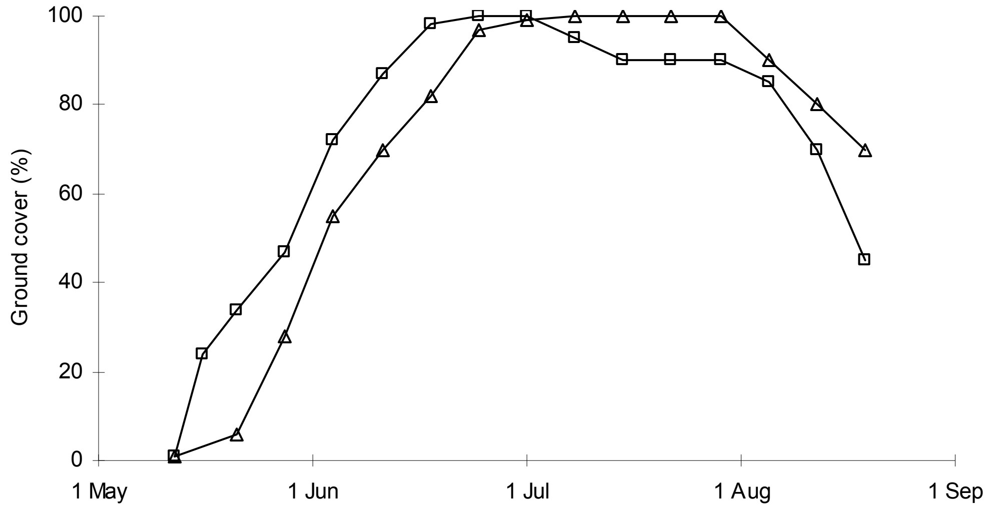


FIGURE 20. GROUND COVER DEVELOPMENT FOR LADY ROSETTA, WOODYARD (□) AND COURAGE, NORTH WHINNS (△).

13.2.2. Commercial crop sampling

Each commercial crop was sampled on three occasions during the season. For Lady Rosetta, stem and tuber populations were reasonably consistent at each harvest (Table 56) and were similar to those found in the replicated N-response experiment (see Table 58). Total tuber FW yield increased from c. 9 t/ha at the first sampling to 54 t/ha at the final sampling. Total DM yield and N uptake at the end of the season were 13.5 t/ha and 184 kg N/ha, respectively. The stem population at the first sampling of the Courage crop was larger than at subsequent harvests (Table 57). However, the tuber population at the first sampling was much smaller and this suggests that the first sampling was taken whilst the crop was still initiating. The commercial Courage crop at North Whinns achieved a final, total FW yield of 66 t/ha. The total DM yield of the Courage crop at final harvest was larger than that of the Lady Rosetta crop as was the N uptake (Table 57).

Date of sampling	**Stem population (000/ha)**	**Tuber population > 10 mm (000/ha)**	**Tuber FW yield > 10 mm (t/ha)**	**Total DM yield (t/ha)**	**Total N uptake (kg N/ha)**
10 June	137 (± 7.1)	733 (± 51.9)	8.5 (± 0.64)	3.33 (± 0.130)	98 (± 6.1)
2 July	130 (± 5.8)	744 (± 64.3)	30.1 (± 2.20)	9.20 (± 0.248)	133 (± 4.0)
29 August	125 (± 1.7)	625 (± 39.3)	54.2 (± 1.92)	13.46 (± 0.569)	184 (± 7.2)

TABLE 56. COMPONENTS OF YIELD AND N UPTAKE OF LADY ROSETTA, BUCHERS

Date of sampling	Stem population (000/ha)	Tuber population > 10 mm (000/ha)	Tuber FW yield > 10 mm (t/ha)	Total DM yield (t/ha)	Total N uptake (kg N/ha)
10 June	164 (± 9.3)	339 (± 41.1)	1.2 (± 0.26)	1.45 (± 0.093)	62 (± 4.0)
2 July	140 (± 7.5)	664 (± 51.3)	25.4 (± 3.77)	6.85 (± 0.86)	143 (± 25.8)
11 September	147 (± 3.1)	674 (± 19.9)	65.5 (± 2.32)	16.59 (± 0.761)	192 (± 5.1)

TABLE 57. COMPONENTS OF YIELD AND N UPTAKE OF COURAGE, NORTH WHINNS

13.2.3. Modelling of yield development

The CUF yield model was used to simulate tuber yield production and analysis of differences between modelled and observed yields can be used to identify possible causes of loss of yield potential. The main inputs to the CUF yield model were ground covers measured at each site and incident solar radiation. For the Lady Rosetta crop, radiation data were obtained from Broom's Barn, Higham, Suffolk and for the Courage crop it was obtained from a meteorological station at South Pickenham operated by David Martin Associates. For both sites, the final reading of ground cover was taken on 20 August and the exact pattern of canopy senescence until final harvest in not known. Despite this limitation, the CUF yield model produced reasonably good simulations of tuber yield development at both sites (Figure 21). At Buchers, the model overestimated yield and whilst this may be a consequence of insufficient ground cover data, it may also mean that yield at this site was limited by factors not accounted by the model i.e. disease or water stress. However, for both sites tuber FW yields were reasonably well correlated with the amount of radiation absorbed by the crop and to canopy persistence. Thus, factors such as insufficient or excess water and diseases that can reduce yield by reducing radiation utilization efficiency were probably of limited significance.

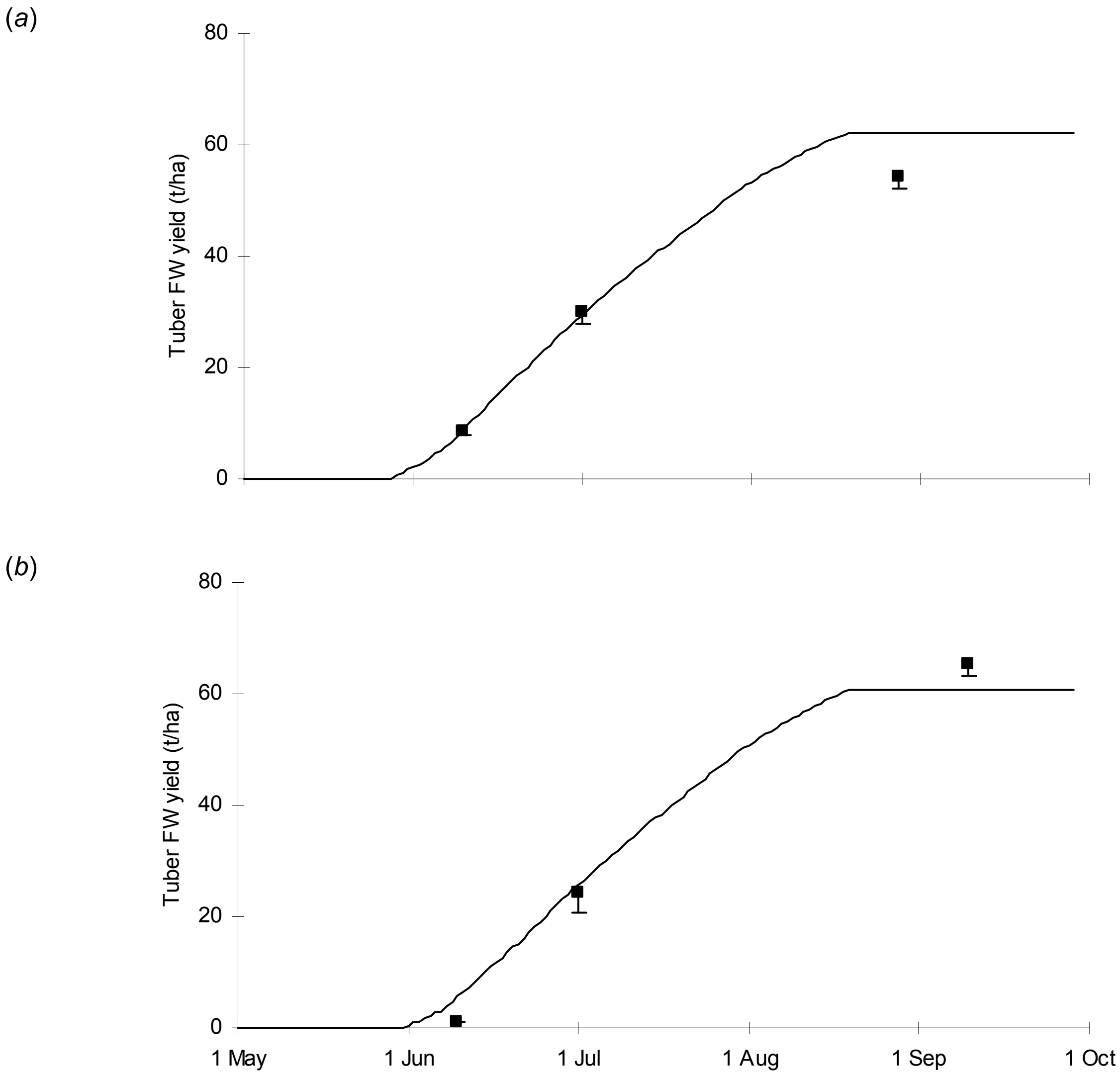


FIGURE 21. COMPARISON MODELLED YIELD (BLACK LINE) AND SAMPLED YIELD (■ AND 1 S.E.) FOR (A) LADY ROSETTA AT BUCHERS AND (B) COURAGE AT NORTH WHINNS

13.2.4. Crop nitrogen uptake and canopy persistence

Analysis using the CUF yield model showed that the yield of both crops was mainly related to canopy persistence and, in turn, radiation absorption. The next stage of the analysis was to investigate whether canopy persistence could be explained in terms of total N uptake and the rates of redistribution of N from the haulm to the tubers. The rate of tuber N uptake in relation to radiation absorption was estimated from linear regression and the asymptotic values for total N uptake were estimated from fitting exponential curves. These data show (Figure 22) that the rate of tuber N uptake in Lady Rosetta was slower than that of Courage (13.4 compared with 16.6 kg N/TJ) and it also had a smaller total N uptake than Courage (174 compared with 197 kg N/ha). Crops with large yield potentials typically have total N uptake in excess of 220-250 kg N/ha. Using these data, the CUF N model estimated that the Lady Rosetta crop had the potential to absorb c. 12.7 TJ/ha of energy before the canopy was completely senesced compared with c. 12.3 TJ/ha for the Courage crop. These predictions were reasonably similar to the measured values (13.6 and 12.4 TJ/ha for Lady Rosetta and Courage, respectively). This suggests that these crops achieved the potential set by their N uptake and thus they did not senesce prematurely as a consequence of water stress or disease. Since yield potential is governed largely by total N uptake, it would seem that the performance of these crops was mainly limited by their inability to take up sufficient N.

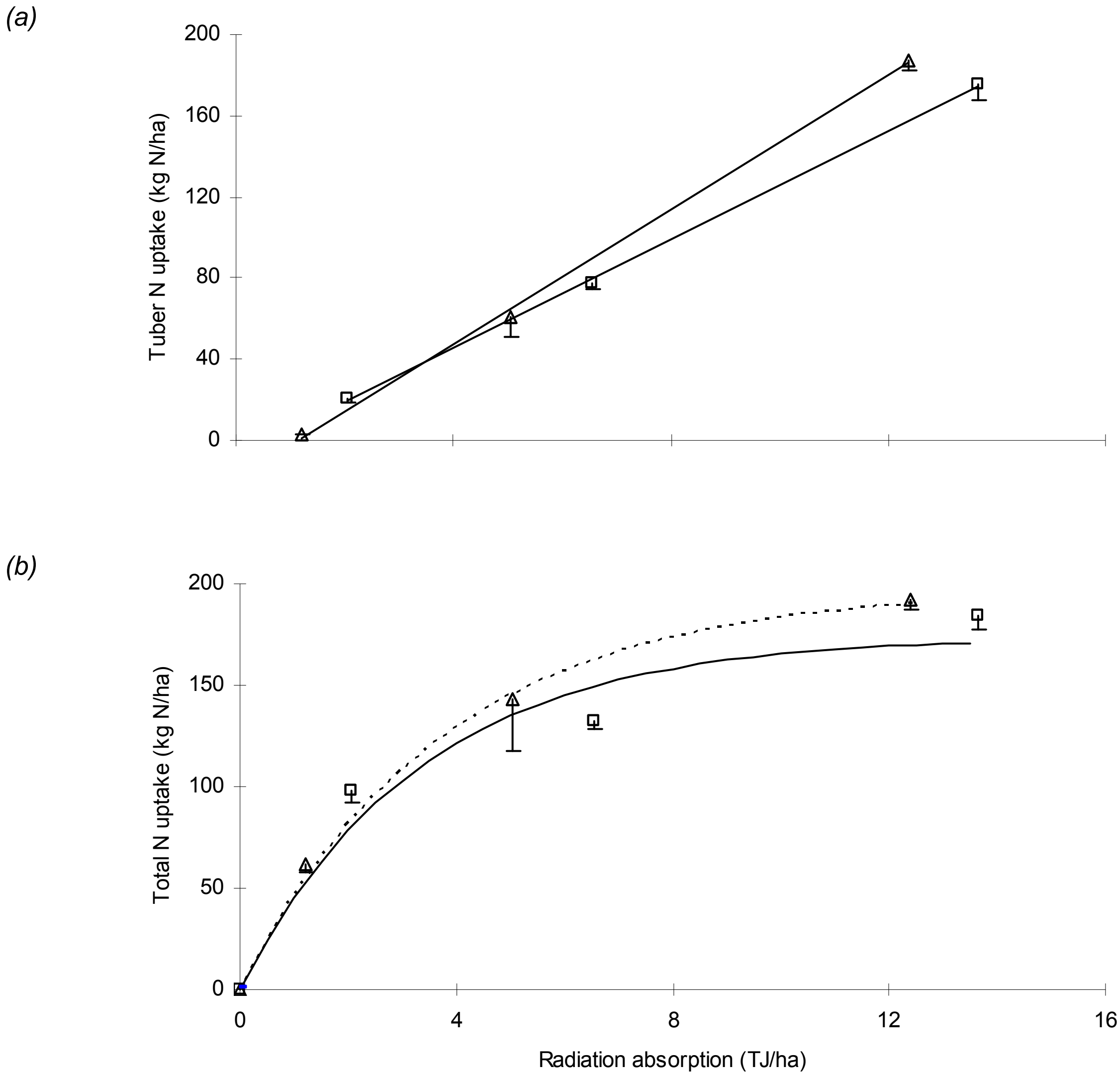


FIGURE 22. NITROGEN UPTAKE BY TUBERS (A) AND TOTAL (B). MEASURED AND FITTED REGRESSION VALUES FOR LADY ROSETTA (□ AND SOLID LINES) AND COURAGE (△ AND DASHED LINES).

13.2.5. Nitrogen response experiments

The next stage of the analysis was to test whether crop N uptake (and therefore yield potential) was limited by N applications that were too small. This was tested by doing an N-response experiment at each site. The two N-response experiments showed that N application rate (0–280 kg N/ha as a top-dressing in addition to 130 kg N/ha applied at planting) had no statistically significant effect on plant, stem and tuber population and the mean values of these variates for both experiments are shown in Table 58.

	Lady Rosetta Buchers Woodyard	Courage North Whinns
Plant population (000/ha)	32.7 (± 0.31)	36.4 (± 0.59)
Stem population (000/ha)	123.7 (± 6.84)	152.4 (± 8.31)
Tubers > 10 mm per stem	5.14 (± 0.359)	4.05 (± 0.114)
Tuber population > 10 mm (000/ha)	633 (± 51.8)	615 (± 34.7)

TABLE 58. AVERAGE VALUES FOR PLANT, STEM AND TUBER POPULATIONS AT BUCHERS AND NORTH WHINNS

The effects of N application rate on tuber FW yield, tuber DM concentration and mean tuber size are shown in Table 59. The average total yield (> 10 mm) for Lady Rosetta was 58 t/ha and the average yield > 40 mm was 53 t/ha. These yields were similar to those found in sampling the commercial crop. Due to the relatively large standard errors, increasing the N application rate from 0 to 280 kg N/ha (in addition to the 130 kg N/ha basal dressing) had no statistically significant tuber yield > 10 or > 40 mm. Tuber DM concentration averaged 23.7 % and although the effects of N were statistically significant, the changes were relatively small and erratic. The average tuber size for the whole experiment was 54.3 mm and increasing the N application rate from 0 to 280 kg N/ha (over the basal N dressing) increased mean tuber size from c. 50 to 57 mm. The average total and > 40 mm tuber yield of Courage grown at North Whinns was 59.1 and 55.1 t/ha, respectively. Total yield was not significantly affected by N application rate but the data suggest that an application of 40-80 kg N/ha (in addition to the basal application at planting of 130 kg N/ha) may have been appropriate. Overall, the tuber DM concentration averaged 24.9 % and the largest decrease in tuber DM concentration occurred when the N application rate was increased from 0 to 40 kg N/ha over the basal dressing. Larger N application had relatively little effect on tuber DM concentration. For the whole experiment the mean tuber size averaged 54.1 mm and the effects, whilst statistically significant, were relatively small and erratic.

These experiments suggest that the commercial applications of 250 kg N/ha (as 130 + 60 + 60 kg N/ha) should have been more than sufficient for both crops and thus the next step in this analysis is determine why N applications in excess of the optimum did not translate into large N uptakes and large yield potentials.

N application rate* (kg N/ha)	Lady Rosetta, Buchers Woodyard				Courage, North Whinns			
	Tuber yield > 10 mm (t/FW/ha)	Tuber yield > 40 mm (t/ha)	Tuber DM concentration (%)	Mean tuber size (mm)	Tuber yield > 10 mm (t/FW/ha)	Tuber yield > 40 mm (t/ha)	Tuber DM concentration (%)	Mean tuber size (mm)
0	51.7	45.6	23.2	49.9	51.8	46.5	26.4	51.8
40	52.5	47.0	23.5	52.5	55.0	51.7	24.3	53.7
80	48.7	42.8	23.9	51.4	64.7	60.6	24.6	55.2
120	59.0	54.0	23.3	54.3	62.1	59.0	24.6	54.0
160	62.0	57.5	24.0	55.8	60.2	56.9	24.9	54.1
200	60.5	55.9	23.9	56.4	55.7	51.0	24.7	53.8
240	69.2	65.0	24.5	56.6	62.7	59.0	24.7	56.0
280	62.4	59.1	23.7	57.2	60.4	56.4	24.8	54.0
Mean	58.3	53.3	23.7	54.3	59.1	55.1	24.9	54.1
S.E.	5.46	5.39	0.19	1.11	4.17	4.58	0.83	1.22

* In addition to a basal N application rate of 130 kg N/ha

TABLE 59. EFFECT OF N APPLICATION RATE ON YIELD, TUBER DRY MATTER (DM) CONCENTRATION AND MEAN TUBER SIZE OF LADY ROSETTA AND COURAGE

13.2.6. Efficiency of N use

There are several factors that may reduce the availability of soil mineral fertilizer N to the crop. These include: applications of N that are applied too late to be efficiently taken up by the crop; leaching of N as a consequence of irrigation and freak rainfall events causing fields to exceed field capacity; fertilizer spreading techniques that result in a spatial separation between fertilizer N and plant roots and soil conditions that slow or the stop rapid expansion of root systems.

13.2.7. Timing of N applications in relation to crop development

Both crops received 130 kg N/ha at planting and they then received two further within-season applications of 60 kg N/ha. For the Lady Rosetta at Buchers, these N applications were on 8 May (4 days before crop emergence) and 30 May (c. 18 DAE). For the Courage crop at North Whinns, application dates were 12 May (c. at emergence) and 9 June (28 DAE). Studies have consistently shown that crops lose their ability to take up N as the season progresses and N applied much after TI (i.e. three to four weeks after emergence) is unlikely to have much affect on yield potential. For the Lady Rosetta and Courage crops, the final N applications were probably sufficiently early in the season for the crops to have the ability to efficiently take up N from the soil solution. Therefore, the inability of the crops to use within-season applications of N did not appear to contribute to the reduced total N uptakes and reduced yield potentials.

13.2.8. Leaching of N as a consequence of drainage

Leaching of nitrate N from potato fields is often invoked as a cause of significant N loss leading to loss of yield potential and possible environmental damage. Irrigation for the Lady Rosetta and Courage crops was scheduled using the CUF Irrigation Scheduling Model. A subroutine within this model estimates the quantity of water that drains from the soil and is unavailable to the crop. Figure 23 shows the cumulative drainage losses for both crops and the vertical bars illustrate the timing of the within-season N applications in relation to the cumulative drainage. For the Courage crop at North Whinns, total season-long drainage losses were estimated to be c. 22 mm and leaching of N was unlikely to be a significant cause for poor crop performance. However, for the Lady Rosetta crop cumulative drainage to 20 August totalled 129 mm and there was a significant drainage event (40 mm) that was coincident with the final application of N. It is possible that this drainage event was responsible for moving some N beyond the roots of the crop and thus making it unavailable and this may one reason for poor crops performance at the site. Application of N to wet soil may also lead to significant denitrification losses but there are no data to assess this possibility. It is also interesting to note that there was significant drainage towards the end of the growing season and for much of August the soil may have been close to saturation. This may explain why the CUF yield model slightly overestimated yield for this crop since it may have been stressed due to excess water within the soil profile.

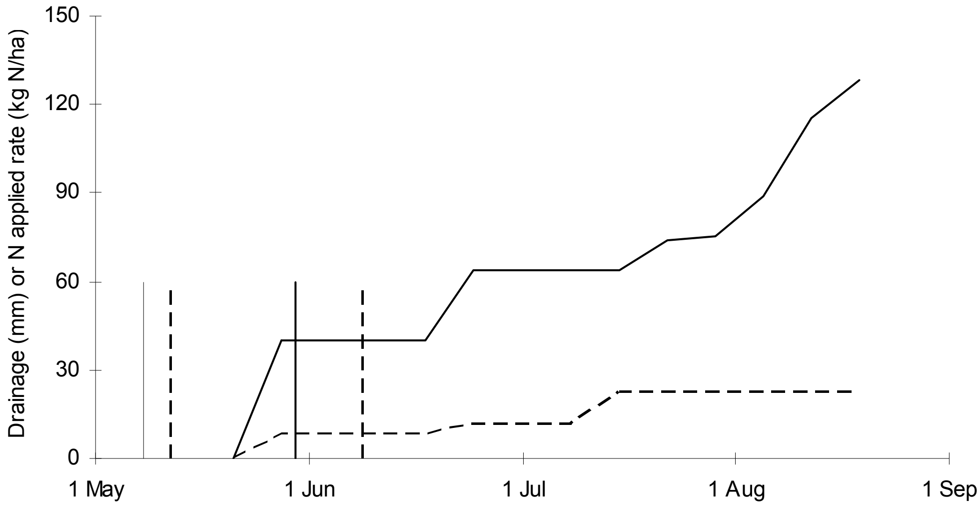


FIGURE 23. TIMING OF N APPLICATION (VERTICAL LINES) IN RELATION TO CUMULATIVE DRAINAGE FOR LADY ROSETTA, BUCHERS (SOLID LINE) AND COURAGE, NORTH WHINNS (DASHED LINE).

13.2.9. Soil sampling – soil mineral N

Soil mineral nitrogen (0-90 cm) was measured in both commercial crops on three occasions. For the Lady Rosetta crops at Buchers, the first soil sampling (8 May) was taken before crop emergence and before the first of the 60 kg N/ha top dressings. At this sampling, N within the profile was similar for positions 'A' and 'C' but there was more N in position 'B' the ridge centre (Table 60). The second sampling was taken on 10 June (29 DAE) and by this stage crop growth and N uptake had reduced soil mineral N within the ridges to 119 kg N/ha. There was much more N in the wheelings (247 kg N/ha) and in the centre of the bed (171 kg N/ha). At final harvest on 29 August (*c.* 109 DAE), there was little difference in soil mineral N at any sampling position.

Sample location	Depth (cm)	8 May	10 June	29 August
Position 'C'	0-30	39 (± 2.5)	110 (± 10.8)	19 (± 1.4)
Wheeling	30-60	55 (± 2.1)	69 (± 10.2)	12 (± 3.0)
	60-90	40 (± 2.9)	68 (± 11.2)	35 (± 9.0)
	0-90	134 (± 6.3)	247 (± 29.3)	66 (± 12.0)
Position 'B'	0-30	56 (± 4.4)	44 (± 17.5)	21 (± 1.4)
Ridge centre	30-60	114 (± 1.9)	27 (± 6.3)	14 (± 1.1)
	60-90	48 (± 5.3)	48 (± 5.5)	22 (± 5.3)
	0-90	217 (± 8.1)	119 (± 19.0)	57 (± 5.8)
Position 'A'	0-30	42 (± 8.5)	73 (± 28.3)	15 (± 1.0)
Bed centre	30-60	58 (± 7.0)	43 (± 15.5)	9 (± 1.5)
	60-90	55 (± 8.3)	55 (± 9.9)	20 (± 5.4)
	0-90	155 (± 5.1)	171 (± 51.4)	45 (± 7.1)

TABLE 60. SPATIAL AND TEMPORAL VARIATION IN SOIL MINERAL N, LADY ROSETTA, BUCHERS

Table 61 gives values for soil mineral N for the Courage field at North Whinns. The second sample was taken on 10 June (29 DAE) one day after the final top-dressing.

Large quantities of soil mineral N were again found in the wheeling (310 kg N/ha) with much less found in the ridge (162 kg N/ha). At final harvest on the 11 September (122 DAE) there was little spatial variation in soil mineral N, as found at Buchers. Whilst the absolute amount of soil mineral N varied between the two fields, the spatial and temporal variation in soil mineral N was similar.

Sample location	Depth (cm)	8 May	10 June	11 September
Position 'C'	0-30	61 (± 11.2)	133 (± 21.7)	15 (± 1.0)
Wheeling	30-60	56 (± 10.3)	111 (± 18.4)	18 (± 3.8)
	60-90	24 (± 1.6)	66 (± 4.5)	40 (± 3.3)
	0-90	141 (± 21.7)	310 (± 22.8)	73 (± 6.5)
Position 'B'	0-30	116 (± 12.6)	44 (± 13.0)	17 (± 1.7)
Ridge centre	30-60	75 (± 6.1)	67 (± 3.5)	23 (± 1.4)
	60-90	38 (± 2.5)	51 (± 7.8)	29 (± 6.3)
	0-90	229 (± 17.1)	162 (± 13.1)	68 (± 7.4)
Position 'A'	0-30	57 (± 10.7)	101 (± 34.5)	15 (± 1.1)
Bed centre	30-60	71 (± 6.3)	82 (± 21.2)	16 (± 2.0)
	60-90	30 (± 6.3)	80 (± 27.5)	17 (± 2.0)
	0-90	158 (± 18.4)	263 (± 69.7)	48 (± 4.4)

TABLE 61. SPATIAL AND TEMPORAL VARIATION IN SOIL MINERAL N, COURAGE, NORTH WHINNS

13.2.10. Soil sampling – soil penetration resistance

In conjunction with measurement of soil mineral N, measurements were also made of soil penetration resistance using an Eijkelkamp Penetrograph recording penetrometer. Previous work using this instrument shows that the rate of rooting halves once soil resistance exceeds 1 MPa and effectively ceases at 3 MPa (Stalham et al. 2007). Figure 24 shows penetration resistance for both fields measured on 10 June. For both fields, soil penetration resistance was lowest when sampled in the middle of the ridge and highest in the wheeling. Irrespective of where the samples were taken, the data also suggest that the root system was probably confined to within the top 60 cm of soil. This restriction on rooting was found early in the crops' development and may have restricted nutrient uptake and thus limited yield potential. The soil mineral N and penetrometer data also show that the wheelings either side of the bed contain large amounts of plant available N but are probably not easily accessed by plant roots. Thus N in this region will not be used efficiently by the crop and will be at risk of loss. Methods other than broadcasting of top-dressings may reduce the risk of N accumulating in wheeling and improve N use efficiency.

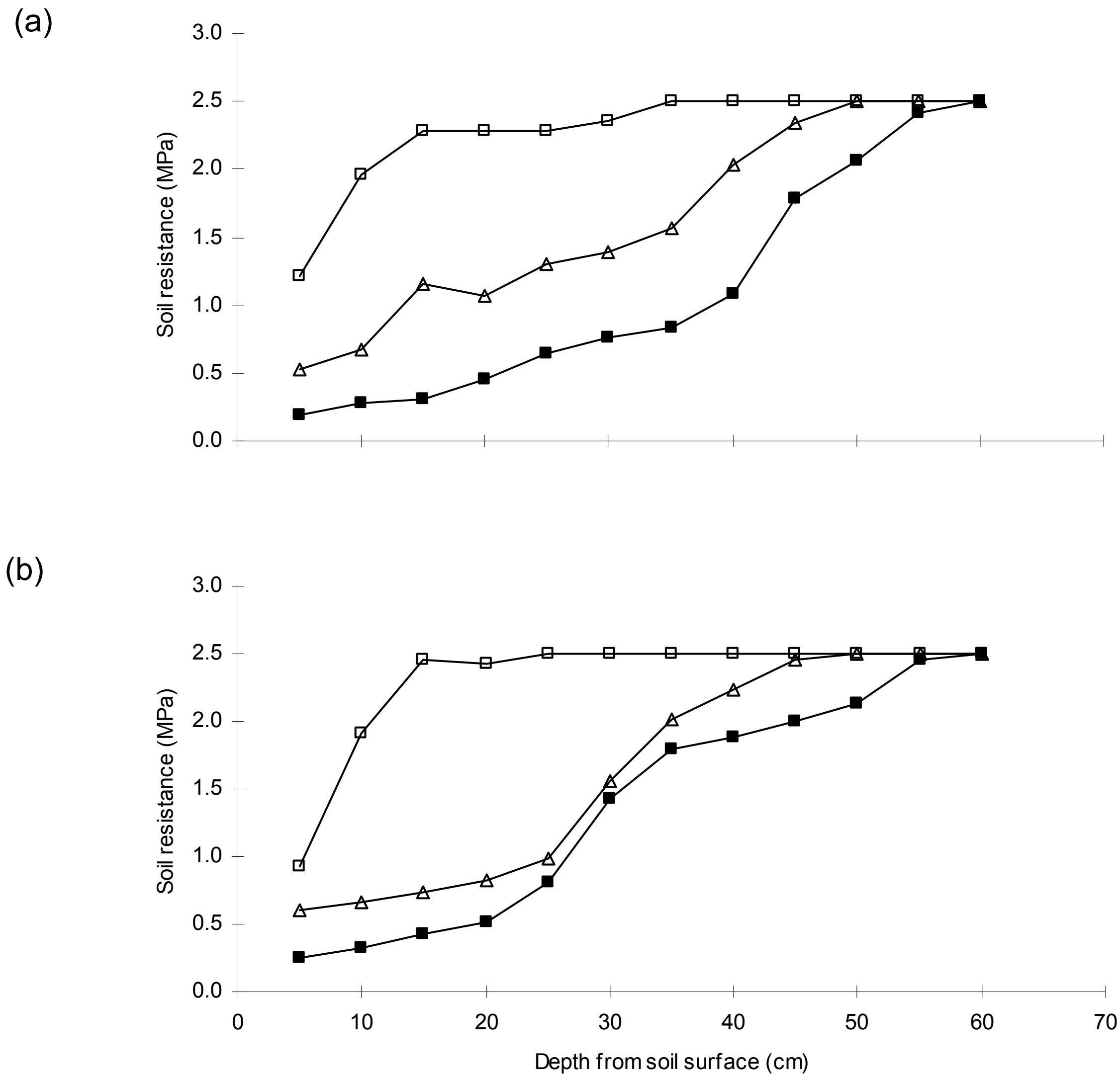


FIGURE 24. SOIL PENETRATION RESISTANCE ON 10 JUNE FOR (A) LADY ROSETTA, BUCHERS AND (B) COURAGE, NORTH WHINNS. SAMPLING POSITIONS: RIDGE CENTRE, ■; BED CENTRE, △ AND WHEELING □.

13.3. Conclusions

The analysis of the growth and yield of these two crops suggests:

1. Their yield was largely explicable in terms of ground cover persistence and incident radiation. However, for the Lady Rosetta at Buchers some yield may have been lost due to soils being saturated with water towards the end of the season.
2. Canopy persistence of both crops was explicable in terms of total N uptake and rate of transfer of N from haulm to tuber. Thus lack of yield potential was probably due to insufficient N uptake early in the season.
3. An N response experiment suggested that the commercial application of 250 kg N/ha should not have limited yield.
4. The timing of the top-dressings should not have unduly reduced the efficiency of N uptake.
5. It was possible that a proportion of the last application of N applied to the Lady Rosetta crop at Buchers may have been lost as a consequence of leaching or

denitrification and this could have limited the amount of N available to the crop and reduced yield.
6. Soil sampling indicated that broadcasting the top-dressing may result in relatively large amounts of N accumulating in the wheelings either side of the two-row bed. This is due to broadcast prills rolling down the flanks of the ridges into wheelings. Compared with N in the ridge or in the bed centre, this N is probably not easily available to the crop. Improved N use efficiency may be achieved with modifications to the method of N application.
7. Penetrometer readings suggest that at both sites root penetration may have been hampered by excessive soil resistance and few roots penetrated deeper than 60 cm. Nitrogen uptake may have been limited due to the paucity of roots, particularly in wheelings where large amounts of fertilizer N may accumulate.

14. SPEARHEAD 2009, LADY ROSETTA

14.1. Material and Methods specific to 2009

Details of the two sites are given in Table 62. The soil texture at Buchers was a sandy-loam with 1.8 % organic matter (by loss on ignition), the soil at Knights was loamy sand with 2.2 % organic matter.

Site and field	OS Grid	Date of planting	1st N application		2nd N application	
			Date	**(kg N/ha)**	**Date**	**(kg N/ha)**
Buchers, Thorns	TL 957795	19 March	3 March	180	20 May	60 or 30
Knights, Hollow Heath	TL 819991	28 April	17 April	180	1 June	60 or 30

TABLE 62. SITE DETAILS FOR TWO COMMERCIAL CROPS OF LADY ROSETTA, 2009

14.1.1. Commercial crop sampling

As in 2008, emergence, ground cover and yield development were monitored in two commercial crops. However, in addition, unreplicated strips with a reduced amount of N (210 kg N/ha compared with the standard rate of 240 kg N/ha) were also sampled during the course of the season. Emergence and ground cover development of the commercial crops given the standard rate of N was measured by Spearhead staff as part of the CUF irrigation scheduling system. The commercial crops with the standard and reduced N applications were sampled by CUF staff on three occasions during the growing season. At each harvest four replicate areas each 3 m by one row (2.74 m2) were taken from representative areas of the commercial crop. These samples were processed as described on page 13.

14.1.2. Nitrogen response experiments

At each site an N-response experiment tested the effect of N application rate on tuber FW yield. Each experiment included eight rates of supplementary N (0 to 210 kg N/ha in 30 kg N/ha increments) and each treatment was replicated four times and allocated at random to blocks. Both N-response experiments were machine planted and the N-response experiments were superimposed on a uniform, basal application of 180 kg N/ha. Each plot was four rows (3.66 m) wide and 7.0 m long. A single harvest was taken on 8 September (Buchers) and 16 October (Knights). The N treatments were applied, by hand on 20 May (Buchers) and 4 June (Knights) using ammonium nitrate (34.5 % N). The crops were sampled and processed using the same protocol as described previously (page 13).

14.2. Results and Discussion

14.2.1. Emergence and ground covers

For the crop at Buchers, 50 % plant emergence was achieved on 24 April (c. 36 days after planting, DAP) and at Knights on 22 May (24 DAP). Both crops attained 100 % ground cover (Figure 25). Despite having an earlier date of emergence, the initial ground cover expansion of the Buchers crop was more rapid and the canopy maintained 100 % ground cover for longer than Knights.

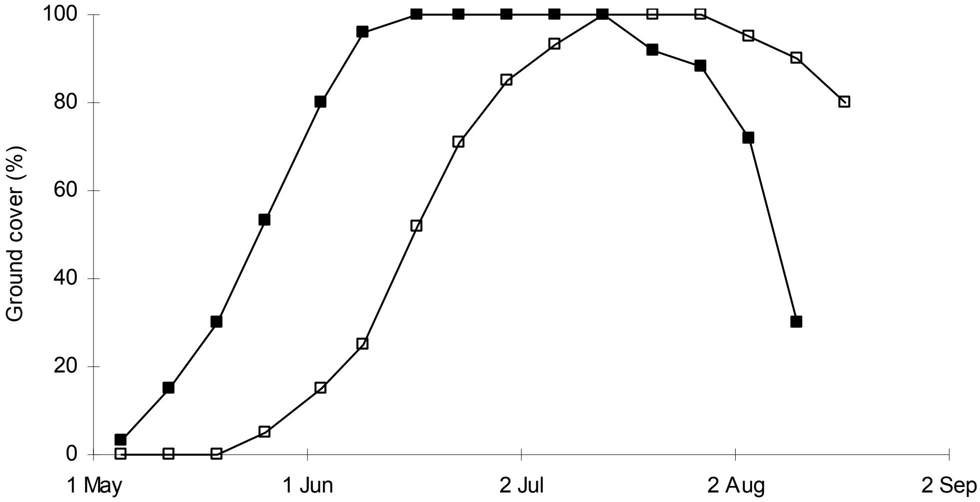


FIGURE 25. GROUND COVER DEVELOPMENT FOR LADY ROSETTA, BUCHERS ■ AND KNIGHTS □, 2009.

14.2.2. Commercial crop sampling

At Buchers, stem and tuber populations were reasonably consistent at each harvest (Table 63) irrespective of N application rate. When 240 kg N/ha had been applied, tuber FW yield increased from c. 9 t/ha at the first sampling to 64 t/ha at the final sampling whilst total DM yield and N uptake at the end of the season were 16.1 t/ha and 196 kg N/ha, respectively. When 210 kg N/ha was applied, tuber FW yield and total DM yield at final harvest were 58 and 15.4 t/ha, respectively and the total N uptake was 164 kg N/ha. For both the standard and modified crops, tuber DM concentration at final harvest averaged 24.8 %. Once the standard errors are taken into account, there was probably no significant difference between yield and N uptake between the standard and reduced N application rate. Furthermore, should the differences in yield and N uptakes be real, due to the design of the comparison, they cannot necessarily be attributed to differences in N supply and may have been due to variation in soil texture across the field. For the crop grown at Knights, the stem population was not affected by N application rate but tuber population may have been slightly smaller in the crop that received 210 kg N/ha. For the standard crop, tuber FW yields increased from 7 to 50 t/ha between the first and final harvest and, at final harvest, the total DM yield was 13.2 t/ha and the total N uptake was 186 kg N/ha. For crops that received 210 kg N/ha, tuber FW, total DW and total N uptake were numerically larger than those found in the standard crop. However, as at Buchers, these differences are within that expected from variability and cannot be attributed to the effects of reduced N input. At final harvest, the average tuber DM concentration for the standard and modified crop was 25.6 %. In a similar study in 2008, the tuber FW yield of a Lady Rosetta crop was 54 t/ha and the total DM yield was 13.5 t/ha.

Date of sampling	Total N applied (kg/ha)	Stem population (000/ha)	Tuber population > 10 mm (000/ha)	Tuber FW yield > 10 mm (t FW/ha)	Total DM yield (t/ha)	Total N uptake (kg N/ha)
Buchers						
28 May	240	110 (± 2.7)	602 (± 25.4)	3.1 (± 0.71)	2.16 (± 0.227)	90 (± 9.2)
18 June	240	111 (± 7.1)	624 (± 30.8)	22.1 (± 1.49)	7.48 (± 0.422)	204 (± 6.5)
8 September	240	96 (± 2.7)	562 (± 25.4)	63.8 (± 3.74)	17.01 (± 1.259)	196 (± 14.0)
28 May	210	108 (± 3.5)	587 (± 32.4)	2.8 (± 0.11)	1.90 (± 0.025)	74 (± 2.2)
18 June	210	107 (± 4.8)	603 (± 19.4)	25.5 (± 1.30)	7.99 (± 0.277)	179 (± 12.9)
8 September	210	105 (± 2.3)	587 (± 7.7)	57.8 (± 3.82)	15.38 (± 1.243)	164 (± 30.0)
Knights						
25 June	240	128 (± 7.9)	594 (± 28.4)	7.1 (± 0.93)	3.55 (± 0.193)	140 (± 5.2)
23 July	240	116 (± 8.2)	581 (± 48.0)	32.2 (± 1.92)	9.88 (± 0.576)	181 (± 13.5)
16 October	240	107 (± 6.2)	536 (± 48.1)	49.6 (± 036)	13.24 (± 0.203)	186 (± 7.8)
25 June	210	118 (± 8.3)	490 (± 42.6)	5.9 (± 0.40)	3.03 (± 0.084)	124 (± 5.0)
23 July	210	108 (± 6.9)	558 (± 26.7)	28.5 (± 4.13)	9.82 (± 1.212)	200 (± 17.5)
16 October	210	114 (± 3.1)	500 (± 20.4)	51.3 (± 2.38)	14.77 (± 1.239)	248 (± 29.5)

TABLE 63. COMPONENTS OF YIELD AND N UPTAKE OF LADY ROSETTA AT BUCHERS AND KNIGHTS

14.2.3. Modelling of yield development

Gross, commercially harvested yields were 59 and 46 t/ha at Buchers and Knights, respectively. There was close agreement between the CUF yield model with hand-dug samples and the commercially achieved yields (Figure 26). At Knights, whilst modelled yields were close to hand-sample yields both slightly overestimated gross commercial yield and this was probably due to within-field variation that was not adequately accounted for.

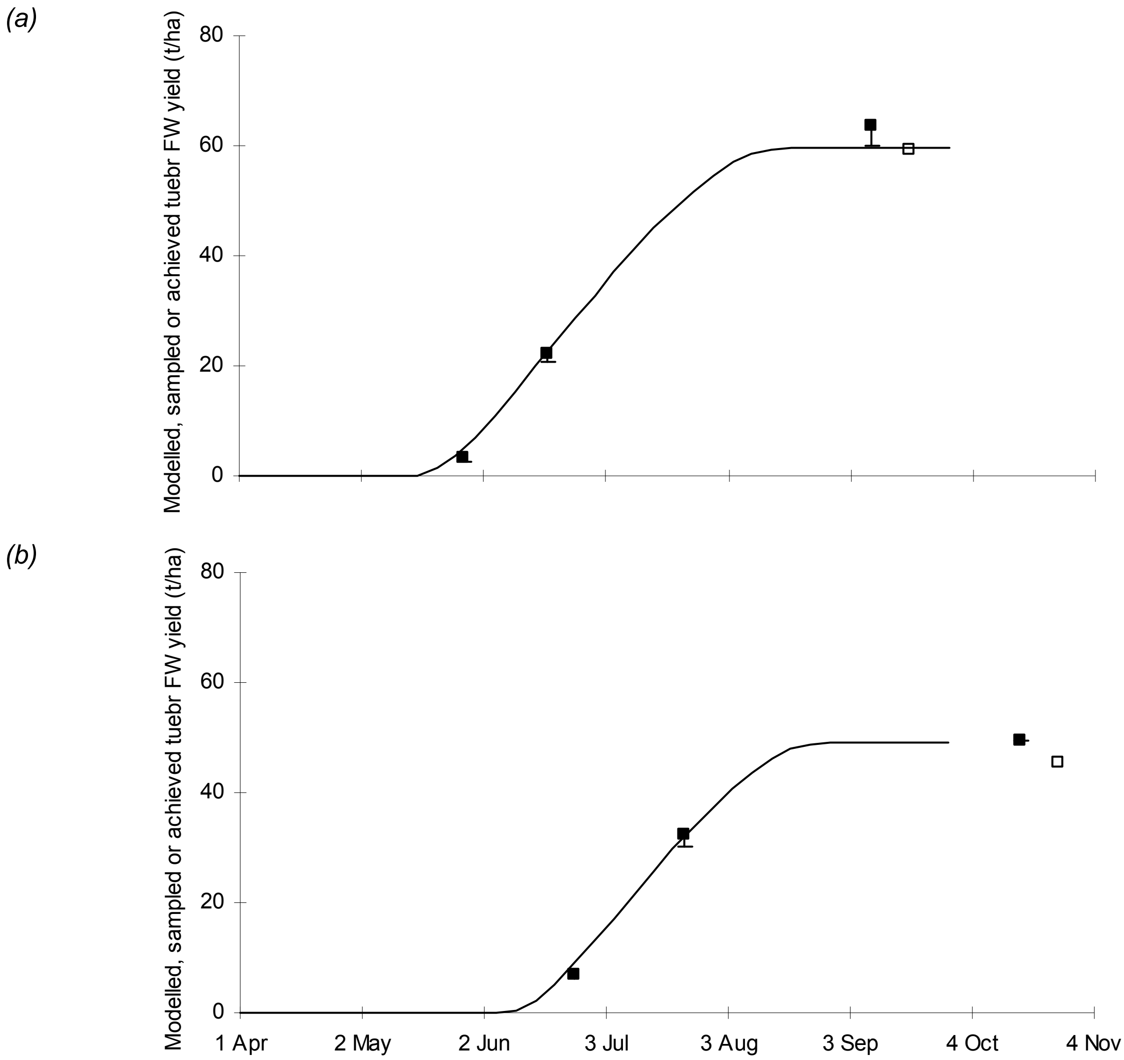


FIGURE 26. MODELLED (BLACK LINE), SAMPLED (■ AND 1 S.E.) AND COMMERCIALLY ACHIEVED YIELD (□) FOR (A) BUCHERS AND (B) KNIGHTS. BOTH CROPS RECEIVED 240 KG N/HA.

14.2.4. Crop nitrogen uptake and canopy persistence

Variation in yield of the Lady Rosetta crops was correlated with canopy duration. It was estimated that the crop at Buchers absorbed 13.19 TJ/ha of solar radiation compared with 10.46 TJ/ha at Knights. The next stage of the analysis investigated whether these differences in canopy persistence, radiation absorption and yield could be explained in terms of total N uptake and the rate of redistribution of N to the tubers. Estimates of maximum total N uptake were 213 kg N/ha for the crop grown at Buchers compared with 185 kg N/ha for the Lady Rosetta grown at Knights and the rate of tuber N uptake was 15.4 kg N/TJ at Buchers compared with 17.1 kg N/TJ at Knights (Figure 27). Thus, when compared with the Buchers field, the yield potential at the Knights field was limited by both a reduced N uptake and a faster rate of transfer of N into the tubers. In general, the observed data were well described by the linear (tuber N uptake) and exponential (total N uptake) curves and this suggests that these crops achieved the potential set by their N uptake and thus they did not senesce prematurely as a consequence of water stress or disease. Since yield potential is governed largely by total N uptake, it appears that the performance of the Knights crop in particular was mainly limited by inability to take up sufficient N. The initial rate of total N uptake at Knights was faster than that at Buchers and if this had been maintained the total N uptake of the Knights crop would have exceeded that of the Buchers crop. However, for the Buchers crop maximum haulm N uptake was achieved on 13 June (50 DAE) compared with 30 June (39 DAE) for the crop grown at Knights and therefore the period of rapid N uptake at Knights was curtailed and this resulted in reduced N uptake and reduced yield potential.

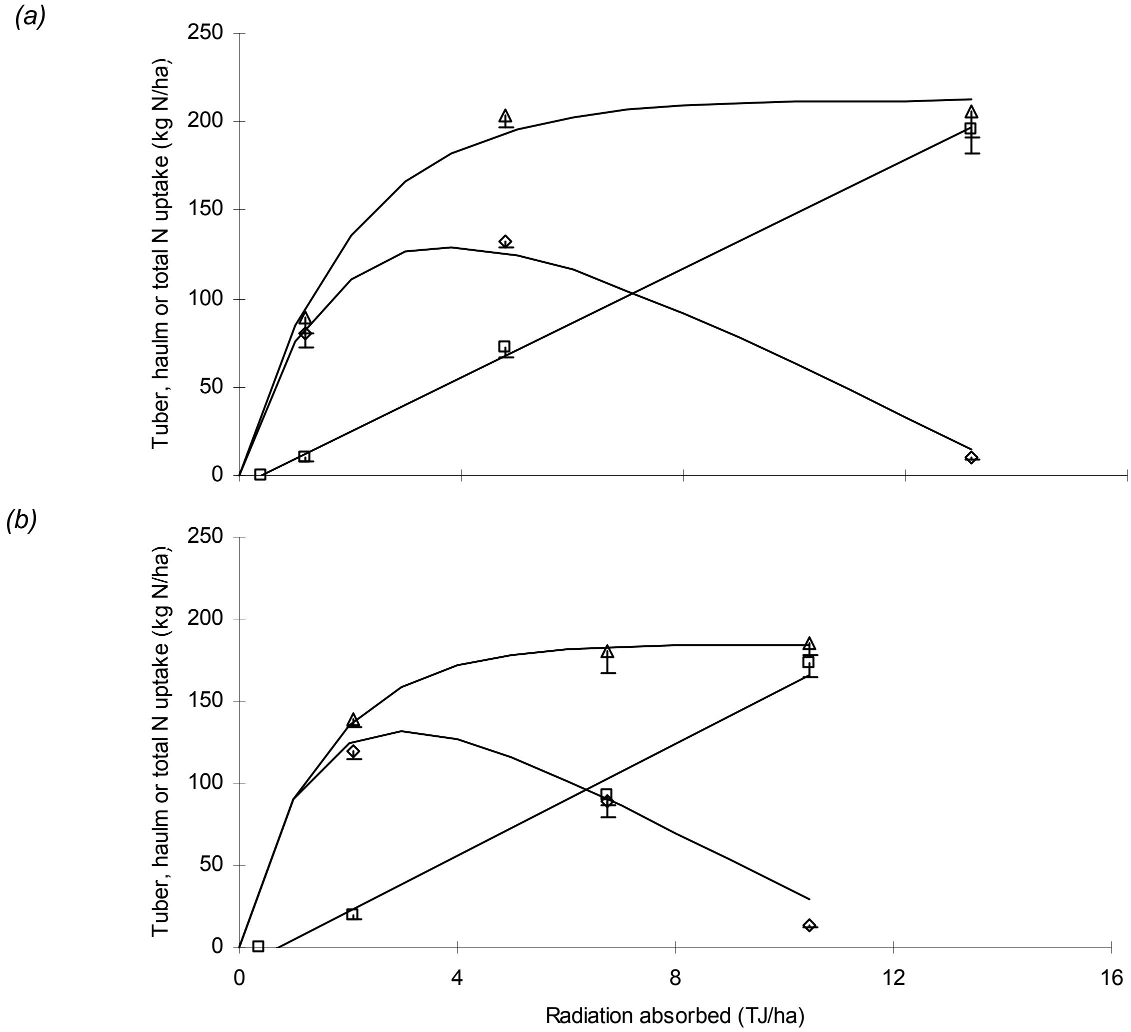


FIGURE 27. NITROGEN UPTAKE AT (A) BUCHERS AND (B) KNIGHTS. TUBER N, □; TOTAL N, △ AND HAULM N, ◊. LINES ARE DERIVED FROM FITTED REGRESSIONS. EACH MEAN WAS DERIVED FROM FOUR REPLICATE VALUES.

14.2.5. Nitrogen response experiments

The next stage of the analysis assessed whether crop N uptakes (and therefore yield potential) was limited by commercial N applications that were too small. This was tested by conducting an N-response experiment at each site. The two N-response experiments showed that N application rate (0–210 kg N/ha as a top-dressing in addition to 180 kg N/ha applied at planting) had no statistically significant effect on plant, stem and tuber populations and the mean values for these variates at both experiments are shown in Table 64.

	Buchers	**Knights**
Plant population (000/ha)	32.8 (± 0.00)	52.3 (± 2.03)
Stem population (000/ha)	103.7 (± 6.10)	113.5 (± 10.66)
Tubers > 10 mm per stem	5.67 (± 0.308)	4.14 (± 0.261)
Tuber population > 10 mm (000/ha)	584 (± 22.3)	467 (± 47.3)

TABLE 64. PLANT, STEM AND TUBER POPULATIONS (MEAN OF N TREATMENTS) AT BUCHERS AND KNIGHTS

The effects of N application rate on tuber FW yield >10 and > 40 mm, tuber DM concentration and mean tuber size (μ) are shown in Table 65. At Buchers, N application affected total tuber FW yield, tuber yield > 40 mm and mean tuber size but there was no systematic response to N and much of the variation in tuber FW yield was probably independent of N application rate. The optimum N application for the top dressing at Buchers was probably 30-60 kg N/ha. At Buchers, increasing the top dressing from 0 to 210 kg N/ha had no effect on tuber DM concentration. At Knights, increasing the N application rate from 0 to 210 kg N/ha had no effect on total tuber yield or tuber yield > 40 mm, tuber DM concentration or mean tuber size. Thus, at Knights the optimum top dressing was zero. The N-response experiments showed that at the standard commercial N application rate (240 kg N/ha) crop performance was unlikely to have been limited by the amount N applied, particularly at Knights which had the smaller yield.

Site	N top dressing (kg N/ha)	Tuber yield > 10 mm (t FW/ha)	Tuber yield > 40 mm (t/ha)	Tuber DM concentration (%)	Mean tuber size (mm)
Buchers	0	60.7	57.9	23.9	55.5
	30	57.2	53.4	23.4	54.2
	60	63.1	60.4	23.6	56.3
	90	61.5	59.1	24.1	58.4
	120	69.0	66.4	25.1	58.9
	150	62.7	60.1	25.1	57.1
	180	71.2	68.7	25.2	58.3
	210	66.6	64.0	25.1	59.6
	S.E. (21 D.F.)	2.58	2.77	0.60	0.68
	Mean	64.0	61.2	24.4	57.3
Knights	0	50.0	47.1	27.0	56.0
	30	50.3	47.3	26.2	55.6
	60	47.7	45.4	26.8	56.0
	90	53.4	50.2	26.0	56.9
	120	46.3	44.1	27.2	56.6
	150	44.2	42.1	26.7	56.1
	180	52.2	49.7	27.4	56.3
	210	43.1	40.5	27.0	55.8
	S.E. (21 D.F.)	2.80	2.61	0.52	1.04
	Mean	48.4	45.8	26.8	56.2

TABLE 65. EFFECT OF N APPLICATION RATE ON YIELD, TUBER DRY MATTER (DM) CONCENTRATION AND MEAN TUBER SIZE OF LADY ROSETTA AT BUCHERS AND KNIGHTS

14.2.6. Efficiency of N use

Factors that may reduce the availability of soil mineral and fertilizer N to the crop include: (a) applications applied too late to be efficiently taken up by the crop; (b) leaching of N as a consequence of irrigation and unusual rainfall events causing fields to exceed field capacity; (c) fertilizer spreading techniques that result in a spatial separation between fertilizer N and plant roots and (d) soil conditions that inhibit rapid expansion of root systems.

14.2.7. Timing of N applications in relation to crop development

In 2008, both crops received 130 kg N/ha at planting and then two further applications of 60 kg N/ha giving a total N application of 250 kg N/ha (Table 55). In 2009, the N applications were simplified to 180 kg/ha before planting and a 60 kg N/ha top dressing. For Buchers, the top dressing was applied at 26 DAE whereas for Knights it was 10 DAE. Studies at CUF have consistently shown that crops lose their ability to take up N as the season progresses and N applied much after tuber initiation (i.e. 3-4 weeks after emergence) is unlikely to have much effect on yield potential. For both the 2009 crops, the final N applications were sufficiently early in the season for the crops to efficiently take up N from the soil solution so inefficient use of N due to late application was probably not a contributory factor to reduced N uptake and yield potentials, particularly at Knights.

14.2.8. Leaching of N as a consequence of drainage

Leaching of nitrate N from potato fields is often invoked as a cause of significant N loss leading to loss of yield potential and possible environmental damage. Irrigation for both crops was scheduled using the CUF Irrigation Scheduling Model. A subroutine within this model estimates the quantity of water that drains from the soil and is unavailable to the crop. At Buchers, the total drainage was estimated to be 16 mm and leaching of N was unlikely to be a significant factor in poor efficiency of N use. At Knights total drainage was estimated to be 42 mm spread over seven events during the season. The most serious drainage event was 17 mm on 20 July but by this time the crop had taken up most of its N (Table 63) and it is unlikely that crop performance was impaired by this drainage event. In 2008, there was some evidence that crop performance may have been limited due to soil water logging for several days at a time but there was little evidence of this occurring in 2009 at either site.

14.2.9. Soil sampling – soil mineral N

Soil mineral nitrogen (0-90 cm) was measured in both commercial crops on three occasions. For the crop at Buchers (Table 66), the first soil sampling was taken 5 DAE and before the top dressing of 60 kg N/ha. At this sampling, there was numerically more N in the ridge and in the centre of the bed than in the wheeling. The second soil sampling was taken when the crop had received its entire N application. Nitrogen uptake by the crop had reduced the amount of N within the ridge to 179 kg N/ha. There was much more N in the wheelings (243 kg N/ha) and in the centre of the bed (341 kg N/ha) than in the ridge centre. At final harvest on 8 September (c. 137 DAE), there was little difference in soil mineral N at any sampling position.

Sample location	Depth (cm)	29 April	28 May	8 September
Wheeling	0-30	134 (± 36.8)	159 (± 69.2)	37 (± 2.8)
	30-60	22 (± 4.5)	67 (± 37.0)	20 (± 2.5)
	60-90	14 (± 1.8)	17 (± 2.1)	10 (± 0.8)
	0-90	170 (± 42.0)	243 (± 63.1)	67 (± 4.8)
Ridge centre	0-30	337 (± 93.1)	132 (± 31.7)	33 (± 3.2)
	30-60	39 (± 12.2)	28 (± 5.5)	27 (± 2.5)
	60-90	23 (± 6.0)	19 (± 4.8)	15 (± 1.9)
	0-90	399 (± 107.2)	179 (± 37.1)	75 (± 1.9)
Bed centre	0-30	200 (± 52.4)	257 (± 55.8)	24 (± 1.8)
	30-60	20 (± 4.3)	52 (± 21.8)	12 (± 3.0)
	60-90	22 (± 6.5)	32 (± 15.9)	8 (± 0.7)
	0-90	242 (± 52.8)	341 (± 89.7)	44 (± 2.1)

TABLE 66. SPATIAL AND TEMPORAL VARIATION IN SOIL MINERAL N (KG N/HA) AT BUCHERS. EACH VALUE IS THE MEAN OF FOUR REPLICATES

Table 67 gives values for soil mineral N at Knights. The second sample was taken on 25 June several days after the final top-dressing. Large quantities of soil mineral N were again found in the wheeling and in the ridge centre with much less found in the centre of the bed. At final harvest on the 16 October (147 DAE) there was little spatial variation in soil mineral N, as found at Buchers. The large standard errors associated with the mean (particularly at Knights) make interpretation of these data less straightforward than in 2008. However, in all four site-season combinations there was little spatial difference in the distribution of soil mineral N at the final sampling. Furthermore, soils at the final sampling contained less mineral N than samples taken 30-40 DAE. It is probable that reductions in soil mineral N in the ridge centre and bed centre were largely a consequence of N uptake whereas in the wheeling the reduction may have been mainly due to immobilization into the soil organic matter or leaching and denitrification.

Sample location	**Depth (cm)**	**28 May**	**25 June**	**16 October**
Wheeling	0-30	112 (± 35.0)	115 (± 67.7)	47 (± 11.2)
	30-60	132 (± 22.7)	202 (± 76.3)	40 (± 5.5)
	60-90	76 (± 29.1)	178 (± 45.1)	25 (± 5.9)
	0-90	301 (± 53.0)	494 (± 185.5)	106 (± 12.0)
Ridge centre	0-30	720 (± 184.8)	376 (± 117.1)	56 (± 11.2)
	30-60	88 (± 16.3)	82 (± 39.8)	44 (± 13.4)
	60-90	40 (± 9.4)	52 (± 14.3)	23 (± 3.7)
	0-90	848 (± 187.5)	510 (± 148.0)	123 (± 24.5)
Bed centre	0-30	93 (± 12.1)	38 (± 5.9)	21 (± 4.8)
	30-60	48 (± 12.5)	46 (± 11.8)	24 (± 3.0)
	60-90	24 (± 10.1)	34 (± 7.0)	12 (± 3.2)
	0-90	159 (± 23.3)	119 (± 22.4)	57 (± 7.7)

TABLE 67. SPATIAL AND TEMPORAL VARIATION IN SOIL MINERAL N (KG N/HA) AT KNIGHTS. EACH VALUE IS THE MEAN OF FOUR REPLICATES

14.2.10. Soil sampling – soil penetration resistance

Previous work on soil penetration resistance show that the rate of rooting halves once soil resistance exceeds 1 MPa and effectively ceases at 3 MPa (Stalham et al. 2007). Figure 28 shows penetration resistance for both fields measured on two occasions. For both fields, soil penetration resistance was lowest when sampled in the middle of the ridge and highest in the wheeling. Irrespective of where the samples were taken, the data also suggest that the root system was probably confined to within the top 50 cm of soil. The data also suggest that penetration resistance increased as the season progressed. For example, at Bucher, penetration resistance in the centre of the ridge exceeded 3 MPa at c. 42 cm on 29 April (5 DAE) and 32 cm on 28 May (34 DAE). Since the gravimetric soil moisture content of the ridge was similar at both samplings, the increase in penetration resistance may be due to slumping of the ridge under gravity or soil particle transport due to water movement through the soil profile. This restriction on rooting was found early in the crops' development and may have restricted nutrient uptake and thus limited yield potential. The soil mineral N and penetrometer data also show that the wheelings either side of the bed contained large amounts of plant available N which was probably not easily accessed by plant roots. Thus N in this region may not be used efficiently by the crop and will be at risk of loss. Methods other than broadcasting of top-dressings may reduce the risk of N accumulating in wheelings and improve N use efficiency.

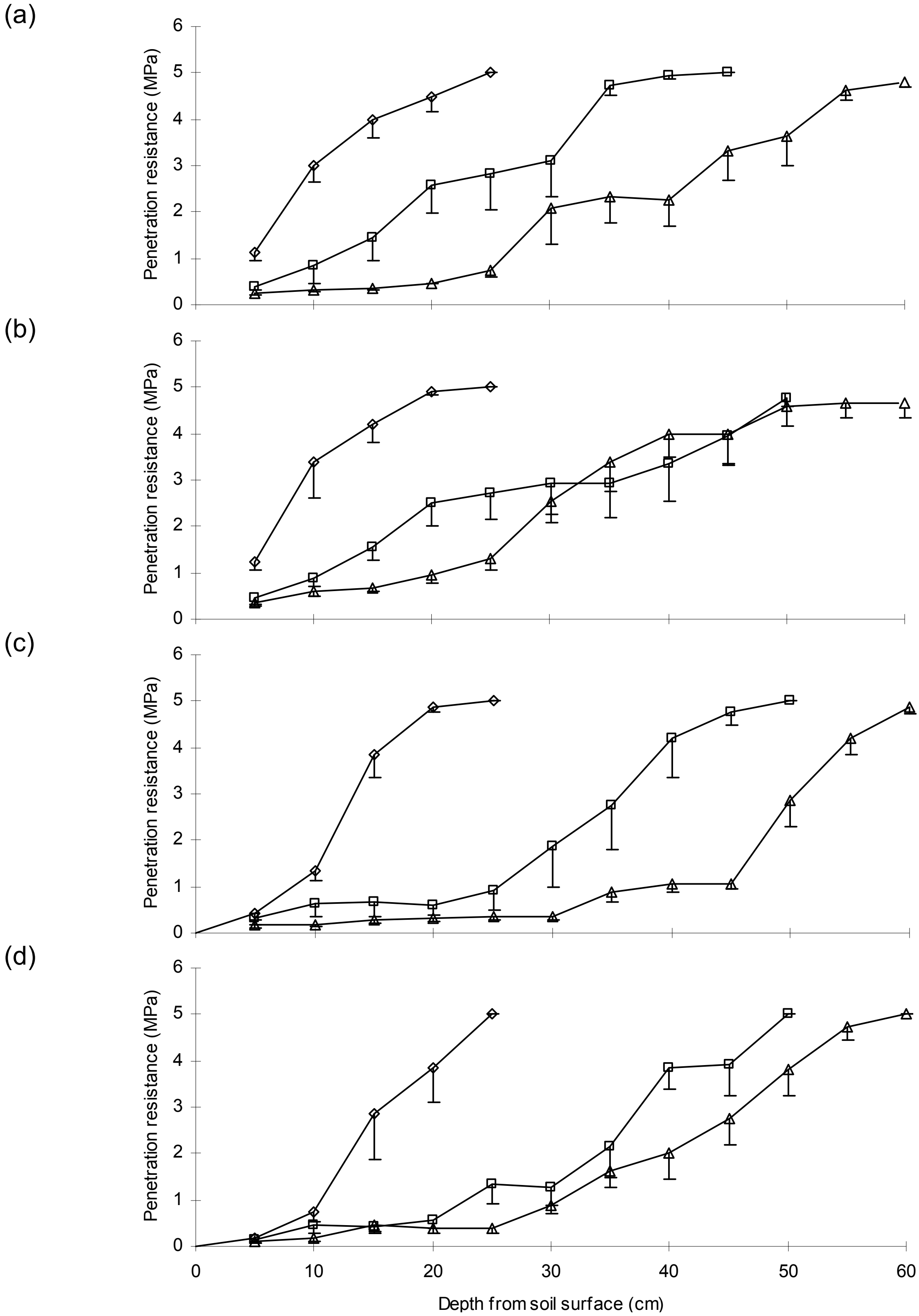


FIGURE 28. SOIL PENETRATION RESISTANCE FOR LADY ROSETTA CROPS (A) BUCHERS 29 APRIL; (B) BUCHERS 28 MAY; (C) KNIGHTS 28 MAY AND (D) KNIGHTS 25 JUNE. SAMPLING POSITIONS: RIDGE CENTRE, △; BED CENTRE, □ AND WHEELING ◊.

14.3. Conclusions

Yield of both crops was largely explicable in terms of ground cover persistence and incident radiation. There was no evidence that the yield of either crop was limited by inadequate or excess water. In turn, canopy persistence of both crops was explicable in terms of total N uptake and rate of transfer of N from haulm to tuber. Thus lack of yield potential for the Lady Rosetta crop grown at Knights was probably due to insufficient N uptake early in the season. However, N response experiments suggested that the commercial applications of 240 kg N/ha should not have limited yield at either site and the timing of the top-dressings would not have unduly reduced the efficiency of N uptake. Despite some drainage, leaching of N was probably not a significant factor at either site in 2009. Soil sampling, indicated that broadcasting the top-dressing may result in relatively large amounts of N accumulating in the wheelings either side of the two-row bed. This is due to broadcast prills rolling down the flanks of the ridges into wheelings. Compared with N in the ridge or in the bed centre, this N is probably not easily available to the crop. Improved N use efficiency may be achieved with modifications to the method of N application. Penetrometer readings suggest that at both sites root penetration may have been hampered by excessive soil resistance and few roots penetrated deeper than 50-60 cm. Nitrogen uptake may have been limited due to the paucity of roots, particularly in wheelings where large amounts of fertilizer N may accumulate.

15. SPEARHEAD 2010, LADY ROSETTA

15.1. Material and Methods specific to 2010

The work was done at two sites on the Palgrave Estate near Swaffham, Norfolk, rented by Spearhead International Ltd of Burwell, Cambridgeshire, used for the production of processing crops. Some details of these two sites are given in Table 68.

Site and field	OS Grid	Date of planting	1st N application Date	1st N application (kg N/ha)	2nd N application Date	2nd N application (kg N/ha)
Ireland 16	TF 812106	20 April	20 April	160	17 June	50
Gravel Pit	TF 850080	7 May	7 May	160	18 June	50

TABLE 68. SITE DETAILS FOR COMMERCIAL CROPS OF LADY ROSETTA GROWN BY SPEARHEAD

15.1.1. Commercial crop sampling

As in previous seasons, emergence, ground cover and yield development were monitored in two commercial crops. Emergence and ground cover development were monitored by Spearhead Staff as part of the CUF irrigation scheduling system. Each crop was sampled by CUF staff on three occasions during the growing season. The Lady Rosetta crop at Ireland 16 was sampled on 17 June, 15 July and 15 September whilst the crop at Gravel pit was sampled on 17 June, 26 July and 4 October. At each harvest, five replicate areas each 3 m by one row (2.74 m2) were taken from representative areas of the crop. The number of plants and stems was recorded and all tubers > 10 mm were collected. All the haulm was returned, together with the tubers, to CUF for weighing after which a representative sub-sample of (c. 1 kg) haulm was removed. The tuber and haulm samples were processed as described elsewhere in this report.

15.1.2. Amount of top-dressing N in wheelings and its value to the crop

The purposes of this component of the study were (a) to measure the amount of N that falls into the wheeling (region ‘C’ in Figure 19) and (b) to assess how efficiently the N in the wheeling was used by the potato crop. Prior to commercial top-dressing of N by a spinning-disk spreader, pairs of plastic sheets (each 5.4 m long and 0.31 m wide) were laid in the wheeling each side of a pair of rows and weighed down with bricks. In total, five pairs of sheets were used and these were located close to the areas allocated for the sampling of the commercial crop (see above). After application, the prills of fertilizer on each sheet were carefully transferred into plastic bags and returned to CUF for weighing. Thus, in each field, five areas were created that had received the normal commercial N application except for an amount that had fallen into the wheeling and was removed. These areas of crop were sampled on the same date as the final sampling of the commercial crop using the same protocols.

15.1.3. Nitrogen response experiments

At each site an N-response experiment tested the effects of N application rate on tuber FW yield. Each experiment comprised four replicate blocks into which main-plots with three rates of basal N application (80, 120 and 160 kg N/ha) were allocated at random. The basal application was applied, at planting, by a Horstine Airstream applicator which placed bands of fertilizer below and to either side of the potato seed. Each main-plot was then subdivided into five sub-plots to which five rates of N top-dressing were allocated at random. The top-dressing rates were chosen so that when added to the basal dressing, the total amount of N applied was 160, 190, 220, 250 or 280 kg N/ha. The top dressings were applied by hand on the same date as the commercial application (Table 68) and both basal and top-dressings were supplied as ammonium nitrate (c. 34.5 % N). Main-plots were four rows (3.66 m) wide by either 35 m long (Ireland 16) or 45 m long (Gravel Pit), whilst sub-plots were four rows wide by 5 m long. To provide sufficient length of row for the spreader to adjust application rates, either 10 m (Ireland 16) or 20 m (Gravel Pit) discards were left between adjacent main-plots. A single harvest was taken on 15 September (Ireland 16) and 4 October (Gravel Pit). Harvests (3 m of row) were taken from row two or thee of each four row sub-plot leaving c. 1m discards at each end. The number of plant and stems was recorded and all tubers > 10 mm were collected for grading and processing at CUF using the protocols described earlier.

15.1.4. Rooting Density

Root length density (RLD, cm root/cm3) was estimated at Gravel Pit on 19 August and at Ireland 16 on 26 August. At each site, five replicate areas of commercial crop that had received the standard N application rate were identified. Cores (20 × 10 × 10 cm) were taken from position ‘A’, ‘B’ and ‘C’ (Figure 19). Two cores were taken at position ‘C’ (20-30 and 30-40 cm depth relative to the soil surface at position ‘B’) and three cores were taken at positions ‘A’ and ‘B’ (10-20, 20-30 & 30-40 cm depth relative to the soil surface at position ‘B’). Soil cores were transferred to plastic bags and stored at 2 °C until washing. Prior to washing, the contents of the bag was weighed (mean weight c. 3200 g) and a 250 g sub-sample was taken. The soil cores were washed over a series of sieves (2.0, 0.6 and 0.2 mm) to collect the roots. The roots were then floated off and washed into a plastic tray or collected from the sieves using tweezers. Newman’s (1966) grid intersection method as modified by Marsh (1971) and Tennant

(1975) was then used to estimate root length. Each sample was counted three times using a grid that, ideally, gave c. 200 intersections.

15.2. Results and Discussion

15.2.1. Emergence and ground covers

The date of 50 % plant emergence was 22 May (Ireland 16) and 5 June (Gravel Pit) and the pattern of ground cover development at both sites is shown in Figure 29. At Gravel Pit, the rate of ground cover expansion slowed from early July onward and complete ground cover was only maintained for c. 1 week before the onset of canopy senescence.

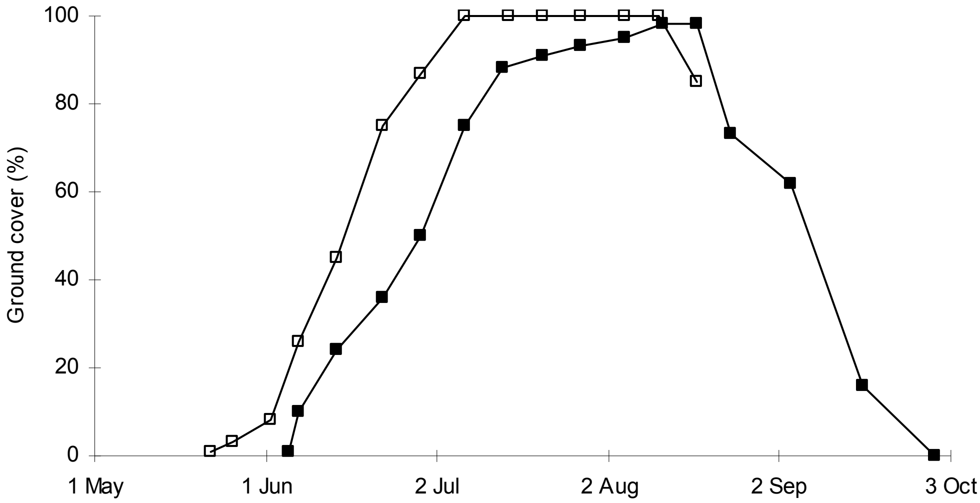


FIGURE 29. GROUND COVER DEVELOPMENT FOR LADY ROSETTA IN IRELAND 16, □ AND GRAVEL PIT, ■.

15.2.2. Commercial crop sampling

At Ireland 16, stem populations were reasonably consistent and averaged 126 000/ha over the three harvests (Table 69) and tuber populations > 10 mm for the second and third harvests averaged 616 000/ha. Between the first and third harvests, tuber FW yield increased from 0.8 to 44.6 t/ha. Total DM yield and N uptake at the final harvest were 11.3 t/ha and 177 kg N/ha, respectively. At Gravel Pit, stem populations were reasonably consistent for the three harvests and averaged 111 000/ha. The first sampling (17 June) was taken 12 DAE a few days before tuber initiation and therefore no tubers were recorded. For the second and third harvests, tuber populations > 10 mm averaged 559 000/ha. Between the second and third harvests, tuber FW yields increased from 20.7 t/ha to 54.4 t/ha and at the third harvest, total DW yield and N uptake were 14.3 t/ha and 225 kg N/ha, respectively. For the five Lady Rosetta crops monitored since 2008 as part of this project, tuber FW yields have averaged 52.1 t/ha (Table 70). During this period, the amount of N applied to these crops has decreased from 250 to 210 kg N/ha. Although the sample size is small and there are other confounding factors, the data suggest that for these crops of Lady Rosetta, N application rates can be reduced without compromising yield potential. These data are consistent with findings in the ongoing CUF-Potato Council Grower Collaboration project (Allison & Firman 2011).

Site and date of sampling	Total N applied (kg N/ha	Stem population (000/ha)	Tuber population > 10 mm (000/ha)	Tuber FW yield > 10 mm (t/ha)	Total DW yield (t/ha)	Total N uptake (kg N/ha)
Ireland 16						
17 June	210	134 (±2.7)	564 (±29.0)	0.8 (±0.11)	1.34 (±0.022)	61 (±3.1)
17 July	210	125 (±3.5)	635 (±27.4)	27.7 (±0.60)	8.80 (±0.161)	225 (±8.4)
15 September	210	118 (±3.4)	597 (±14.8)	44.6 (±2.38)	11.34 (±0.648)	177 (±9.2)
Gravel Pit						
17 June	210	109 (±13.4)	n.a.	n.a.	0.45 (±0.400)	18 (±1.7)
26 July	210	106 (±15.0)	564 (±37.5)	20.7 (±0.49)	7.37 (±0.179)	204 (±14.7)
4 October	210	117 (±9.4)	554 (±38.3)	54.4 (±2.95)	14.28 (±0.719)	239 (±12.1)

TABLE 69. COMPONENTS OF YIELD AND N UPTAKE OF LADY ROSETTA AT IRELAND 16 AND GRAVEL PIT, SWAFFHAM, NORFOLK

Year	Variety	Site	Total N (kg N/ha)	Tuber FW yield >10 mm (t/ha)	Total DW yield (t/ha)	Total N uptake (kg N/ha)
2008	Lady Rosetta	Woodyard	250	54.2 (±1.92)	13.46 (±0.569)	184 (±7.2)
	Courage	North Whinns	250	65.2 (±2.32)	16.59 (±0.761)	192 (±5.1)
2009	Lady Rosetta	Thorns	240	57.8 (±3.82)	15.38 (±1.243)	164 (±30.0)
	Lady Rosetta	Hollow Heath	240	49.6 (±0.36)	13.24 (±0.203)	186 (±7.8)
2010	Lady Rosetta	Ireland 16	210	44.6 (±2.38)	11.34 (±0.648)	177 (±9.2)
	Lady Rosetta	Gravel Pit	210	54.4 (±2.95)	14.28 (±0.719)	239 (±12.1)

TABLE 70. COMPARISON OF YIELDS AND N UPTAKES OF LADY ROSETTA AND COURAGE CROPS MONITORED 2008-2010

15.2.3. Modelling of yield development

Commercially-harvested yields at Ireland 16 and Gravel Pit were 44.2 and 44.3 t/ha, respectively. These yields represent sold tonnage and the gross yield (which included tubers too small to be harvested and other losses) will be slightly larger. For the purpose of comparisons with sampled and modelled yield the gross yield for both crops was assumed to be 46.4 t/ha (i.e. c. 5 % larger). Figure 30 compares estimates of yield from hand-dug samples, modelled yield and the commercially-harvested gross yield for Ireland 16 and Gravel Pit. At Gravel Pit, there was good agreement between the modelled yield and the commercial yield with the hand-dug samples overestimating the commercial yield by c. 8 t/ha. At Ireland 16, there was better agreement between the hand-dug samples and commercial harvest but the model overestimated yield. The reasons for this overestimate are not certain but may have been due to the model overestimating RUE. At Gravel Pit the season-long integrated ground cover was 6895 % days and this canopy absorbed 11.18 TJ/ha of energy. Total (haulm and tuber) DM yield at final harvest was 16.0 t/ha and thus the average RUE was 1.40 t DM/TJ, a typical value consistent with other experiments in 2010. In Ireland 16, the integrated ground cover was 6366 % days resulting in 12.62 TJ/ha of energy being absorbed. Total DM production at final harvest was 11.3 t/ha and the average RUE was 0.90 t DM/TJ. Even allowing for overestimates of ground cover or poor recovery of senesced haulm at final harvest, the RUE at Ireland 16 seems unusually small. The discrepancy was unlikely to be due to drought stress since analysis using the CUF Irrigation model suggested that for the majority of the season, soil moisture deficits at Ireland 16 were kept below limiting deficits. However, there may have been a brief period during late June when the cop may have failed to meet atmospheric water demand, and the RUE may have been reduced but this was unlikely to have had a large effect on yield. The irrigation model also identified periods when soils were above field capacity and some drainage occurred (see later section). The wet period in late July and early August may have resulted in some temporary soil water logging and consequent loss of yield. Recent work (Bange et al. 2004) has shown that cotton crops grown in waterlogged soils had RUEs 35 % smaller than those grown in drier soils. There has been little equivalent work on the effect of soil saturation on the growth and yield of potato, although Stalham (2010) found the canopies of crops grown in saturated soils had reduced persistence. However, we have no detailed information on how periods of soil saturation may reduce RUE in the short-term and reduce ground cover in the longer-term. In summary, the modelling data suggest that the crop at Gravel Pit grew in a way predictable by its canopy persistence but the performance of the crop Ireland 16 may been limited by factors other than canopy persistence and radiation absorption.

(a)

(b)

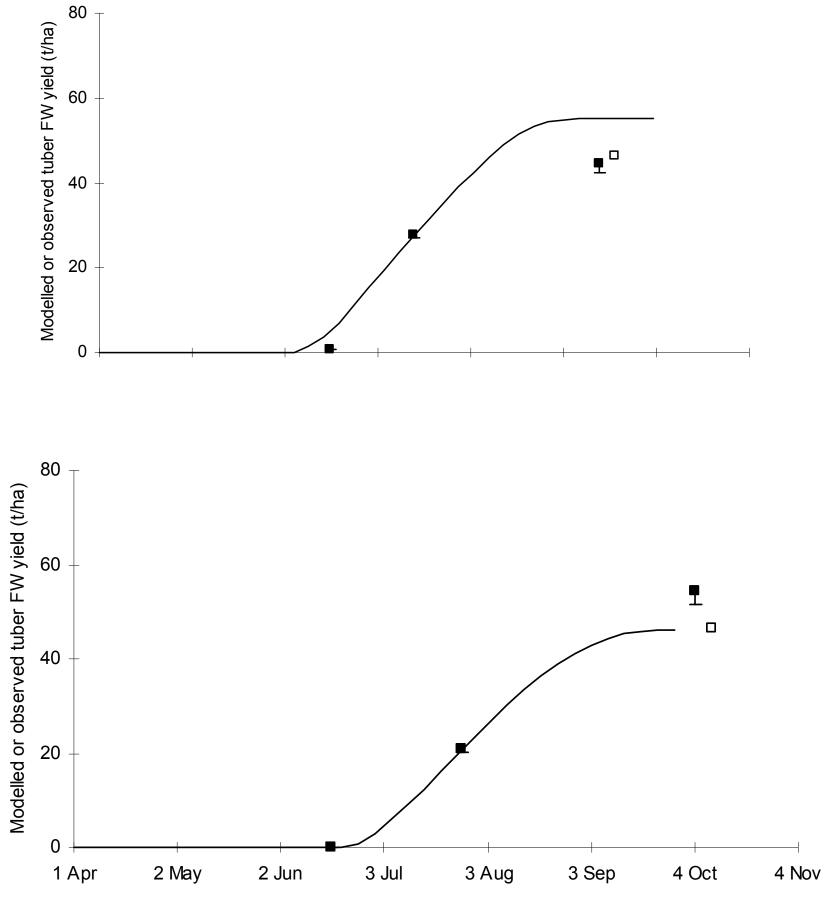


FIGURE 30. MODELLED (BLACK LINE), SAMPLED (■) AND COMMERCIALLY-ACHIEVED YIELD (□) FOR (A) IRELAND 16 AND (B) GRAVEL PIT.

15.2.4. Crop nitrogen uptake and canopy persistence

Estimates of maximum total N uptake were similar for both crops (235 kg N/ha at Ireland 16 and 225 kg N/ha for Gravel Pit (Figure 31). Maximum haulm N uptake was estimated to be 142 and 112 kg N/ha at Ireland 16 and Gravel Pit, respectively. The rate of tuber N uptake at Ireland 16 was 14.5 kg N/TJ energy absorbed which was slightly smaller than values found in a similar experiment in 2009 (mean 16.3 kg N/TJ) but slightly larger than in 2008 (13.4 kg N/TJ). At Gravel Pit the rate of tuber N uptake was relatively fast (21.0 kg N/TJ) and is consistent with less energy being absorbed by the canopy during the season than in Ireland 16 despite having a similar total N uptake. Using the N uptake data, analysis showed that the crop at Gravel Pit had the potential to absorb c. 11.3 TJ/ha and it absorbed 11.2 before it completely senesced. As discussed in the previous section the growth of the crop at Ireland 16 was somewhat unusual. On the basis of its haulm N uptake and its rate of tuber N uptake, the crop at Ireland 16 had the potential to absorb c. 14.2 TJ/ha but it only absorbed 12.62 TJ/ha. These data also suggest that this crop was not able to fully exploit the N it had invested in its canopy and this may also be indicative of stress.

(a)

(b)

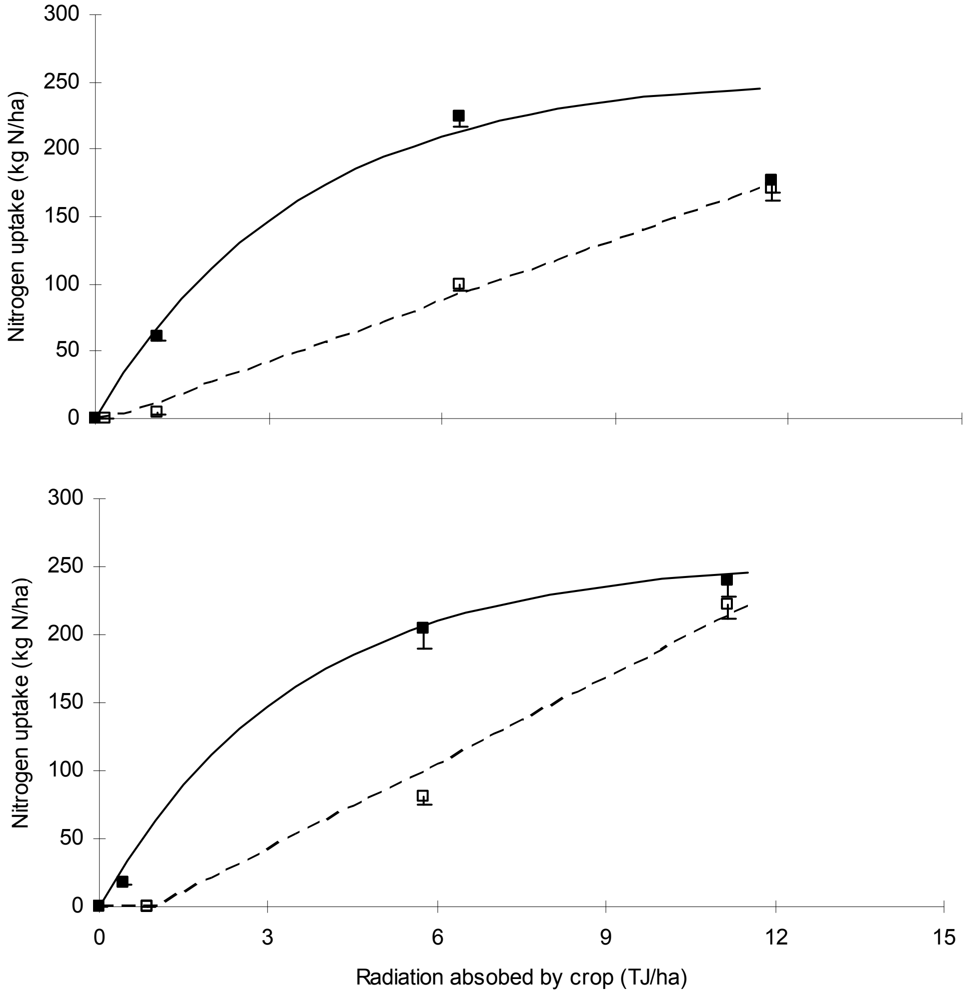


FIGURE 31. NITROGEN UPTAKE OF LADY ROSETTA AT (A) IRELAND 16 AND (B) GRAVEL PIT. TOTAL N, ■ AND SOLID BLACK LINE AND TUBER N, □ AND DASHED BLACK LINE.

15.2.5. Crop usage of N fertilizer in wheelings

An average of 50 kg N/ha was applied as a top dressing at both sites. Measurements of ridge and wheeling dimensions showed that the average wheeling width was c. 30.5 cm or 16.7 % of the distance between wheeling centres (Figure 19). The weight of fertilizer N collected on the polythene sheets laying in the wheeling is shown in Table 71. At Ireland 16, 93 kg N/ha was measured in the wheeling which was equivalent to an average field rate of c. 16 kg N/ha. Therefore, of the 50 kg applied as a top-dressing about one third ended up in the wheeling. These values also suggest that apart from prills that fall directly into the wheeling, a substantial amount also bounce off the flanks and top of the ridge. At Gravel Pit, a slightly larger amount of N was recovered in the wheeling. This difference in amount may be due to the top-dressing at Ireland being applied at 26 DAE when ground covers were c. 55 % compared with Gravel Pit where the top-dressing was applied at 13 DAE when ground covers were c. 30 %. The larger canopy at Ireland 16 probably intercepted some prills and stopped them falling into the wheeling. Whilst a larger canopy may prevent some N getting into the wheeling, this strategy will tend to increase the risk of fertilizer prills scorching the canopy. Furthermore, if the top-dressing is applied too late then the N will not be used efficiently by the crop.

	Ireland 16	**Gravel Pit**
Actual amount of N in wheeling bottom (kg N/ha)	93 (±8.7)	110 (±7.1)
Field average amount of N in wheeling bottom (kg N/ha)	16 (±1.4)	18 (±1.2)

TABLE 71. ACTUAL AND FIELD-AVERAGE AMOUNT OF N FERTILIZER FOUND IN WHEELING BOTTOMS RESULTING FROM A TOP-DRESSING OF 50 KG N/HA

It has been assumed that N fertilizer falling into the wheelings is not used efficiently by the crops and since rooting density is likely to be less than in the ridge and as wheelings are often wetter than ridges, N falling into the wheelings could lost by leaching or denitrification. The effect of removing N from the wheelings on components of yield is shown in Table 72. The total N application rate where the N was left in the wheeling (i.e. the standard commercial crop) was 210 kg N/ha but removing the N from the wheeling reduced the total N application rate to 194 and 192 kg N/ha at Ireland 16 and Gravel Pit, respectively. At both sites, once the standard errors associated with the means are considered, the plant, stem and tuber populations in area with and without top-dressing N in the wheelings were similar. At Ireland 16, reducing the total amount of N applied from 210 to 194 kg N/ha was associated with an increase in tuber FW yield from 44.6 to 48.4 t/ha but in Gravel Pit the yield was numerically smaller. When averaged over sites, removing the N from the wheeling had no effect on tuber yield. A paired T-test at each site also indicated that any difference in yield was not statistically significant. Whilst this is a small sample size, these data are consistent with the hypothesis that N fertilizer in the wheelings is not used efficiently by the crop. A practical solution to this problem may be to use liquid top dressings which could be banded on the ridges thus minimising the amount of N in the wheelings. Alternatively, more N could be applied as the basal application which would remove or reduce the need for any further N applications.

	Ireland 16 (15 September)		Gravel Pit (4 October)	
	N in furrow	N removed	N in furrow	N removed
Plant population (000/ha)	45.2 (±0.89)	45.9 (±0.89)	34.3 (±0.89)	35.0 (±1.46)
Stem population (000/ha)	118 (±3.4)	128 (±5.7)	117 (±9.4)	123 (±15.5)
Tuber population > 10 mm (000/ha)	597 (±14.8)	647 (±23.8)	554 (±38.3)	535 (±44.5)
Tuber FW yield > 10 mm (t/ha)	44.6 (±2.38)	48.4 (±1.22)	54.4 (±2.95)	50.5 (±0.45)
Tuber DM concentration (%)	24.1 (±0.33)	24.7 (±0.21)	26.3 (±0.26)	26.4 (±0.21)
Mean tuber size (mm)	49.1 (±0.88)	49.1 (±1.05)	55.7 (±1.30)	54.7 (±1.64)

TABLE 72. EFFECT OF REMOVING N FROM FURROW-BOTTOMS ON YIELD OF LADY ROSETTA AT TWO LOCATIONS

15.2.6. Nitrogen response experiments

Basal or total N application had no effect on plant, mainstem or tuber populations and the values for each site are shown in Table 73. At both sites, the average mainstem and tuber populations were similar to those recorded in the commercial crops (Table 73). At Ireland 16, increasing the basal N application rate from 80 to 120 kg N/ha increased tuber DM concentration from 23.1 to 24.2 %, but the effects of total N application rate were not statistically significant. The mean tuber DM concentration at Gravel Pit was 26.0 % and this was not affected by either the quantity of basal or total N applied. At Ireland 16, increasing the basal N application rate from 80 to 160 kg N/ha increased tuber FW yield from 46.4 to 54.4 t/ha (Table 74). Increasing the total amount of N applied from 160 to 280 kg N/ha had no statistically significant effect on yield. At Gravel Pit, the mean yield was 46.6 t/ha and increasing the basal N application rate from 80 to 160 kg N/ha resulted in a small numeric increase in yield but this was not statistically significant. As found at Ireland 16, increasing the total amount of N applied from 160 to 280 kg N/ha had no effect on yield. Collectively, these data show that, for these two sites, tuber FW yield was largest when the amount of N applied at planting was largest. Since, the effect of total N application rate on tuber yield was not statistically significant, the optimum N application rate at both sites was probably c. 160 kg N/ha. It seems probable that the largest yield could have been achieved at both sites by applying 160 kg N/ha at planting and omitting any further top-dressings. It is not known whether tuber yield could have been larger if more than 160 kg N/ha had been applied at planting and this could be investigated in future experiments. However, increasing the amount of N placed close to the seed tuber at planting may result in slow and erratic plant emergence and experiments that test increased rates of placed fertilizer will need to carefully monitor emergence and early canopy development in relation to prevailing environmental conditions.

	Ireland 16	Gravel Pit
Plant population (000/ha)	27.0 (±2.11)	33.5 (±2.57)
Stem population (000/ha)	120 (±17.1)	126 (±15.2)
Tuber population > 10 mm (000/ha)	646 (±78.3)	573 (±54.7)

TABLE 73. AVERAGE PLANT, STEM AND TUBER POPULATIONS IN THE NITROGEN RESPONSE EXPERIMENTS AT IRELAND 16 AND GRAVEL PIT

Ireland 16	Total N applied (kg N/ha) 160	190	220	250	280	Mean
Basal N (kg N/ha)						
80	42.3	42.8	48.3	50.7	48.1	46.4
120	50.1	52.1	47.5	54.0	55.9	51.9
160	54.0	52.4	53.7	57.2	54.5	54.4
Mean	48.8	49.1	49.8	54.0	52.8	50.9
S.E. Basal N (6 D.F.) 1.64; S.E. Total N (36 D.F.) 1.68; S.E. Basal*Total N (36 D.F.) 3.08, except when comparing the same amount of basal N, 2.91						
Gravel Pit						
Basal N (kg N/ha)						
80	45.4	47.3	45.1	44.6	46.0	45.7
120	47.9	44.6	47.0	48.9	46.5	47.0
160	47.5	45.6	47.5	48.7	46.6	47.2
Mean	47.0	45.8	46.5	47.4	46.4	46.6
S.E. Basal N (6 D.F.) 1.10; S.E. Total N (36 D.F.) 1.01; S.E. Basal*Total N (36 D.F.) 1.92, except when comparing the same amount of basal N, 1.76						

TABLE 74. EFFECT OF BASAL AND TOTAL N APPLICATION RATE ON TUBER FW YIELD (T/HA) AT IRELAND 16 AND GRAVEL PIT

15.2.7. Efficiency of N use

15.2.8. Timing of N application in relation to crop development

In 2010, commercial crops received 160 kg N/ha at planting and a single application of 50 kg N/ha as a top dressing. For the crop of Lady Rosetta grown at Ireland 16, the top dressing was applied 26 DAE whereas at Gravel Pit it was 13 DAE. Studies at CUF have shown that the rate of total N uptake decreases as the season progresses and fertilizer applied much after tuber initiation is unlikely to have much effect on total N uptake nor, in consequence, on yield. For both crops in 2010, the top dressings were applied sufficiently early in the season for the crops to use the N relatively efficiently.

15.2.9. Leaching of N as a consequence of drainage

Leaching of N from potato fields is often invoked as a cause of significant N loss leading to reduction in yield potential and possible environmental damage. Irrigation for both Lady Rosetta crops was scheduled using the CUF Irrigation model and a sub-routine within the model can estimate the amount of water that drains from the soil and becomes unavailable to the crop. At Ireland 16, the amount of drainage from May to August was estimated to be c. 62 mm compared with 49 mm at Gravel Pit. At both sites c. half of the drainage occurred between 6 and 9 June. The N concentration of this drainage water was not measured, but it is possible that some N was moved below the rooting system. However, there was little evidence that total N uptake of either crop of Lady Rosetta was impaired by this loss since measurement showed total N uptake values similar to or greater than those measured in previous seasons (Table 69 and Table 70).

15.2.10. Soil sampling – soil mineral N

Soil mineral N was measured at both sites on two occasions and for both crops the first sample was taken immediately before top-dressing and the second at final harvest (Table 75). For the first sampling at Ireland 16 i.e. most mineral N was in the centre of the ridge (position 'B' in Figure 19) and relatively little N was found in the wheelings (position 'C' in Figure 19). At final harvest, the amount in the ridge and centre of the bed had decreased but there was slightly more N in the wheeling. For the first sampling at Gravel Pit, the distribution of soil mineral N was similar to that at Ireland 16 – most N was in the ridge centre and least in the wheeling. Between the first and second samplings the amount of mineral N had decreased in all locations. When averaged over the three sample locations, the average amount of mineral N at final harvest at Ireland 16 was 72 kg N/ha compared with 45 kg N/ha at Gravel Pit. In similar experiments in 2008 and 2009, the average amount of N remaining in the soil varied from 56 kg N/ha (Woodyard, 2008) to 95 kg N/ha (Hollow Heath, 2009).

Table 76 relates the amount of basal N applied at planting and the application method to the amount of N measured in the wheelings before the top dressings were applied. Broadcasting the basal N application at planting was associated with larger amounts of mineral N in the wheelings particularly when 180 kg N/ha was broadcast in 2009. However, placing 160 kg N/ha was associated with the smallest amount of mineral N in the wheelings. These data should be interpreted with care since the comparisons are confounded and there are no direct comparisons between broadcasting and placement in any individual site and year. However, these data suggests that placing the N reduced the amount of N found in the wheelings and since other work suggest than N in the wheeling is not used efficiently by the crop, placement of N may have some advantages.

		Ireland 16		**Gravel Pit**	
Sample location	**Depth (cm)**	**17 June**	**15 September**	**18 June**	**5 October**
Wheeling	0-30	17 (±2.4)	21 (±5.5)	33 (±8.9)	12 (±1.9)
	30-60	18 (±9.6)	18 (±6.3)	17 (±1.7)	13 (±1.3)
	60-90	15 (±5.5)	20 (±3.4)	19 (±2.4)	14 (±1.8)
	0-90	37 (±17.3)	59 (±11.6)	69 (±11.4)	39 (±3.4)
Ridge centre	0-30	85 (±56.5)	16 (±1.7)	88 (±22.3)	9 (±0.7)
	30-60	52 (±18.5)	68 (±39.9)	187 (±69.2)	16 (±1.0)
	60-90	24 (±2.1)	35 (±15.6)	58 (±14.1)	31 (±7.9)
	0-90	162 (±52.4)	118 (±57.0)	322 (±60.3)	56 (±6.7)
Bed centre	0-30	15 (±0.7)	14 (±0.8)	29 (±2.3)	9 (±1.3)
	30-60	29 (±5.5)	10 (±1.2)	37 (±3.1)	14 (±1.9)
	60-90	25 (±3.8)	19 (±9.0)	25 (±1.4)	16 (±2.1)
	0-90	69 (±6.3)	38 (±9.5)	91 (±2.3)	39 (±3.1)

TABLE 75. SPATIAL AND TEMPORAL VARIATION IN SOIL MINERAL N (KG N/HA) AT IRELAND 16 AND GRAVEL PIT. EACH VALUE IS THE MEAN OF FOUR REPLICATES

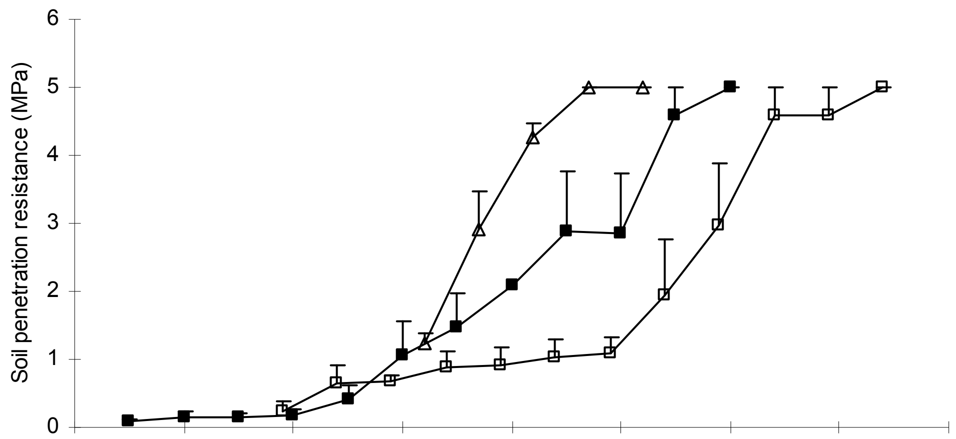
Season	Field	Variety	Basal N (kg N/ha)	Method of application	Date of planting	Date of sampling	N in wheeling (kg N/ha)
2008	Woodyard	Lady Rosetta	130	Broadcast	13 March	8 May	155 (±5.1)
2008	North Whinns	Courage	130	Broadcast	8 April	8 May	158 (±18.4)
2009	Thorns	Lady Rosetta	180	Broadcast	19 March	29 Apr	170 (±42.0)
2009	Hollow Heath	Lady Rosetta	180	Broadcast	28 April	28 May	301 (±53.0)
2010	Ireland 16	Lady Rosetta	160	Placed	20 April	17 June	37 (±17.3)
2010	Gravel Pit	Lady Rosetta	160	Placed	7 May	18 June	69 (±11.4)

TABLE 76. COMPARISON OF AMOUNT OF SOIL MINERAL N (0-90 CM) FOUND IN WHEELINGS IN 2008–2010 IN RELATION TO BASAL N APPLICATION AT PLANTING. SOIL SAMPLES WERE TAKEN BEFORE TOP-DRESSINGS WERE APPLIED AND EACH VALUE IS THE MEAN OF FOUR REPLICATES

15.2.11. Soil sampling – soil penetration resistance

Previous work on penetration resistance has shown that the rate of potato root extension halves once soil resistance exceeds 1 MPa and it effectively ceases above 3 MPa (Stalham et al. 2007). Figure 32 shows soil penetration resistance at three positions in both fields of Lady Rosetta. For both sites, the soil resistance in the wheeling increased rapidly with depth and was c. 3 MPa at a depth of 30–35 cm relative to the top of the ridge. Similarly large resistances in the wheelings were found in previous studies in 2008 and 2009. Whilst this soil resistance generally prevents root extension some roots may be able to penetrate by growing around stones and clods. At Ireland 16, soil resistance in the centre of the bed was less than 3 MPa up to a depth of c. 60 cm whereas resistance was 3 MPa in the ridge-centre at c. 50 cm. At Gravel Pit, the increase in soil resistance with depth in the ridge- and bed-centres was similar and both locations had soil resistance of 3 MPa at c. 50 cm. The data suggest that the soils at Gravel Pit were slightly more compact than at Ireland 16 and this difference may explain the slight slowing in ground cover expansion noted earlier (Figure 29).

(a)



(b)

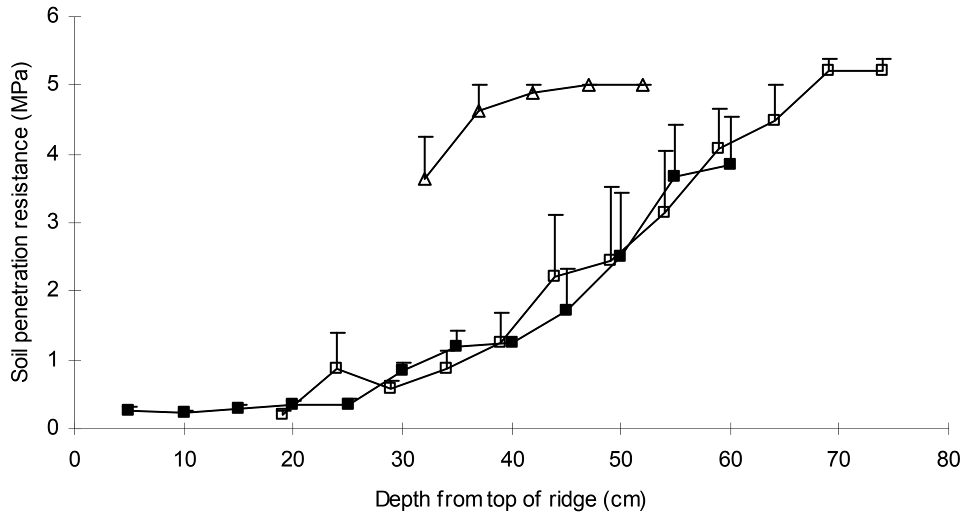


FIGURE 32. SOIL PENETRATION RESISTANCE FOR LADY ROSETTA CROPS (A) IRELAND 16, 18 JUNE AND (B) GRAVEL PIT, 17 JUNE. SAMPLING POSITIONS: RIDGE CENTRE, ■; BED CENTRE, □ AND △, WHEELING.

15.2.12. Rooting Density

Due to the very slow root extraction process, root cores from only three replicates were extracted at Gravel Pit. In general, root length densities were larger at Ireland 16 than at Gravel Pit and, irrespective of site or position, there were relatively few roots at 30-40 cm depth (Table 77). When compared with other sampling positions there were relatively few roots within the wheelings (position 'C'). At Ireland 16, paired T-tests showed that root densities in the wheeling were significantly smaller at 20-30 cm depth than in position A. At 30-40 cm depth, root densities were also numerically smaller in position C than in position A or B but the difference was not statistically significant. At Gravel Pit, root densities at 20-30 or 30-40 cm depth in position C were numerically smaller than densities at equivalent depths in either position A or B but, due to the limited replication and relatively large errors, these differences were not significantly different.

Position Depth (cm)	A 10-20	A 20-30	A 30-40	B 10-20	B 20-30	B 30-40	C 20-30	C 30-40
Ireland 16								
Mean	1.68	1.87	0.67	1.97	1.78	0.56	1.04	0.34
S.E.M.	0.373	0.247	0.153	0.373	0.385	0.078	0.191	0.060
Gravel Pit								
Mean	1.55	0.76	0.37	1.42	0.85	0.28	0.42	0.04
S.E.M.	0.338	0.027	0.131	0.508	0.174	0.158	0.237	0.008

TABLE 77. EFFECT OF SAMPLING POSITION AND DEPTH ON ROOT LENGTH DENSITY (CM/CM^3) AT TWO SITES. DEPTHS ARE RELATIVE TO THE SOIL SURFACE AT POSITION 'B'

Collectively, these data support the hypotheses that rooting density in the wheeling (position C) tends to be smaller than that at an equivalent depth under the planted ridge (position B) or in the centre of the ridges (position A). As average root length density under the wheeling was < 50 % of that in the ridge it would seem logical that, where possible, N fertilizer should be kept out of the wheelings since it is unlikely to be used efficiently by the crop. Furthermore, since the wheelings are often wetter than ridges, N falling into the wheelings is probably at greater risk of loss from either denitrification or from leaching.

15.3. Conclusions

These experiments have shown that the yield of the two Lady Rosetta crops was not limited by N supply and this is consistent with findings in similar experiments in 2008 and 2009. The study has also shown that yields have been maintained whilst N application rates have been reduced. This finding is consistent with results obtained from the Grower Collaboration Project. In part, the potential for reduction in N fertilizer application rates is due to a probable starting point of excess application but this study has also indicated that savings in N fertilizer can also be made by more efficient use of N fertilizer. Increases in N use efficiency can benefit the grower and the wider environment. Analysis of data from 2008–2010 has shown that the yields of these crops were generally explicable in terms of canopy persistence and radiation absorption and, with the possible exception of Ireland 16 in 2010, factors such as water availability, pests and diseases had relatively little effect on the final achieved yield. Collectively, these data suggest that yields were not limited by inputs and thus larger yields would not automatically result from increased applications of N or water. Over the three seasons of this study, hand-dug sample yields at final harvest have ranged from 44.6 t/ha (Lady Rosetta, Ireland 16, 2010) to 65.5 t/ha (Courage, North Whinns, 2008) and averaged 54.6 t/ha. The causes for this variation in yield and the small yields at some sites is not known but may due to combinations of physical factors such as compaction and cloddiness or excess water and biological factors such as pathogens, cyst and free-living nematodes. Future work will concentrate on quantifying the effects of some of these factors which will lead to a better understanding of yield formation and yield variation in commercial crops.

16. SOIL CONDITIONS, CROP GROWTH, N NUTRITION AND YIELD

16.1. Introduction

Experiments in 2006 and 2007 tested the effects of soil cultivation, irrigation and N application rate on yields and N nutrition of Maris Piper. In these experiments, soils that were cultivated whilst too wet suffered yield penalties and these yield penalties were only partially removed by scheduling irrigation and N applications. Analysis of N uptake data showed that treatment differences in total DW and tuber FW yield were explicable in terms of N uptake and partitioning between haulm and tubers. The objective of the 2008 experiment was to further investigate the effects of soil conditions, water and nitrogen supply on crop growth and yield.

16.2. Materials and Methods

16.2.1. CUF 2008

The experiment in 2008 tested all combinations of two cultivation regimes (Unsmeared, Smeared); three irrigation regimes (Unirrigated, Irrigated, Over-irrigated), two clod size distributions (Cloddy, Fine) and two nitrogen (N) application rates (0 and 200 kg N/ha). The experiment was a randomized split-plot design with four replicates containing cultivation, irrigation and cloddiness treatments allocated at random to mainplots and nitrogen fertilizer treatments allocated at random to sub-plots.

16.2.2. Cultivation, irrigation and cloddiness treatments

Details of the sequence of cultivations, irrigation and planting operations are given in Table 78. The average soil texture was a sandy loam but with coarser- and finer-textured areas within the experimental area. Stone content was slight to moderate (7-14 % volumetric) in the top 35 cm. Plots where the intention was to create a fine tilth were rotavated shallowly soon after ploughing and some time before the main cultivation to reduce the clod size. To create wet soil for the main cultivation, half the plots were irrigated in the afternoon preceding cultivation. The water content of the soil at 20-25 cm depth was measured immediately post-irrigation using a Delta-T Devices Theta Probe ML-2. The Unsmeared plots had a soil water content of 30.1 % and the Smeared plots 37.7 %. Following overnight drainage, the water content at cultivation depth was 30.2 % and 33.1 % for Unsmeared and Smeared, respectively. The main cultivation treatment was carried out in the lowest possible gear and with high rotor speed to create as much smearing in the wetted soil as possible. The flat profile remaining after the main cultivation was ridged within 2 hours.

Operation	Date
Plough @ 25–30 cm	2 April
Rotavate with Howard rotavator @ 10-15 cm (Fine plots only)	3 April
Irrigation (21.1 mm) on Smeared plots	24 April (12:35-17:00 h)
Rumpstad Rotoridger (ridging bodies removed) @ 25 cm	25 April (8:30-11:00 h)
Ridged with fixed-body Cousins ridger	25 April (12:00 h)
Planted and fertilizer applied	28 April
Re-ridged with fixed-body Cousins ridger	28 April

TABLE 78. DETAILS OF CULTIVATION AND IRRIGATION OPERATIONS AROUND PLANTING, CUF 2008

16.2.3. Irrigation

Overhead irrigation was applied through a boom (RST Irrigation) and hose reel (Perrot SA, SH63/280) combination. Plots were differentially irrigated by turning nozzles on or off along the length of the boom. Nozzles were spaced at c. 0.5 m, so individual plots could be irrigated. Where the randomisation of plots necessitated, the flow of water to the boom was turned off and the boom wound in using the tractor PTO shaft until the next strip of plots. Mean irrigation amounts were estimated from 32 raingauge readings per irrigation treatment, situated at ground level and not shielded by foliage. Irrigation timings and amounts are shown in Table 79. The Unirrigated treatments received only rainfall whilst the Irrigated plots were targeted not to exceed 30 mm soil moisture deficit (SMD). The Over-irrigated plots had irrigation applied 2-4 days after a previous irrigation or closely following large rainfall events so that appreciable over-fill of the soil occurred.

	Irrigation treatment	
Date	Irrigated	Over-irrigated
19 June	18.7	18.7
26 June	21.6	21.6
1 July	21.6	21.6
3 July		29.9
18 July		30.1
25 July	24.4	24.4
29 July		30.4
1 August	17.9	17.9
4 August		30.0
14 August		30.2
29 August	21.5	21.5
Total	125.7	276.3

TABLE 79. IRRIGATION TIMINGS AND AMOUNTS (MM) FROM PLANTING TO FINAL HARVEST, CUF 2008

16.2.4. Crop planting, sampling and analysis

The experiment was planted by hand using Maris Piper (certification grade SE1; 25-35 mm; 2030 count/50 kg) into pre-formed ridges on 28 April. The ridges had 76.2 cm centres and the within-row spacing was 25 cm giving an intended plant population of 52 500/ha. Each plot was eight rows (6.1 m) wide and 8.0 m long for 200 N treatments and 4.5 m for 0 N. There was a 2 m gap between strips of plots to allow irrigation nozzles to be switched on or off between plots. The N treatments were applied as ammonium nitrate fertilizer immediately after planting as a single dressing. The fertilizer was then incorporated and the ridges reformed using a fixed-body Cousins ridger.

Plant emergence was measured every 3-5 days until complete and ground covers were measured weekly from 50 % plant emergence to final harvest using a grid. Crop samples to measure yield and N uptake were taken on four occasions (24 June, 21 July, 26 August and 24 September). Samples were process and data were analysed as described on page 13.

16.2.5. CUF 2009

The experiment examined all combinations of four soil water contents (25 cm depth) at cultivation (Moist, Field Capacity (FCap), Wet and Over-wet (OWet)); two irrigation regimes (Unirrigated (Un) and Irrigated (Irr)) and two dates of planting (15 and 29 April). The experiment was a randomized block design with three replicates containing cultivation, irrigation and planting date treatments allocated at random to plots.

16.2.6. Cultivation, irrigation and date of planting treatments

Details of the sequence of cultivations, irrigation and planting operations are given in Table 80. The average soil texture was a sandy clay loam (28 % clay) but with coarser- (sandy loam) and finer- (clay loam) textured areas within the experiment. Stone content was slight (mean 5.8 %). To create wet soil for the main cultivation, all plots except the Moist cultivation treatment were irrigated just prior to cultivation. The water content of the soil at 25 cm depth was measured immediately post-irrigation using a Delta-T Devices Theta Probe ML-2 and HH2 meter and then every 3-12 hours as the soil initially drained of excess water and then dried through evaporation. The intention was to cultivate at 26, 29, 32 and 36 % water content for the Moist, Field Capacity, Wet and Over-wet treatments, respectively, but the actual water contents were as detailed in Table 81. At the earliest planting, 18.8 mm of irrigation increased the soil water content at 25 cm from 26.9 to 36.1 %, whereas it only increased it from 26.5 to 33.9 % at the later planting owing to the topsoil being drier (Table 81). The cultivation treatment was carried out using a Howard rotavator operating at the slowest possible forward speed and with high rotor speed to allow the tines to spend as much time as possible working at the cultivation front. The flat profile remaining after rotavating was ridged using a Cousins fixed-body ridger for planting when the last cultivation treatment had been completed.

Operation	Plots treated	Planting date 15 April	 29 April
Plough @ 25–30 cm	All	3 March	3 March
Spring tine @ 10-15 cm	All	6 April	6 April
Irrigation (18.8 mm)	Field Capacity, Wet, Over-wet	7 April (13:00-15:40 h)	27 April (12:00-15:00 h)
Rotavate @ 20-25 cm	Moist	7 April (11:00 h)	27 April (9:00 h)
	Field Capacity	8 April (16:20 h)	29 April (10:00 h)
	Wet	8 April (10:00 h)	28 April (11:00 h)
	Over-wet	7 April (16:00 h)	27 April (16:00 h)
Ridged	All plots	9 April (14:00 h)	29 April (12:00 h)
Planted	All plots	15 April (8:30 h)	29 April (14:00 h)
Re-ridged	All plots	15 April (14:00 h)	29 April (16:00 h)

TABLE 80. DETAILS OF CULTIVATION AND IRRIGATION OPERATIONS, CUF 2009

Operation	Treatment	Moisture content at operation 15 April	 29 April
Plough	All	32.9 ± 0.29	32.9 ± 0.29
Pre-irrigation	All	26.9 ± 1.42	26.5 ± 1.61
Post irrigation	Field Capacity, Wet, Over-wet	36.1 ± 0.79	33.9 ± 0.90
Rotavate	Moist	26.9 ± 1.42	26.5 ± 1.61
	Field Capacity	29.6 ± 1.63	28.6 ± 1.21
	Wet	32.2 ± 1.15	32.0 ± 0.50
	Over-wet	36.2 ± 1.21	34.7 ± 0.90

TABLE 81. SOIL WATER CONTENT (% VOLUMETRIC) AT 25 CM DEPTH AT VARIOUS OPERATIONS, CUF 2009

Overhead irrigation was applied through a boom (RST Irrigation) and hose reel (Perrot SA, SH63/280) combination. Unirrigated treatments received only rainfall whilst the Irrigated plots were targeted not to exceed 25 mm soil moisture deficit using the CUF Potato Irrigation Scheduling model. Nine applications (20.3-25.8 mm) totalling 223 mm were made on 3, 19 and 26 June, 3 and 14 July, 17 and 25 August and 7 and 17 September.

16.2.7. Crop planting, sampling and analysis

The experiment was planted by hand using Maris Piper (certification grade E1; 35-40 mm; mean weight 40 g) into pre-formed ridges on the dates shown in Table 80. The ridges had 76 cm centres and the within-row spacing was 30 cm giving an intended plant population of 43 700/ha. Each plot was four rows (3.0 m) wide and 12 m long. There was a 5 m gap between strips of plots to allow tractors to turn and irrigation nozzles to be switched on or off between plots. Following planting, the ridges were re-built using a Cousins fixed-body ridger. A solution of concentrated (34.6 % vol.) ammonium nitrate fertilizer (180 kg N/ha) was applied using a tractor sprayer on 30 April.

Plant emergence in the two central harvest rows was measured every 1-4 days until complete and ground covers were measured weekly from 50 % plant emergence to final harvest in two positions within each plot using a grid. Crop samples to measure yield were taken on four occasions. The initial sample was on 19 June for 15 April planting and 23 June for 29 April planting and subsequent harvests for both plantings were on 17 July, 6 August and 28 September. At each harvest, eight plants (1.83 m2) were taken from the two central harvest rows of each plot.). Samples were process and data were analysed as described on page 13.

16.2.8. CUF 2010

The cultivation experiment in 2010 examined all combinations two primary cultivation techniques (Plough and Non-plough), two dates of cultivation (Early and Late), two varieties (Lady Rosetta and Maris Piper) and two rates of N fertilizer (0 and 180 kg N/ha). The experiment was a split-plot design with cultivation treatments as main-plots and variety and N-rate allocated to sub-plots with three replicates.

16.2.9. Cultivation, irrigation and date of planting treatments

Details of the sequence of cultivation and planting operations are given in Table 82. The average soil texture was a clay loam (48 % sand, 27 % silt and 25 % clay) but with lower clay content (23 %) in the middle of the experimental area than at either end (26 %). Stone content was moderate (mean 12 %). The water content of the soil at 25 cm depth was measured immediately prior to each cultivation operation by digging a pit with a spade and using a Delta-T Devices Theta Probe ML-2 and HH2 meter. Six replicate readings were taken in different locations within each plot.

	Cultivation			
Operation	**Plough Early**	**Non-plough Early**	**Plough Late**	**Non-plough Late**
Simba SLD @ 30 cm	4 September	4 September	4 September	4 September
Plough @ 30 cm	16 March		6 April	
Keeble Progressive @ 15 cm				6 April
Keeble Progressive @ 20 cm				8 April
Keeble Progressive @ 30 cm				13 April
Rumptstad Rototiller @ 25 cm	16 March	16 March	14 April	14 April
Re-ridge (Cousins)	14 April	14 April	14 April	14 April
Plant	19 April	19 April	19 April	19 April

TABLE 82. DETAILS OF CULTIVATION AND IRRIGATION OPERATIONS, CUF 2010

Overhead irrigation was applied through a boom (RST Irrigation) and hose reel (Perrot SA, SH63/280) combination. Plots were targeted not to exceed 30 mm soil moisture deficit (SMD) using the CUF Potato Irrigation Scheduling model. Nine applications (17-26 mm) totalling 206 mm were made on 28 May, 18, 21 and 30 June, 7, 13, 19, 23 and 30 July. No irrigation was required in August and September.

16.2.10. Crop planting, sampling and analysis

The experiment was planted by hand using Maris Piper (certification grade E1; 25-30 mm; mean weight 21 g) and Lady Rosetta (grade SE2; 35-40 mm; mean weight 36 g) seed into pre-formed ridges. The ridges had 76 cm centres and the within-row spacing was 25 cm giving an intended plant population of 52 500/ha. Each plot was four rows (3.0 m) wide and 12 m long and was planted at right angles to the normal row direction in the field so that the cultivation treatments could be carried out effectively. No fertilizer other than nitrogen for N treatments was applied as soil indices for P, K & Mg were high (4, 2+, 2, respectively).

Plant emergence in the two central harvest rows was measured every 1-4 days until complete and ground covers were measured weekly from 50 % plant emergence to final harvest in two positions within each plot using a grid. Crop samples to measure yield and nitrogen uptake were taken on four occasions, 18 June, 22 July, 23 August and 27 September. At each harvest, 12 plants (2.29 m^2) were taken from the two central harvest rows of each plot.

17. CUF 2008

17.1. Results and Discussion

17.1.1. Emergence, ground covers and radiation absorption

The mean date for 50 % plant emergence was 26 May (28 DAP). Soil conditions (smearing or cloddiness) had no significant effect on plant emergence, however, increasing the N application rate from 0 to 200 kg N/ha delayed 50 % emergence by c. 1 day. Complete emergence was achieved in most plots. The effects of irrigation regime, soil condition (Smeared and Unsmeared) and N application rate on ground cover are shown in Figure 33 and key ground cover data and radiation absorption data are shown in Table 83.

When averaged over all treatments, the maximum ground cover was c. 98 % and maximum ground cover was significantly increased by applying irrigation, growing the crop in Unsmeared soil and applying 200 kg N/ha. Applying 200 kg N/ha resulted in complete ground cover irrespective of soil conditions or the amount of irrigation. The rate of increase of ground cover was estimated from the parameters of a logistic (growth) curve fitted to pre-senescence ground cover data. These data show that the rate of increase of ground cover was increased by applying water and N and when the crop was grown in Unsmeared soils. The average canopy persistence was 8927 % days (compared with 7818 and 8804 % days in similar experiments in 2006 and 2007, respectively). When averaged over factors, canopy persistence was increased by c. 800 % days when irrigation was applied and by c. 1400 % days when the N application rate was increased from 0 to 200 kg N/ha. Growing the crop in Smeared soil reduced canopy persistence by c. 500 % days. Whether the soil was cloddy or not had no significant effect on the maximum ground cover attained, the rate of ground cover expansion, or integrated ground cover. The overall average radiation absorption by the crop was 13.16 TJ/ha (in 2006 and 2007 the values were 13.14 and 13.22 TJ/ha, respectively). Radiation absorption was increased by N and water but was decreased when the crops was grown in Smeared soil. Soil cloddiness had no statistically significant effect on radiation absorption by the crop.

	Maximum ground cover (%)	Rate of GC increase, 40-60 % (%/day)	Integrated GC (% days)	Radiation absorption (TJ/ha)
Mean	97.7	3.40	8927	13.16
Unirrigated	96.0	3.10	8324	12.38
Irrigated	98.1	3.54	9180	13.49
Over-irrigated	99.0	3.56	9277	13.61
S.E. (33 D.F.)	0.54	0.102	127.8	0.184
Smeared	96.9	3.14	8657	12.76
Unsmeared	98.5	3.66	9197	13.56
S.E. (33 D.F.)	0.44	0.083	104.3	0.150
Fine tilth	97.9	3.32	8805	13.01
Cloddy tilth	97.5	3.47	9049	13.32
S.E. (33 D.F.)	0.44	0.083	104.3	0.150
0 kg N/ha	95.4	2.71	8210	12.15
200 kg N/ha	100.0	4.09	9643	14.17
S.E. (36 D.F.)	0.52	0.064	104.2	0.140

TABLE 83. MAIN EFFECTS OF IRRIGATION, CULTIVATION AND N APPLICATION RATE ON MAXIMUM GROUND COVER, THE RATE OF GROUND COVER EXPANSION FROM 40 TO 60 % GROUND COVER, SEASON-LONG INTEGRATED GROUND COVER AND RADIATION ABSORPTION

17.1.2. Number of stems, tuber and tuber fresh weight FW yields

When averaged over all treatments, the number of mainstems was c. 93 000/ha and this value was very consistent between samplings (Table 84). Neither irrigation nor soil conditions had any consistent, statistically significant effect on stem population. However, the number of mainstems was consistently reduced by c. 8 000/ha when the N application rate was increased from 0 to 200 kg N/ha. Reductions in stem population in response to N applications have been observed in other experiments at CUF (i.e. Variety and N Experiment p. 38) but at present the reason for this reduction is not known. The number of tubers at the first harvest (29 DAE) was smaller than that found at subsequent harvests and this may be because some stems had only recently initiated and some tubers were still smaller than 10 mm. For the second, third and fourth harvests, tuber populations were significantly larger in the Smeared soils. Despite N application reducing the number of stems, applying 200 kg N/ha increased the tuber population from the second harvest onwards. This was brought about by an increase in the number of tubers set and retained per stem, e.g. at final harvest, the number of tubers > 10 mm per main stem was 4.9 when no N was applied and 5.9 when 200 kg N/ha had been applied.

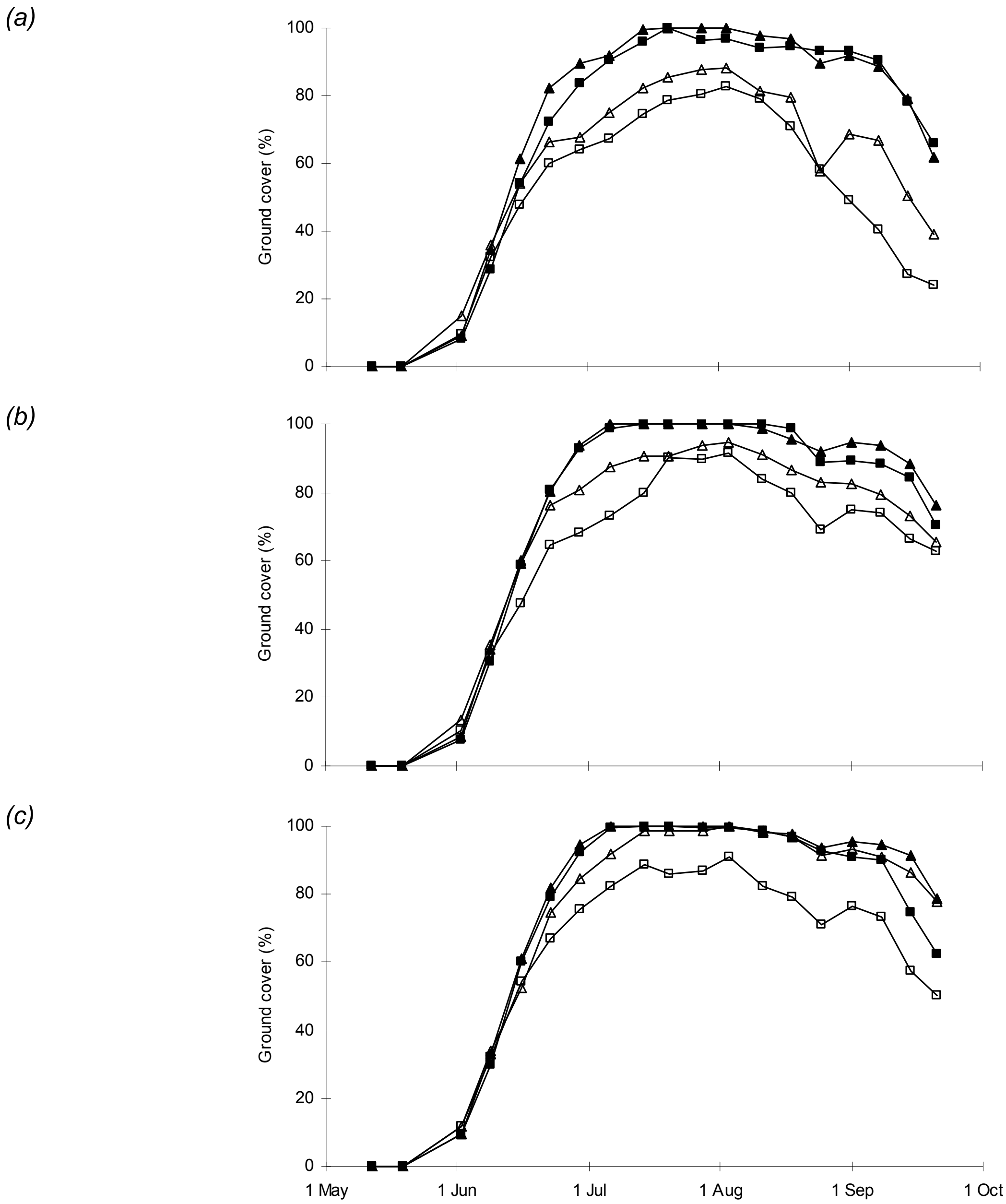


FIGURE 33. EFFECT OF SOIL CULTIVATIONS, IRRIGATION AND N APPLICATION RATE ON DEVELOPMENT OF GROUND COVER. (A) UNIRRIGATED; (B) IRRIGATED; (C) OVER-IRRIGATED. SMEARED-N0, □; SMEARED-N200, ■; UNSMEARED-N0, △; UNSMEARED-N200, ▲.

	Harvest 1 24 June (29 DAE)		Harvest 2 21 July (56 DAE)		Harvest 3 26 August (92 DAE)		Harvest 4 24 Sept. (121 DAE)	
	Stems (000/ha)	Tubers (000/ha)	Stems (000/ha)	Tubers (000/ha)	Stems (000/ha)	Tubers (000/ha)	Stems (000/ha)	Tubers (000/ha)
Mean	93.3	438	92.3	508	93.0	492	94.0	497
Unirrigated	90.6	425	90.2	490	89.8	478	94.1	496
Irrigated	94.4	429	94.3	510	95.8	504	91.3	489
Over-Irrigated	94.7	459	92.5	524	93.3	495	96.7	505
S.E. (33 D.F.)	2.28	14.2	2.40	11.9	2.45	12.3	2.69	10.4
Smeared	90.9	418	91.4	514	92.3	508	92.9	508
Unsmeared	95.6	458	93.2	502	93.6	477	95.2	485
S.E. (33 D.F.)	1.87	11.6	1.96	9.7	2.00	10.1	2.19	8.5
Fine tilth	93.1	435	93.1	510	93.8	499	93.4	497
Cloddy tilth	93.4	441	91.5	505	92.1	585	94.7	497
S.E. (33 D.F.)	1.87	11.6	1.96	9.7	2.00	10.1	2.19	8.5
0 kg N/ha	97.4	458	96.9	479	96.6	464	97.8	475
200 kg N/ha	89.1	418	87.7	537	89.4	521	90.2	518
S.E. (36 D.F.)	1.48	9.7	1.42	9.3	1.48	10.4	1.80	9.4

TABLE 84. MAIN EFFECT OF IRRIGATION, CULTIVATION AND N APPLICATION RATE ON NUMBER OF MAINSTEMS AND NUMBER OF TUBERS > 10 MM ON FOUR OCCASIONS

Between the first harvest (29 DAE) and the final harvest (121 DAE) average tuber FW yields increased from 5.3 to 66.6 t/ha (Table 85). For comparison, average tuber FW yields in 2006 and 2007 were 52 and 58 t/ha, respectively. At each harvest, tuber FW yields were significantly increased by irrigation and at the third and final harvests tuber FW yields were also significantly greater in Over-irrigated treatments compared with Irrigated. Despite being grown in what may have been perceived as a wet season, the Over-irrigated treatments increased yields by 17.5 t/ha when compared with the Unirrigated plots and 4.8 t/ha when compared with Irrigated. For all four harvests, the yields in Smeared soils were significantly smaller than those in Unsmeared soils and at final harvest the yields in the Smeared soils were c. 5 t/ha smaller. At the first harvest, increasing the N application rate from 0 to 200 kg N/ha reduced tuber FW yield by c. 1.5 t/ha. This reduction in yield may have been a consequence of the effects of N on emergence but it is more likely that it was due to the effects of N on DM partitioning between haulm and tubers. At final harvest, yields where no N was applied were c. 12 t/ha smaller than where 200 kg N/ha had been applied. Whether the crop was grown in a cloddy or in a fine-tilthed seed bed had no statistically significant effect on tuber FW yield at any harvest. The effects of irrigation and N application rate on tuber yields in Smeared and Unsmeared soils are shown in Table 86. These data show that when no N was applied, yields were reduced in Smeared soil, however, the yield penalty due to smearing was removed when 200 kg N/ha was applied. These data do not allow us to say whether crops grown in Smeared soils needed extra N to achieve their yield potential. However, these data do show that in N deficient crops (i.e. where no N had been applied) the yield penalty is larger if soil conditions are poor. When no irrigation was applied, tuber yields in the Smeared and Unsmeared soils were similar. When irrigation was applied, yields were increased in crops grown in both Smeared and Unsmeared soil but the response to water was larger in the Unsmeared soil. The extra response may have been due to more extensive rooting in the Unsmeared soils and plants being able to make better use of the irrigation water.

	Harvest 1 24 June c. 29 DAE	Harvest 2 21 July c. 56 DAE	Harvest 3 26 August c. 92 DAE	Harvest 4 24 September c. 121 DAE
Mean	5.26	31.2	56.2	66.6
Unirrigated	4.64	25.8	47.0	56.7
Irrigated	5.43	32.7	58.8	69.1
Over-irrigated	5.70	35.0	62.9	74.1
S.E. (33 D.F.)	0.229	0.78	1.24	1.71
Smeared	4.85	29.8	54.7	64.2
Unsmeared	5.66	32.5	57.7	69.0
S.E. (33 D.F.)	0.187	0.64	1.01	1.39
Fine tilth	5.30	31.1	56.3	66.6
Cloddy tilth	5.21	31.2	56.2	66.6
S.E. (33 D.F.)	0.187	0.64	1.01	1.39
0 kg N/ha	5.98	30.0	53.5	60.7
200 kg N/ha	4.53	32.3	58.9	72.5
S.E. (36 D.F.)	0.166	0.42	0.95	0.96

TABLE 85. MAIN EFFECTS OF CULTIVATION, IRRIGATION AND N APPLICATION RATE ON TUBER FW YIELD > 10 MM (T/HA) ON FOUR SAMPLING OCCASIONS

	Smeared soil	Unsmeared soil	Mean
Unirrigated	56.5	56.9	56.7
Irrigated	66.2	72.0	69.1
Over-irrigated	70.0	78.1	74.1
S.E. (33 D.F.)	2.41		1.71
0 kg N/ha	55.8	65.7	60.7
200 kg N/ha	72.6	72.3	72.5
S.E. (36 D.F.)	1.69		0.96

TABLE 86. COMBINED EFFECTS OF IRRIGATION OR N APPLICATION RATE ON TUBER FW YIELD > 10 MM (T/HA) IN SMEARED AND UNSMEARED SOIL AT FINAL HARVEST

The effects of soil cultivation, irrigation and N application on tuber DM concentration are discussed in the report for Project R406 (Stalham & Allison 2011).

17.1.3. Total dry matter yield, radiation use efficiency and the onset of tuber bulking

The mean total DM yield at final harvest was 17.58 t DM/ha (Table 87) compared with 17.26 t/ha in 2007 and 14.20 t/ha in 2006. Soil smearing reduced total DM yields by c. 1.2 t/ha whereas increasing the N application rate from 0 to 200 kg N/ha increased total DM yield by c. 2.7 t/ha. When compared with no irrigation, Over-irrigation increased total DM yield by c. 4 t/ha. Whole-season RUE for each plot was estimated from the slopes of regression lines that fitted total DW yield against radiation absorption. The overall, average RUE for total DM production was 1.38 t DM/TJ and this value is very similar to the average found for a similar experiment in 2007 (1.36 t DM/TJ) but larger than the average in 2006 (1.13 t DM/TJ). Radiation use efficiency was increased in irrigated crops but was not affected by soil conditions or by

N application rate. In conjunction with its effect on ground cover (Table 83), the effects of irrigation on RUE were responsible for the significant increase in total DM and tuber FW yield. On average, absorption of each TJ of energy was associated with the production of 1.30 t of tuber DM. The efficiency of tuber DM production was increased by irrigation but was not affected by either soil conditions or N application rate.

Ongoing studies in the USA and UK have shown that there is often a significant lag between tuber initiation (which typically occurs 19-25 DAE) and the onset of the linear phase of tuber bulking and this lag is often associated with rapid, early season N uptake. In similar experiments in 2006 and 2007, the average start date of tuber bulking was estimated to be at c. 24 and 26 DAE, respectively. In 2008, the average interval between emergence and tuber bulking was 26 days (Table 87) and the delay was increased when 200 kg N/ha had been applied. However, this delay in the onset of tuber bulking was relatively small in relation to the potential length of the growing season and was unlikely to have had much effect on yield.

	Total DM yield at Harvest 4 (t DM/ha)	**Radiation use efficiency total DM (t/TJ)**	**Radiation use efficiency tuber DM (t/TJ)**	**Onset of tuber bulking (DAE)**
Mean	17.58	1.38	1.30	26.3
Unirrigated	15.29	1.26	1.20	26.8
Irrigated	18.07	1.40	1.32	26.1
Over-irrigated	19.37	1.46	1.39	26.0
S.E. (33 D.F.)	0.418	0.020	0.027	0.43
Smeared	16.99	1.37	1.31	25.9
Unsmeared	18.17	1.38	1.29	26.7
S.E. (33 D.F.)	0.341	0.016	0.022	0.35
Fine tilth	17.66	1.39	1.33	26.2
Cloddy tilth	17.49	1.36	1.28	26.3
S.E. (33 D.F.)	0.341	0.016	0.022	0.35
0 kg N/ha	16.23	1.38	1.33	25.2
200 kg N/ha	18.92	1.37	1.28	27.3
S.E. (36 D.F.)	0.286	0.013	0.018	0.46

TABLE 87. MAIN EFFECTS OF CULTIVATION, IRRIGATION AND N APPLICATION RATE ON TOTAL DRY MATTER (DM) YIELD, RADIATION USE EFFICIENCY AND THE ONSET OF TUBER BULKING

Table 88 summarises the main effects on tuber FW yields of the cultivation, irrigation and N treatments in 2006, 2007 and 2008. Cultivating wet soils, resulting in a smeared layer at 25-30 cm depth resulted in significant yield loss in 2006 and 2008. In 2007, the soils were allowed to drain for longer before the soils were cultivated and combined with better drying conditions resulted in less damage to the soil structure. It is important to note, that the period of drying in all three seasons varied by only a few hours and thus delaying cultivation by a short period after rain can have a dramatically increase yield potential and reduce the inputs needed to achieve the yield potential. Irrigation increased yield in all three seasons by c. 13 t/ha and as noted earlier in the report, correctly scheduled irrigation can give large increases in yield in seasons that may be thought to be unresponsive to water applications. In 2006, N application had no effect on tuber FW yield whilst in 2007 and 2008 applying N increased yield by 21 and 12 t/ha, respectively.

Treatments		Tuber yield (t/ha) 2006	Tuber yield (t/ha) 2007	Tuber yield (t/ha) 2008
Soil cultivation	Smeared	46.9	58.0	64.2
	Unsmeared	57.1	58.1	69.0
Irrigation	Unirrigated	45.9	51.0	56.7
	Irrigated	58.1	65.1	69.1
N application rate	0 kg N/ha	50.4	46.8	60.7
	300/200* kg N/ha	52.8	67.6	72.5

*200 kg N/ha in 2008

TABLE 88. MAIN EFFECTS OF CULTIVATIONS, IRRIGATION AND N APPLICATION ON TUBER FW YIELD (T/HA) IN 2006-2008

18. CUF 2009

18.1. Results and Discussion

18.1.1. Emergence, ground covers and radiation absorption

The average date of 50 % plant emergence was 23 May (27 days after planting, DAP) for the first planting and 1 June (22 DAP) for the second planting. For the first planting, increasing the soil moisture content when the soil was cultivated resulted in a delay in crop emergence but this effect was not seen at the second planting, although the Moist cultivation regime was slower to reach 50 % emergence than other cultivation regimes owing to dry soil at seed depth. All plots achieved complete or near-complete emergence. The effects of the treatment combinations on ground cover development are shown in Figure 34 and key data on ground cover development and radiation absorption are shown in Table 89. The rate of ground cover expansion was estimated by fitting a logistic (growth) curve to pre-senescence values of ground cover against time. The average rate of ground cover expansion (between 40 and 60 % ground cover) was 4.7 %/day. In a similar experiment in 2008, the average rate of ground cover expansion was 3.4 %/day suggesting that in 2009 environmental condition were better. This analysis also showed that the rate of expansion was faster for the later-planted plots and in crops that had received irrigation when compared with Unirrigated. All plots achieved 100 % ground cover. Canopy senescence started in late August. On average, the canopies of the Unirrigated crops maintained complete ground cover for c. 7 days longer than Irrigated crops and at final harvest (28 September) the average ground cover of the Unirrigated crops was 63 % compared with 48 % in the Irrigated crops. The average, season long-integrated ground cover was 9347 % days and this was not significantly affected by any treatment. On average, the 2009 crop was more persistent than the 2008 crop, which averaged 8927 % days. Radiation absorption averaged 14.51 TJ/ha (13.16 TJ/ha in 2008) and the effects of treatments on radiation absorption were small and statistically non-significant.

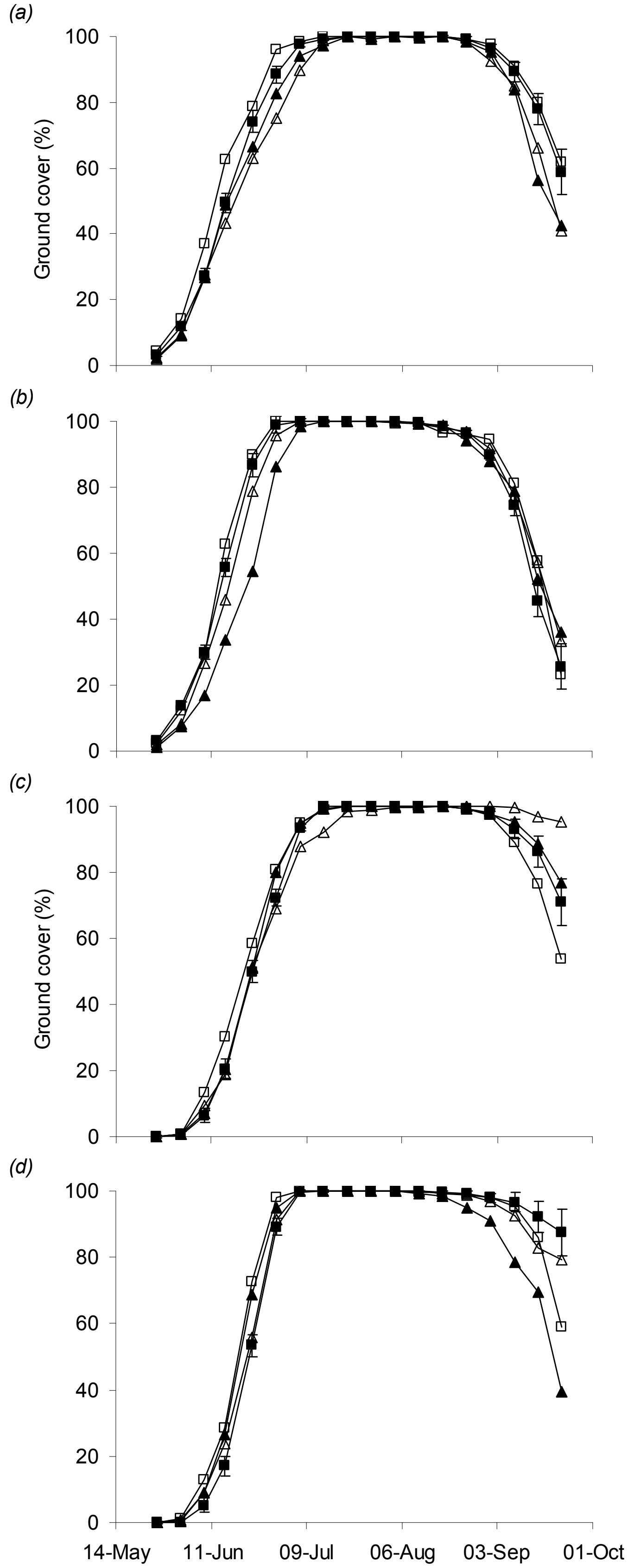


FIGURE 34. EFFECT OF SOIL MOISTURE CONTENT AT CULTIVATION ON GROUND COVER DEVELOPMENT. (*A*) 15 APRIL UNIRRIGATED; (*B*) 15 APRIL IRRIGATED; (*C*) 29 APRIL UNIRRIGATED; (*D*) 29 APRIL IRRIGATED. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E. BASED ON 30 D.F.

		Rate of ground cover increase (%/day)	Integrated ground cover (% days)	Radiation absorption (TJ/ha)
Planting date	15 April	4.31	9379	14.74
	29 April	5.09	9394	14.28
	S.E. (30 D.F.)	0.135	117.8	0.164
Soil cultivation regime	Moist	4.89	9489	14.62
	Field Capacity	4.89	9589	14.95
	Wet	4.61	9110	14.10
	Over-wet	4.43	9359	14.36
	S.E. (30 D.F.)	0.191	166.6	0.232
Irrigation regime	Unirrigated	4.02	9450	14.49
	Irrigated	5.38	9324	14.53
	S.E. (30 D.F.)	0.135	117.8	0.164

TABLE 89. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON RATE OF INCREASE IN GROUND COVER (BETWEEN 40 AND 60 %), SEASON-LONG INTEGRATED GROUND COVER AND RADIATION ABSORPTION

18.1.2. Number of stems and tubers, tuber fresh weight yield and dry matter concentration

When averaged over all treatment combinations the number of mainstems was 135 000/ha and this value was consistent between samplings (Table 90). The effects of soil moisture content at cultivation or irrigation on stem population were generally small but the later planting had more stems than the earlier planting (on average 17 000 stems/ha more) consistent with an increase in seed age between planting. The number of secondary stems was relative small (1 900/ha at the third sampling) and was independent of treatment. For both planting dates the first sampling was done whilst the tuber population was still increasing and there were few tubers > 10 mm. At the second and subsequent harvests, numbers of tubers > 10 mm were greater for the later planting than the earlier planting and greater for the Irrigated than the Unirrigated crops. Effects of soil moisture content at cultivation on tuber population were small and inconsistent.

		19 or 23 June		17 July		6 August		28 September	
		Stems	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**
Date of planting	15 April	126	221	129	453	124	476	125	509
	29 April	145	215	141	521	142	564	143	567
	S.E. (30 D.F.)	3.1	27.2	3.2	14.9	2.7	12.1	3.3	11.8
Soil cultivation regime	Moist	132	213	134	494	132	535	128	549
	Field Capacity	144	277	128	501	138	550	137	532
	Wet	130	205	143	491	128	496	138	529
	Over-wet	136	178	136	463	134	499	134	541
	S.E. (30 D.F.)	4.4	38.5	4.5	21.1	3.8	17.2	4.6	16.6
Irrigation regime	Unirrigated	137	244	138	453	136	486	134	512
	Irrigated	135	192	132	521	130	554	134	564
	S.E. (30 D.F.)	3.1	27.2	3.2	14.9	2.7	12.1	3.3	11.8

TABLE 90. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON NUMBER OF MAINSTEMS (000/HA) AND NUMBER OF TUBERS > 10 MM (000/HA)

At the second sampling (17 July) tuber FW yields were significantly larger for crops that had received irrigation than Unirrigated crops and for crops planted on 15 April rather than 29 April (Table 91). For the earlier planted crops, yields decreased from c. 24 to 18 t/ha as soil moisture content at cultivation increased from Moist to Over-wet but for crops planted on 29 April, yields were numerically smaller for the Moist cultivation regime plots. At the third harvest (6 August), scheduled irrigation increased tuber FW yield by c. 10 t/ha but yield was not affected by date of planting or soil moisture content at cultivation (Table 91). As noted at the second harvest, yields of the crops planted on 15 April decreased from 44 to 35 t/ha as the soil at cultivation became wetter but for crops planted on 29 April, the Moist soil cultivation treatment had the smallest yield. At final harvest in late September, neither planting date nor soil moisture content at cultivation had any significant effect on tuber FW yield, however compared with Unirrigated crops, irrigation increased tuber FW yields by c. 10 t/ha (Table 91). For crops planted on 15 April, yields were numerically larger when the soil had been cultivated Moist or at Field Capacity when compared with yields in soils cultivated when wetter but this difference was not statistically significant. For the later planting, numerical difference in yield between soil moisture contents at cultivation were smaller.

Date of planting	Irrigation regime	Soil cultivation regime	17 July	6 August	28 September
15 April	Unirrigated	Moist	20.5	39.5	54.9
		Field Capacity	20.3	35.5	56.8
		Wet	20.8	35.1	50.0
		Over-wet	15.7	31.3	49.3
	Irrigated	Moist	28.2	47.7	61.1
		Field Capacity	28.8	45.5	63.9
		Wet	21.4	35.7	59.4
		Over-wet	20.4	40.1	61.3
29 April	Unirrigated	Moist	12.9	29.4	53.0
		Field Capacity	18.0	34.3	51.6
		Wet	17.6	32.7	55.0
		Over-wet	17.4	33.1	59.8
	Irrigated	Moist	19.7	42.9	66.0
		Field Capacity	23.5	46.8	70.4
		Wet	23.1	45.8	64.4
		Over-wet	24.3	47.5	67.2
		S.E.	2.08	2.70	3.95
15 April	Mean	Mean	22.0	38.8	57.1
29 April	Mean	Mean	19.6	39.1	60.9
		S.E.	0.74	0.95	1.40
Mean	Unirrigated	Mean	17.9	33.9	53.8
Mean	Irrigated	Mean	23.7	44.0	64.2
		S.E.	0.74	0.95	1.40

TABLE 91. EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON TUBER FW YIELD > 10 MM (T FW/HA). S.E. BASED ON 30 D.F.

Early planted crops had consistently higher tuber DM concentrations than late-planted crops (Table 92). Although irrigation increased DM concentration at the harvests on 17 July and 28 September, following a wet period in mid-July, on 6 August Unirrigated crops had significantly lower DM concentrations than Irrigated crops. For the two harvests in July and August, the effect of cultivation regime on DM concentration differed between planting dates. Late-planted crops had higher DM concentrations when they were planted in soil cultivated at Field Capacity, Wet and Over-wet water contents, this being associated with late emergence of the late-planted Moist-cultivated crop due to the dry seedbed. There was little effect of cultivation regime on DM concentration for the early planting. By final harvest, there was no significant effect of cultivation regime.

		19 or 23 June	17 July	6 August	28 September
Date of planting	15 April	13.8	17.8	20.0	25.6
	29 April	11.9	16.6	18.8	24.9
	S.E. (30 D.F.)	0.39	0.12	0.12	0.17
Soil cultivation regime	Moist	12.2	16.8	19.1	24.8
	Field Capacity	13.0	17.5	19.9	25.6
	Wet	13.2	17.2	19.5	25.6
	Over-wet	13.1	17.2	19.2	25.1
	S.E. (30 D.F.)	0.56	0.16	0.17	0.24
Irrigation regime	Unirrigated	12.7	18.0	18.4	26.5
	Irrigated	13.0	16.4	20.0	24.0
	S.E. (30 D.F.)	0.39	0.12	0.12	0.17

TABLE 92. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON TUBER DRY MATTER (DM) CONCENTRATION (%)

18.1.3. Total dry matter yield, radiation use efficiency and the onset of tuber bulking

Total DM yields at final harvest were independent of planting date, use of irrigation and soil moisture content at cultivation (Table 93). The average RUE for total DM production was 1.31 t DM/TJ and this value is similar to those found in previous seasons. Radiation use efficiency was greater for crops that received scheduled irrigation than Unirrigated crops and similar effects on RUE were seen in the 2008 experiment. Radiation use efficiency was greater for crops planted on 29 April than on 15 April. It is possible that his may have due to the later planted crops growing in a duller radiation environment than the earlier planted crops. However, the smaller RUE of the earlier plantings may also be due to poor recovery of senesced foliage leading to underestimates of total DM yield. The effects of soil moisture content at cultivation on RUE were not significant. On average each TJ of solar energy absorbed by the crop was associated with the production of *c.* 1.12 t tuber DM. This value is value is smaller than that found in 2008 (1.30 t DM/TJ). The RUE for tuber DM production was increased by irrigation but was not significantly affected by any other treatment.

Validation of the CUF yield model has shown that there is often an interval of several days between the initiation of tubers and the onset of the linear phase of tuber bulking. This interval appears to be variety dependent and related to N supply. The average interval between emergence and the apparent onset of tuber bulking was *c.* 28 days (Table 93) and assuming tuber initiation (TI) occurred at *c.* 20 DAE there was an interval of about one week between TI and bulking. Similar values for Maris Piper have been found in previous soil conditions experiments at CUF and also in the 2009 Varietal Characteristics experiment (p. 52). The interval between emergence and tuber bulking was shorter for crops planted on 29 April than on 15 April and in the Unirrigated than the Irrigated crops but soil moisture content at cultivation had no significant effect on the start of bulking.

		Total DM yield on 28 September (t/ha)	RUE total DM (t/TJ)	RUE tuber DM (t/TJ)	Start of tuber bulking (DAE)
Date of planting	15 April	17.43	1.24	1.09	29.8
	29 April	18.67	1.37	1.15	25.3
	S.E. (30 D.F.)	0.461	0.020	0.025	0.63
Soil cultivation regime	Moist	18.03	1.31	1.10	27.4
	Field Capacity	18.47	1.28	1.14	28.2
	Wet	17.46	1.30	1.12	27.4
	Over-wet	18.26	1.32	1.12	27.2
	S.E. (30 D.F.)	0.652	0.028	0.035	0.89
Irrigation regime	Unirrigated	17.73	1.25	1.07	28.8
	Irrigated	18.38	1.36	1.17	26.3
	S.E. (30 D.F.)	0.461	0.020	0.025	0.63

TABLE 93. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON TOTAL DRY MATTER (DM) YIELD, RADIATION USE EFFICIENCY AND THE APPARENT START OF TUBER BULKING

18.1.4. Nitrogen uptake and redistribution

The main effects of treatments on total N uptake at each sampling are shown in Table 94. Irrespective of treatment, most of the N (*c.* 75 %) had been taken up by the second sampling which was 55 DAE for the crop planted on 15 April and 46 DAE for those planted on 29 April. At the first and third samplings, the treatments had no significant effect on total N uptake. At the second sampling, when compared with the Unirrigated crop, total N uptake of the Irrigated crops was significantly increased by 42 kg N/ha. At the final sampling, crops planted on 29 April had larger total N uptakes than those planted on 15 April and, in contrast to observations made at the second harvest, total N uptake was *c.* 30 kg N/ha larger in the Unirrigated crops than the Irrigated crops. Neither planting date nor soil moisture content at cultivation had a statistically significant effect on total N uptake although the total N uptake was *c.* 25 kg N/ha larger for the later plantings (Table 95). In contrast to previous seasons, the Unirrigated plots had a significantly larger total N uptake when compared with the Irrigated plots. Whilst this is a surprising result it is consistent with the ground covers being more persistent in the Unirrigated plots. The rate of tuber N uptake in relation to radiation absorption was estimated from the slope of a straight line fitted to values of tuber N uptake and absorbed radiation. The overall rate of tuber N uptake was 14.2 kg N/TJ, this value was similar to those found in 2006 and 2007 but was larger than the rate estimated for 2008. The rate of tuber N uptake was larger in crops planted on 29 April than 15 April and greater in Unirrigated crops than in Irrigated.

		19 or 23 June	17 July	6 August	28 September
Date of planting	15 April	49	170	196	218
	29 April	48	176	208	244
	S.E. (30 D.F.)	3.2	5.0	6.2	6.2
Soil cultivation regime	Moist	48	175	217	236
	Field Capacity	58	178	199	243
	Wet	43	170	189	215
	Over-wet	45	169	203	230
	S.E. (30 D.F.)	4.6	7.0	8.7	8.8
Irrigation regime	Unirrigated	46	152	207	246
	Irrigated	51	194	197	216
	S.E. (30 D.F.)	3.2	5.0	6.2	6.2

TABLE 94. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON TOTAL (HAULM AND TUBER) N UPTAKE (KG N/HA) ON FOUR OCCASIONS

On average haulm N uptake was 112 kg N/ha but was significantly greater for the second planting date than the first and greater where irrigation had been used than in Unirrigated crops. Soil moisture content at cultivation had little effect on maximum haulm N uptake. A key date in the crop's developments is the date at which the rate of tuber N uptake (that remains more or less constant through the season) exceeds the rate of total N uptake (which decreases as the season progresses). After this date the rate of tuber N uptake exceeds total N uptake and this can only be achieved if the haulm becomes a net exporter of N. On average, this date occurred at 54 DAE and was little affected by planting date of soil moisture at cultivation (Table 95). On average, use of irrigation advanced this date by 13 days when compared with the Unirrigated plots. A similar effect occurred in 2008 but was not statistically significant.

		Rate of tuber N uptake (kg N/TJ)	Maximum total N uptake (kg N/ha)	Maximum haulm N uptake (kg N/ha)	Rate of tuber and total N uptake equal (DAE)
Date of planting	15 April	13.6	242	105	55
	29 April	14.9	265	119	53
	S.E. (30 D.F.)	0.33	8.6	3.0	0.9
Soil cultivation regime	Moist	14.2	259	120	54
	Field Capacity	15.3	268	107	53
	Wet	13.6	231	108	53
	Over-wet	14.0	255	112	55
	S.E. (30 D.F.)	0.47	12.2	4.2	1.2
Irrigation regime	Unirrigated	14.7	277	106	60
	Irrigated	13.8	229	117	47
	S.E. (30 D.F.)	0.33	8.6	3.0	0.9

TABLE 95. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON RATE OF TUBER N UPTAKE, MAXIMUM TOTAL AND HAULM N UPTAKE AND DATE WHEN RATE OF TOTAL N AND TUBER N UPTAKE ARE EQUAL

Analyses of these data show that the Irrigated crop had an initial rate of total N uptake greater than the Unirrigated crop, but the duration of total N uptake was longer in the Unirrigated than the Irrigated crop. Thus, at the second harvest, the Unirrigated crop had a total N uptake less than the Irrigated crop but this situation was reversed by final harvest. It might be expected that since the Unirrigated crop had a larger N uptake its yield should also be larger, however, Table 91 shows that the converse is true. In part, this discrepancy is due to differences in the rates of tuber N uptake and in the amount of N remaining in the canopies at final harvest. However, the main difference was due to the smaller RUE in the Unirrigated crops which meant that whilst it had a more persistent canopy, the radiation absorbed was not used efficiently.

18.2. Conclusions

In this experiment, the effects of soil moisture content at cultivation on the growth, yield and N uptake of the crop were small and generally not statistically significant, despite there being significant differences in soil factors at cultivation depth e.g. bulk density and water holding capacity and small differences in stomatal resistance and rooting density. Similarly, the effects of planting date on yield were small at final harvest. Work at CUF has concentrated on understanding varietal and seasonal variation in the response to N fertilizer. Some of this variation is due to difference in the rate and duration of N uptake during the early part of the season and this had been demonstrated in this experiment. Furthermore this experiment has also shown that reductions in RUE can offset gains in total N uptake so that an increase in canopy duration may not increase yield.

19. CUF 2010

19.1. Results and Discussion

19.1.1. Emergence, ground covers and radiation absorption

For all treatments, the average date of 50 % plant emergence was 24 May (35 days after planting, DAP). Both Lady Rosetta and Maris Piper achieved 50 % emergence on the same date but, on average, the date of 50 % emergence was delayed by 1 day when no N was applied and was also delayed by *c.* 1 day in the Late Plough and Non-plough areas. Initial ground cover expansion was slowed when no N was applied, so that at 25 DAE the average ground cover was 37 % when no N was applied and 53 % when 180 kg N/ha had been applied (Table 96, Figure 35). In the absence of N fertilizer, maximum ground cover was significantly smaller when compared with plots receiving 180 kg N/ha. However, maximum ground cover was not significantly affected by either variety or cultivation regime. The mean, season-long integrated ground cover was 7302 % days and this was not affected significantly by cultivation regime. On average, the integrated ground cover of Lady Rosetta was smaller than that of Maris Piper (6318 compared with 8287 % days) and was also smaller when no N was applied than where the application rate was 180 kg N/ha (5964 and 8641 % days, respectively). More solar radiation was absorbed by Maris Piper (12.60 TJ/ha) than Lady Rosetta (10.45 TJ/ha) and increasing the N application rate from 0 to 180 kg N/ha increased radiation absorption from 9.53 to 13.53 TJ/ha. The cultivation treatments had no significant effect on radiation absorption in either variety.

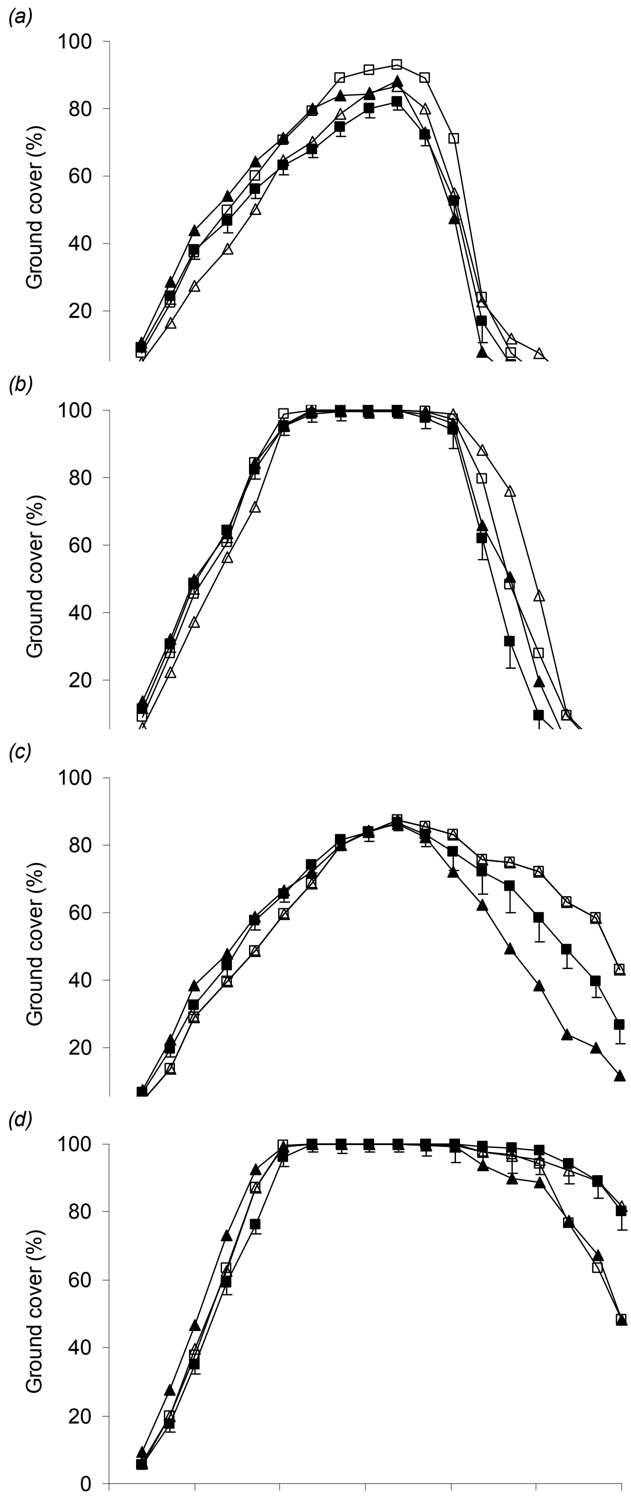


FIGURE 35. EFFECT OF CULTIVATION REGIME, VARIETY AND RATE OF NITROGEN FERTILIZER ON GROUND COVER. (*A*) LADY ROSETTA 0N; (*B*) LADY ROSETTA 180N; (*C*) MARIS PIPER 0N; (*D*) MARIS PIPER 180N. CULTIVATION REGIME: PLOUGH EARLY, ■; PLOUGH LATE, □; NON-PLOUGH EARLY, ▲; NON-PLOUGH LATE, △. S.E. BASED ON 16 D.F.

	GC at 25 DAE (%)	Integrated GC (% days)	Radiation absorbed (TJ/ha)
Lady Rosetta 0 kg N/ha			
Plough Early	38	5383	9.13
Plough Late	40	5555	9.28
Non-plough Early	43	5176	8.87
Non-plough Late	33	4894	8.10
Mean	39	5252	8.85
Lady Rosetta 180 kg N/ha			
Plough Early	54	7204	11.98
Plough Late	54	7629	12.48
Non-plough Early	53	7513	12.42
Non-plough Late	51	7761	12.46
Mean	53	7527	12.34
Maris Piper 0 kg N/ha			
Plough Early	36	7083	10.82
Plough Late	35	6442	10.08
Non-plough Early	37	6429	10.17
Non-plough Late	32	8171	12.13
Mean	35	7031	10.80
Maris Piper 180 kg N/ha			
Plough Early	48	9831	14.60
Plough Late	54	9537	14.53
Non-plough Early	56	9711	14.92
Non-plough Late	54	9943	14.89
Mean	53	9755	14.73
S.E. Var*N (16 D.F.)	1.6; 2.0†	226.4; 343.8†	0.415; 0.490†
S.E. Var*Cult*N (16 D.F.)	3.1; 4.0‡	452.8; 486.1‡	0.587; 0.692‡

†S.E. for comparing treatments with same N rate; ‡S.E. for comparing means with same cultivation and N rate

TABLE 96. EFFECT OF VARIETY, N APPLICATION RATE AND CULTIVATION REGIME ON GROUND COVER 25 DAYS AFTER EMERGENCE (DAE) MAXIMUM GROUND COVER (PERCENT AND ANGULAR TRANSFORMED), WHOLE-SEASON INTEGRATED GROUND COVER AND RADIATION ABSORPTION

19.1.2. Number of stems, tuber and tuber fresh weight FW yields

When averaged over all harvests, cultivation and N application rates, Lady Rosetta had a stem population of 165 000/ha compared with 120 000/ha for Maris Piper (Table 97). For both varieties, stem populations were reasonably consistent at each harvest. The first sample was taken on 14 June (*c.* 21 DAE) during tuber initiation and the mean tuber population > 10 mm at this harvest was smaller when compared with mean tuber populations measured later in the season. When compared with Lady Rosetta, the tuber population of Maris Piper was smaller at all harvests. Numerically, tuber populations were also smaller when no N fertilizer was applied but this effect was only significant at harvests on 22 July and 23 August. The main effects of cultivation regime on tuber populations were always significant but these effects were inconsistent. At the first harvest, the Non-plough Early treatment had the largest tuber population but at all subsequent samplings this treatment had the smallest tuber population. This discrepancy may due to this cultivation treatment achieving 50 % emergence 1-2 days before the others and thus having a larger tuber population at the earliest harvest.

	14 June		22 July		23 August		27 September	
	Stems	**Tubers**	**Stem**	**Tuber**	**Stems**	**Tubers**	**Stems**	**Tubers**
Plough Late	140	286	137	656	145	625	142	648
Plough Early	141	288	136	704	141	656	133	642
Non-plough Late	150	289	144	690	156	681	141	620
Non plough Early	144	445	144	599	142	561	146	582
S.E. (14 D.F.)	4.4	27.0	5.1	19.0	5.5	16.7	3.0	13.3
Lady Rosetta	169	480	161	717	167	700	162	676
Maris Piper	119	175	119	608	125	561	119	569
S.E. (16 D.F.)	3.5	12.3	3.5	11.8	4.2	12.3	2.7	16.9
0 kg N/ha	143	311	139	641	139	592	142	613
180 kg N/ha	144	344	141	684	153	669	139	633
S.E. (14 D.F.)	3.1	19.1	3.6	13.5	3.9	11.8	2.2	9.4

TABLE 97. MAIN EFFECTS OF CULTIVATION REGIME. VARIETY AND N RATE ON STEM AND TUBER POPULATION > 10 MM (000/HA)

At the first sampling, the tuber FW yield of Lady Rosetta (2.5 t/ha) was significantly larger than the yield of Maris Piper (0.8 t/ha). The tuber yield of the Non-plough Early treatment was significantly larger than the other cultivation treatments but this may have been consequence of this cultivation treatment emerging slightly early than the others. At the second sampling (22 July), the yields of the Non-plough Early treatments were larger than in the Non-plough Late but the effect was quite small (Table 98) and, on average, Lady Rosetta had a larger yield than Maris Piper. When compared to no N, applying 180 kg N/ha increased yields by *c.* 4.5 t/ha but this response to N was much larger in Lady Rosetta than in Maris Piper. At the third sampling, the cultivation treatments had no effect on yield and the varietal differences in tuber yields were also small and not statistically significant. The response to N in Lady Rosetta was to increase yield by 17.6 t/ha, whereas in Maris Piper the response was smaller (12.8 t/ha). The final sampling was taken at the end of September when the canopies of Lady Rosetta had completely senesced but the canopies of Maris Piper were still between 15 and 85 % ground cover. Whilst the cultivation treatments had no effect on tuber yield, the yield of Maris Piper was significantly larger than that of Lady Rosetta. Between the third and final sampling, the average yield of Lady Rosetta increased by 3.5 t/ha whereas the yield of Maris Piper increased by 9.4 t/ha. When averaged over both varieties, the response to 180 kg N/ha was 20.5 t/ha and the response to N was similar in each individual variety.

	22 July	23 August	27 September
Plough Early	29.5	47.3	53.1
Plough Late	28.7	49.5	55.5
Non-plough Early	29.8	47.6	54.6
Non-plough Late	26.5	47.2	53.1
S.E. (14 D.F.)	0.50	1.18	1.26
Lady Rosetta	30.6	48.8	51.7
Maris Piper	26.3	47.0	56.4
S.E. (16 D.F.)	0.47	0.63	1.27
0 kg N/ha	26.3	40.3	43.8
180 kg N/ha	30.9	50.5	64.3
S.E. (14 D.F.)	0.35	0.83	0.88
Lady Rosetta 0 kg N/ha	27.2	40.0	42.4
Lady Rosetta 180 kg N/ha	34.0	57.6	61.1
Maris Piper 0 kg N/ha	25.4	40.6	45.3
Maris Piper 180 kg N/ha	27.8	53.4	67.4
S.E. (16 D.F., same N level)	0.66	0.89	1.79
S.E. (16 D.F., different N levels)	0.58	1.04	1.55

TABLE 98. EFFECTS OF CULTIVATION, VARIETY AND N APPLICATION RATE ON TUBER FW YIELD > 10 MM (T/HA)

19.1.3. Total dry matter yield, radiation use efficiency, onset of tuber bulking and modelling of yield development

At the final sampling, cultivation regime had no effect on total DM production (Table 99). When averaged over the other treatments, DM production in Maris Piper was c. 2.2 t/ha larger than in Lady Rosetta. In Lady Rosetta, the response to 180 kg N/ha was 5.3 t/ha whilst in Maris Piper the response was 7.2 t/ha. These treatment differences are consistent with their effects on canopy persistence and radiation absorption (Table 96). Average, season-long, RUE was 1.40 t DM/TJ and was similar to that found for irrigated crops in a similar experiment last year. Radiation use efficiency was not significantly affected by cultivation regime, variety or N application rate. In the 2009 experiment RUE was influenced by planting date and irrigation but was not affected by the contrasting cultivation treatments.

Work at CUF has shown that there is often an interval of several days between tuber initiation and the onset of bulking. The length of this interval appears to be dependent on variety and affected by N nutrition. The average interval between 50 % plant emergence and the apparent onset of tuber bulking was c. 19 days. Cultivation regime had no significant effect on the onset of bulking but, on average, bulking was c. 7 days earlier in Lady Rosetta than in Maris Piper and was delayed by 6 days when the N application rate was increased from 0 to 180 kg N/ha. The effect of N on bulking was also affected by variety: the delay was c. 3 days in Lady Rosetta and *c.* 9 days in Maris Piper. The start of tuber bulking in Maris Piper given 180 kg N/ha (27 DAE) was similar to that found in the 2009 experiment.

	Total DM yield on 27 September (t/ha)	Radiation use efficiency (t DM/TJ)	Start of tuber bulking (DAE)
Plough Early	15.23	1.42	19.6
Plough Late	15.79	1.44	20.0
Non-plough Early	15.18	1.34	18.9
Non-plough Late	15.36	1.41	18.0
S.E. (14 D.F.)	0.422	0.030	1.10
Lady Rosetta	14.31	1.44	15.7
Maris Piper	16.47	1.37	22.5
S.E. (16 D.F.)	0.389	0.029	0.97
0 kg N/ha	12.27	1.37	16.2
180 kg N/ha	18.51	1.43	22.0
S.E. (14 D.F.)	0.298	0.021	0.78
Lady Rosetta 0 kg N/ha	11.68	1.40	14.3
Lady Rosetta 180 kg N/ha	16.95	1.47	17.2
Maris Piper 0 kg N/ha	12.87	1.34	18.0
Maris Piper 180 kg N/ha	20.07	1.39	26.9
S.E. (16 D.F., same N level)	0.550	0.041	1.37
S.E. (16 D.F., different N levels)	0.490	0.036	1.24

TABLE 99. EFFECTS OF CULTIVATION, VARIETY AND N APPLICATION RATE ON TOTAL DRY MATTER (DM) YIELD, RADIATION USE EFFICIENCY AND THE APPARENT START OF TUBER BULKING

The CUF yield model was used analyse the development of tuber yield. The model was parameterised for each treatment using data from the second harvest (taken at c. 59 DAE) and then used to predict yields at the subsequent harvests. The mean, observed tuber yield at these harvests was 50.9 t/ha and the mean, modelled yield was 52.9 t/ha. There was a reasonable correlation between modelled and observed yields (Figure 36a). In general, there was a tendency for the model to overestimate yield in those crops that received no N fertilizer and this was particularly noticeable for Maris Piper. In part, this overestimate was a consequence of the model underestimating tuber DM concentration in the unfertilized crops thereby leading to overestimates in tuber FW yield. However, the main source of the yield overestimate may have been due to possible overestimates of ground cover during the season and/or an overestimate of the proportion of incident radiation captured by the canopy. It is also of interest that the overestimates of yield were associated with crops where the modelled yield had wide confidence limits (Figure 36b). These wide confidence limits in modelled yield were always associated with crops with variable ground covers and in less variable crops the forecasts had much smaller confidence limits (Figure 36c). The accuracy of yield forecasts in variable crops has practical implications and warrants further research.

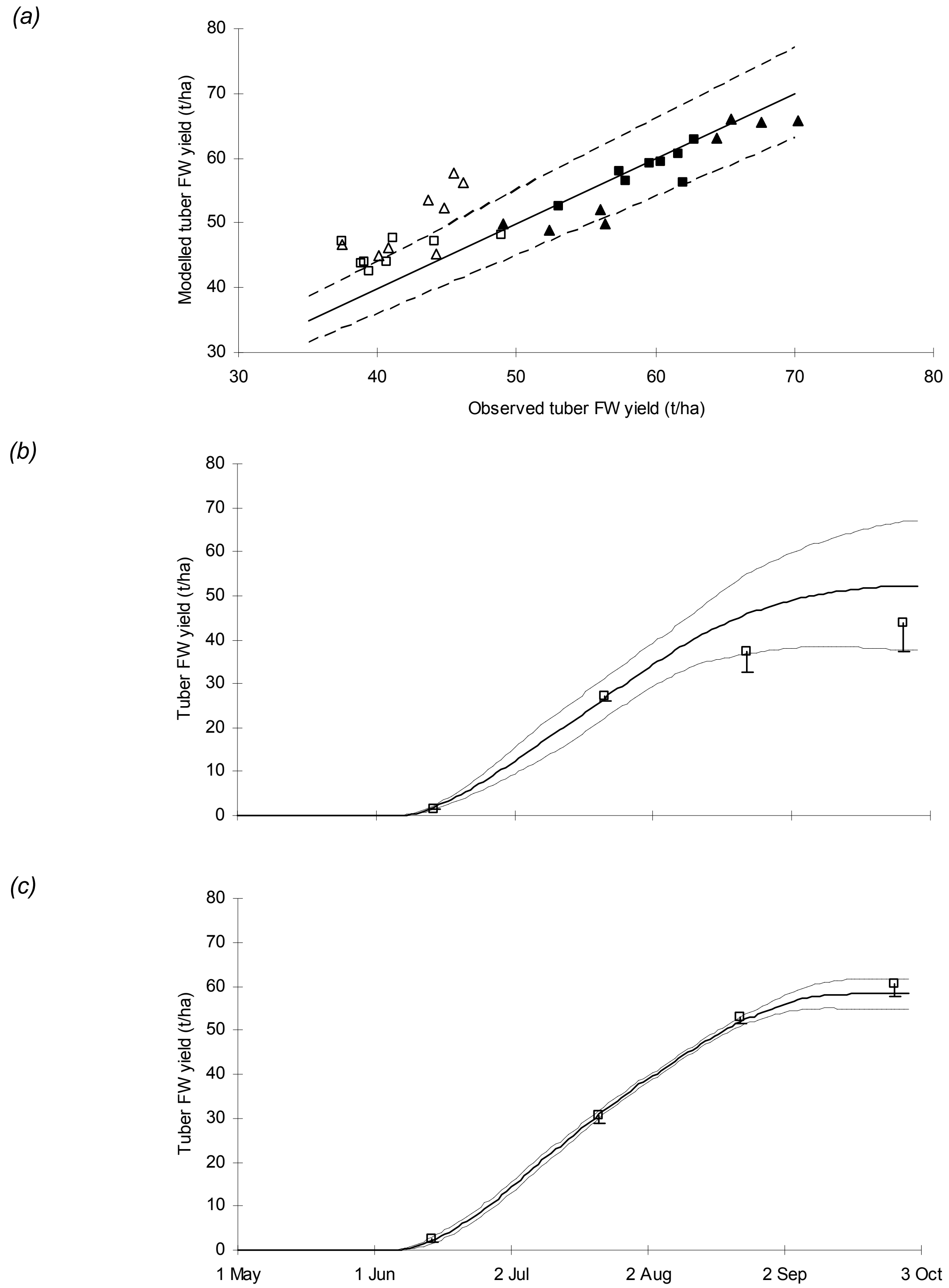


FIGURE 36. COMPARISON OF MODELLED AND OBSERVED YIELDS (*A)* LADY ROSETTA 0N, □; LADY ROSETTA 180N, ■; MARIS PIPER 0 N, △; MARIS PIPER 180N, ▲. SOLID LINE IS 1 : 1 RELATIONSHIP AND DASHED LINE ARE ± 10 %; (*B)* NON-PLOUGH EARLY MARIS PIPER 0N; (*C*) NON-PLOUGH LATE LADY ROSETTA 180N. SOLID LINE IS MEAN MODELLED YIELD, DASHED LINES ARE ± 95 % CONFIDENCE LIMITS OF MODELLED YIELD AND SYMBOLS ARE OBSERVED YIELDS AND 1 S.E.

19.1.4. Nitrogen uptake and redistribution

The effects of the treatments on total N uptake at each sampling are shown in Table 100. Irrespective of treatment, c. 85 % of the total crop N uptake had occurred by the second sampling on 22 July (c. 59 DAE) and this is consistent with many other observations on the pattern of total N uptake by potato crops. At the first sampling, total N uptake differed by 14 kg N/ha between the Plough Early and Non-plough Early treatments and total N uptake was 11 kg N/ha larger for Lady Rosetta than for Maris Piper. Increasing the N uptake from 0 to 180 kg N/ha increased total N uptake by c. 31 kg N/ha. At the second sampling neither cultivation nor variety had any effect on total N uptake but N uptake was increased by 105 kg N/ha in response to an application of 180 kg N/ha. At the penultimate sampling on 23 August, increasing the N application rate from 0 to 180 kg N/ha increased total N uptake by 131 kg N/ha representing a fertilizer N recovery of c. 73 %. Total N uptakes by Lady Rosetta and Maris Piper were similar and N uptake was not affected by cultivation regime. At the final harvest at the end of September, neither cultivation nor variety had any effect on total N uptake but increasing the N application rate from 0 to 180 kg N/ha increased total N uptake from 124 to 245 kg N/ha.

	14 June	22 July	23 August	27 September
Plough Early	45	172	189	182
Plough Late	51	168	207	190
Non-plough Early	59	166	186	183
Non-plough Late	48	160	190	185
S.E. (14 D.F.)	1.8	6.1	5.8	5.2
Lady Rosetta	56	166	192	182
Maris Piper	45	167	194	187
S.E. (16 D.F.)	0.9	4.4	4.0	5.3
0 kg N/ha	35	114	128	124
180 kg N/ha	66	219	258	245
S.E. (14 D.F.)	1.2	4.3	4.1	3.7
Lady Rosetta 0 kg N/ha	39	113	127	125
Lady Rosetta 180 kg N/ha	74	219	257	240
Maris Piper 0 kg N/ha	32	115	128	124
Maris Piper 180 kg N/ha	58	219	259	251
S.E. (16 D.F., same N level)	1.3	6.2	5.7	7.4
S.E. (16 D.F., different N levels)	1.5	6.2	5.7	6.4

TABLE 100. EFFECTS OF CULTIVATION, VARIETY AND N APPLICATION RATE ON TOTAL (HAULM AND TUBER) N UPTAKE (KG N/HA) ON FOUR OCCASIONS

Haulm N uptake was not affected by the contrasting cultivations nor by variety (Table 101) but when the amount of N applied was increased from 0 to 180 kg N/ha, maximum haulm increased from 66 to 144 kg N/ha. This increase was similar in both Lady Rosetta and Maris Piper. For similar N treatments, maximum haulm N uptakes were larger in 2010 than in 2009. A key date in a crop’s development is the date after emergence at which the rate of N uptake by the tubers (which is approximately constant with respect to absorbed radiation) becomes equal to the rate of total N uptake (which is initially rapid but steadily decreases). After this date the crop canopy becomes a net exporter of N and canopy senescence will follow. This date was not affected in 2010 by N application rate or cultivation but did differ by c. 8 days depending on the variety. The rate of tuber N uptake will dictate how quickly reserves of N held in the canopy are depleted and thus when the canopy will be completely senesced. The rate of N uptake was significantly faster in Lady Rosetta than Maris Piper and was also faster when N was applied than where it was withheld completely.

	Rate of tuber N uptake (kg N/TJ)	Maximum total N uptake (kg N/ha)	Maximum haulm N uptake (kg N/ha)	Rate of total and tuber N uptake equal (DAE)
Plough Early	14.3	188	106	44
Plough Late	14.6	203	106	46
Non-plough Early	13.7	188	100	43
Non-plough Late	13.7	191	107	47
S.E. (14 D.F.)	0.32	3.8	4.5	1.0
Lady Rosetta	15.9	190	99	41
Maris Piper	12.3	194	111	49
S.E. (16 D.F.)	0.24	5.5	5.4	1.4
0 kg N/ha	11.7	131	66	45
180 kg N/ha	16.5	254	144	45
S.E. (14 D.F.)	0.23	2.7	3.2	0.7
Lady Rosetta 0 kg N/ha	13.3	132	61	41
Lady Rosetta 180 kg N/ha	18.5	249	137	42
Maris Piper 0 kg N/ha	10.1	130	71	50
Maris Piper 180 kg N/ha	14.5	258	150	48
S.E. (16 D.F., same N level)	0.36	7.8	7.6	2.0
S.E. (16 D.F., different N levels)	0.33	6.1	6.2	1.6

TABLE 101. EFFECTS OF CULTIVATION, VARIETY AND N APPLICATION RATE ON RATE OF TUBER N UPTAKE, MAXIMUM TOTAL AND HAULM N UPTAKE AND DATE WHEN RATE OF TOTAL N AND TUBER N UPTAKE ARE EQUAL

19.2. Conclusions

In this experiment, yield differences due to the effect of N application rate were larger than those due to variety whilst the effects of timing and type of primary cultivation were non-significant. The effect of the treatments on radiation absorption, total DM production and tuber FW yield were explicable by considering the effects of the treatments on the dynamics of N uptake and redistribution.

20. SUMMARY OF EFFECTS OF SOIL CONDITIONS AND N APPLICATION RATE ON TUBER YIELD 2005-2010

The effects of soil cultivations on tuber yield have been studied over many seasons at CUF. The experiments from 2005-2010, whilst having different designs and treatments, used cultivations at different soil moisture contents to generate contrasting soil conditions. Some of these experiments also tested the effects of different amount of N or irrigation. The combined effects of these treatments on crop growth, N uptake and yield were then recorded. Over the six experiments, soil cultivation affected yield in three (Table 102). In 2006 and 2008 cultivating wet soils (resulting in a smeared layer at c. 25 cm below the ridge) reduced tuber FW yields by c. 10 and 5 t/ha, respectively. In 2005, yields were increased by c. 4 t/ha when the soils were cultivated wet but this was attributed to compaction caused by the tractor and implements that were used to cultivate the soil in the Cultivated dry plots before roto-ridging. Thus despite cultivating soils at inappropriate moisture contents, the effects on yield were relatively small (i.e. an average loss of 3.3 t/ha compared with an average yield over six seasons of 58.3 t/ha). However, the experiment in 2006 shows that inappropriate cultivations can cause soil damage and this resulted in a large yield penalty. It is possible that Maris Piper is relatively tolerant of moderately poor soil conditions, however in 2010 Lady Rosetta was also included and cultivation at different soil water contents had little effect on its yield. The soils at Cambridge have a relatively high stone content (12-15 %) and, due to history of FYM applications, have relatively high organic matter content (4-5 %, although this has decreased since application ceased in 1999 when organic matter content was 7-8 %). It is possible that these two factors can, to a certain extent, mitigate against the effects of compaction thereby minimising the effects on yield, but the mechanism of this mitigation needs to be better understood. Work in 2011 will be extended to other soil types in an attempt to better understand the factors affecting a soil's susceptibility to damage.

With the exception of 2009, all experiments tested the effects of two or more N application rates and in each of these experiments, N application rate significantly affected yield. In two experiments (2005 and 2008, Table 103), tuber yields were smaller when no N was applied to crops grown on compacted soils. However, when adequate N was applied there was little difference in yield between crops grown on compacted or uncompacted soils. In the one experiment (2005) where there were four levels of N, there was some indication that the optimum N application was smaller for the crop grown on uncompacted soil. Collectively, these data suggest that for crops grown on compacted soils yields will not be greatly increased by applying more N. However, in those circumstances where the N application is just adequate when soil conditions are good, there may be a yield penalty when soil conditions are poor.

	2005	**2006**	**2007**	**2008**	**2009**	**2010**
Cultivated dry	57.8	57.2	58.1	69.0		
Cultivated wet	62.2	46.9	58.0	64.2		
Cultivated moist					58.8	
Cultivated at field capacity					60.7	
Cultivated wet					57.2	
Cultivated over-wet					59.4	
Ploughed early						55.2
Ploughed late						55.8
Non-ploughed early						56.5
Non-ploughed late						58.0
Mean	60.0	52.0	58.1	66.6	59.0	56.4
S.E. (D.F.)	1.21 (33)	2.94 (6)	1.23 (9)	1.39 (33)	1.98 (30)	1.26 (14)

TABLE 102. SUMMARY OF MAIN EFFECTS OF PRIMARY CULTIVATION ON TUBER FW YIELD > 10 MM (T/HA) IN MARIS PIPER DURING 2005-2010

	Mean	N application rate (kg N/ha)	Cultivated dry	Cultivated wet	S.E. (D.F.)
2008	66.6	0	65.7	55.8	1.39 (33)
		200	72.3	72.6	1.35 (33)†
2005	60.0	0	48.1	62.9	2.42 (25)
		100	57.0	60.0	
		200	61.8	64.3	
		300	64.5	61.7	

†S.E. for comparing means with same cultivation.

TABLE 103. EFFECT OF N APPLICATION RATE AND PRIMARY CULTIVATION ON TUBER FW YIELDS > 10 MM (T/HA) IN THOSE EXPERIMENTS WHERE THERE WAS A SIGNIFICANT EFFECT OF CULTIVATION AND A SIGNIFICANT INTERACTION BETWEEN CULTIVATION AND N APPLICATION RATE

21. EFFECTS OF SHADING, N AND WATER SUPPLY

21.1. Introduction

Earlier shading experiments at CUF in 2006 and 2007 showed that reducing the quantity of incident radiation received by a crop reduced total DW and tuber FW yields. However, the percentage yield reduction in the shaded crops was less than the reduction in incident radiation due to the shaded crops having greater radiation use efficiencies. The experiment also showed that shading had relatively little effect on tuber or total (i.e. tuber and haulm) N uptake at final harvest. The objective of the 2008 experiment was to gather further data on the relationship between incident radiation, radiation absorption, DM production and N uptake. Experiments at CUF using solarimeters (e.g. Firman & Allen 1989; Stalham & Firman 1992) have shown that the relationship between percentage ground cover and percentage absorption of incident radiation is curvilinear. Typically, these studies have shown that 100 % ground cover corresponds to c. 85 % absorption of total incident radiation (although the absorption of photosynthetically active radiation (PAR) is larger). However, for simplicity, much work has assumed that there is simple linear relationship between percentage crop ground cover and percentage radiation absorption. The CUF yield model also makes this assumption but because of the methods used to parameterise the yield model the assumption seldom results in large discrepancies between observed and modelled yield. However, as part of the process of model development, comparisons were made in this experiment between estimates of radiation absorption based on percentage ground cover and measurements made using solarimeters placed in selected treatments.

21.2. Materials and Methods

Details specific to each variety and N experiment at CUF are shown in Table 104 and details of sampling, sample processing and data analysis are shown on page 13. All the experiments were planted manually with dibbers. Nitrogen fertilizer was applied as ammonium nitrate in a single application at planting and shallowly incorporated into the soil by raking. For each experiment, average row spacing was 76.2 cm and within row plant spacing was 25 cm giving an intended plant population of 52 493 /ha. Each treatment combination was replicated four times and allocated at random to blocks. Previous work had shown the intensity of solar radiation under the covers was 0.54 of that above (Allison, 2007) and these were suspended c. 1.5 m above the top of the ridges on wires stapled to fence posts.

Plant emergence was measured every 3 or 4 days from 1st emergence until plant emergence ceased and ground covers were measured by grid weekly. Irrigation was applied by boom and hose reel combination and agrochemicals were applied according to standard farm practice. Harvests were taken from rows two and three of each four row plot. A minimum of a two plant (0.5 m) discard was left between adjacent harvests area or plot ends. The experiment in 2008 and 2009 used Estima since its compact canopy was not impeded by the shade covers. However, it was found that Estima treatments given no N or receiving reduced water inputs often senesced many weeks before other treatments and this compromised the usefulness of the experiments. Therefore, in 2010 Desiree was used in place of Estima since it still reasonably compact but it is relatively indeterminate and drought tolerant. In 2010, pairs of tube solarimeters were placed between rows two and three in each four-row plot and were perpendicular to the rows. Tubes were placed a minimum of 1 m from the plot ends. Solarimeters were only placed in the unshaded plots and so measured the effects of irrigation and N application rate. The top of the solarimeter was *c.* 5 cm from the top of the ridge and care was taken to ensure each tube was level. The voltage output from each pair of tubes was automatically logged and each pair of tubes was calibrated against the radiation sensor on the meteorological station at CUF.

	2008	**2009**	**2010**
Field	Osier	Dry Field	Cage Field
Variety (average seed weight, g)	Estima (25.0)	Estima (24.2)	Desiree
N rates tested (kg N/ha)	0 & 200	0 & 200	0 & 200
Irrigation treatment	-	Restricted & Full	None & Irrigated
Shade treatments	Early & Late	None & shaded	None & shaded
Plot dimensions	4 rows × 6 m	4 rows × 6 m	4 rows × 6 m
Planting date	10 April	16 April	25 April
Shade treatments start	Early, 30 May Late, 9 July	2 June	9 June
Irrigation (mm)	128	44 or 144	0 or 173
Harvest 1	27 June	26 June	2 July
Harvest 2	30 July	28 July	30 July
Harvest 3	28 August	19 August	8 October
Harvest areas (m2)	1.91	1.91	1.91 (Harvest 1 and 2) or 2.29 (Harvest 3)

TABLE 104. TREATMENT DETAILS SHADING EXPERIMENT AT CUF 2008-2010

22. CUF 2008

22.1. Results and Discussion

22.1.1. Emergence, ground covers and radiation absorption

The mean date of 50 % plant emergence was 14 May (34 days after planting) and nearly all plots achieved 100 % plant emergence. Increasing the N application rate from 0 to 200 kg N/ha delayed 50 % plant emergence by c. 2 days. The development of ground cover is shown in Figure 37 and is summarised in Table 105.

(a)

(b)

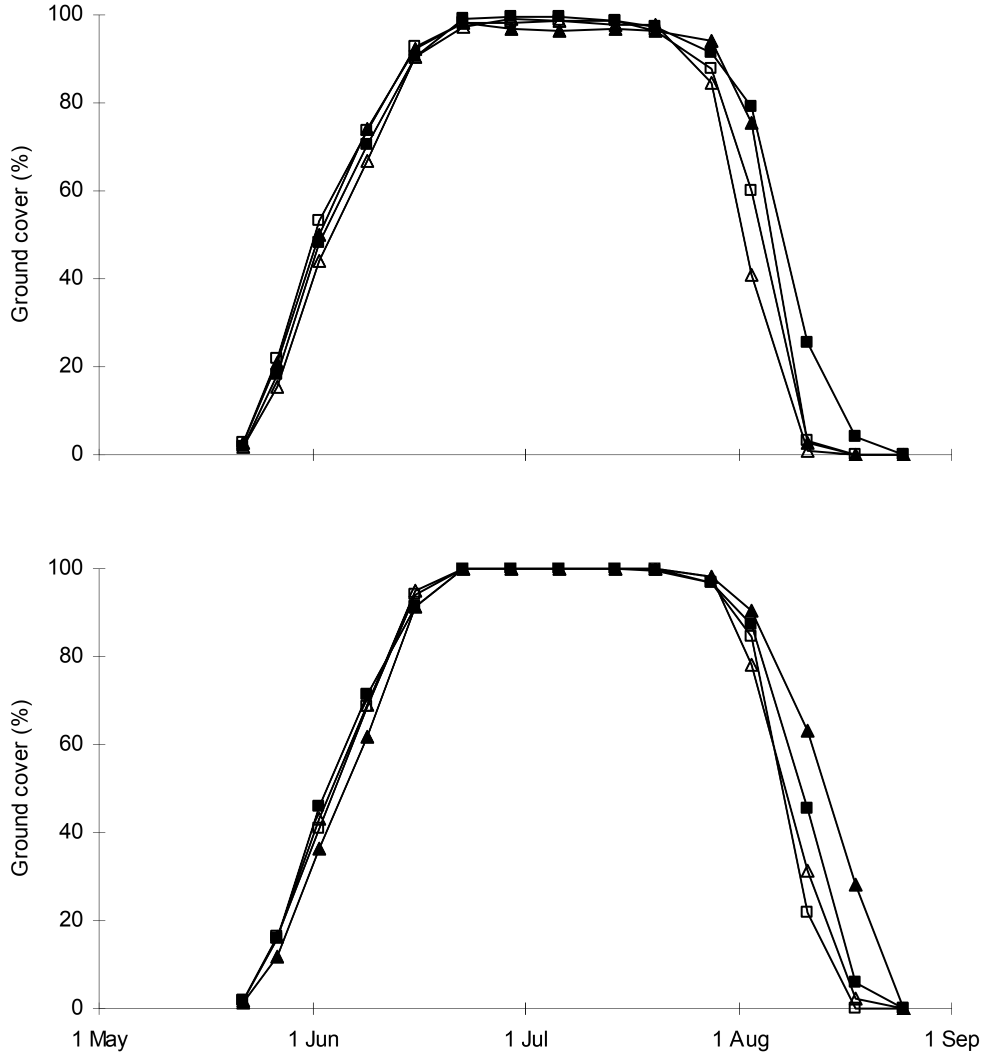


FIGURE 37. GROUND COVER DEVELOPMENT IN ESTIMA. (A) 0 KG N/HA AND (B) 200 KG N/HA. SHADE TREATMENTS: NONE-NONE, □; EARLY-NONE, ■; NONE-LATE, △; EARLY-LATE, ▲.

Irrespective of N application rate, expansion of ground cover was rapid and all crops achieved complete ground cover. When averaged over the shading treatments, 200 kg N/ha increased integrated ground cover by 500 % days (equivalent to an extra 5 days at complete ground cover). In 2007, increasing the N application rate from 0 to 200 kg N/ha increased ground cover persistence from 4307 to 5987 % days. Thus canopies were more persistent in 2008 and gave smaller responses to N fertilizer than in 2007. The early-shaded treatments had significantly more persistent canopies than the unshaded as was found in 2006 and 2007. In 2006, it was found that the shade covers reduced the amount of radiation by c. 45 % and the percentage reduction was independent of the intensity of the incident radiation. Using values for the percentage reduction in incident radiation due to shading it is possible to estimate the amount of radiation absorbed by the shaded and unshaded crops. When averaged over the shading treatments, increasing the N application rate from 0 to 200 kg N/ha increased radiation absorption from 8.36 to 8.87 TJ/ha (Table 105). On average, early shading reduced the amount of radiation absorbed by the crop by 2.5 TJ/ha and late shading by 2.2 TJ/ha. Early and late shading reduced the amount of radiation absorbed by 4.8 TJ/ha when compared with crops that were unshaded through the season.

	Integrated ground cover (% days)		Radiation absorbed (TJ/ha)	
Shading	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
None-None	6191	6498	10.75	11.22
Early-None	6476	6762	8.27	8.70
None-Late	5854	6574	8.46	9.10
Early-Late	6274	6923	5.97	6.45
Mean	6199	6689	8.36	8.87
S.E. (21 D.F.)	N, 67.2; N and Shade, 134.3		N, 0.084; N and Shade, 0.168	

TABLE 105. EFFECT OF N APPLICATION RATE AND SHADING ON INTEGRATED GROUND COVER AND RADIATION ABSORPTION

22.1.2. Yields at the first, second and final harvests

Increasing the N application rate from 0 to 200 kg N/ha significantly reduced the stem population and this effect was consistent for all three harvests (Table 106). This reduction is unusual but has been seen in other experiments at CUF (see Variety and N Experiment p. 38). At present we do not know the mechanism behind the reduction in stem population but it may be a consequence of high levels of N having a phytotoxic effect and reducing stem vigour. Increasing the N application rate from 0 to 200 kg N/ha decreased the tuber population at the first harvest but at subsequent harvests there were no significant differences (Table 107). Early shading reduced tuber population at all three harvests and this effect is consistent with the early shading (that was started at c. 16 DAE) reducing the crop growth rate at the time of tuber initiation (typically 20 DAE). Late shading had no statistically significant effect on tuber populations.

	Harvest 1 (27 June, 44 DAE)	Harvest 2 (30 July, 77 DAE)	Harvest 3 (28 August, 106 DAE)
Mean	89.4	88.7	89.7
0 kg N/ha	98.4	94.8	95.1
200 kg N/ha	80.4	82.7	84.3
S.E. (21 D.F.)	3.02	3.08	2.96
None-None	90.5	87.9	89.9
Early-None	89.2	90.5	89.9
None-Late	85.9	88.6	89.2
Late-Late	91.8	87.9	89.9
S.E. (21 D.F.)	4.28	4.36	4.19

TABLE 106. MAIN EFFECTS N APPLICATION RATE AND SHADE TREATMENTS ON STEM POPULATION (000/HA)

	Harvest 1 (27 June, 44 DAE)	Harvest 2 (30 July, 77 DAE)	Harvest 3 (28 August, 106 DAE)
Mean	449	443	415
0 kg N/ha	479	444	431
200 kg N/ha	418	443	400
S.E. (21 D.F.)	12.9	14.2	13.5
None-None	494	455	423
Early-None	376	428	406
None-Late	490	492	486
Late-Late	434	397	347
S.E. (21 D.F.)	18.3	20.0	19.0

TABLE 107. MAIN EFFECTS N APPLICATION RATE AND SHADE TREATMENTS ON TUBER POPULATION > 10 MM (000/HA)

At the first sampling (27 June, 44 DAE), the mean total DW and tuber FW yields were 5.0 and 17.8 t/ha, respectively (Table 108). Applying 200 kg N/ha had no significant effect on total DM yield but tuber yields were significantly reduced due to effects of N on DM partitioning between haulm and tubers. When averaged over all other factors, early shading reduced total DW yield from 5.7 to 5.3 t/ha and tuber FW yield from 21.3 to 14.4 t/ha. The second harvest was taken on 30 July (77 DAE) and the average total DM yield was 11.3 t/ha and the tuber FW yield was 51.6 t/ha (Table 109). Increasing the N application rate from 0 to 200 kg N/ha increased total DW from 10.9 to 11.8 t/ha and tuber FW yield from 48.6 to 54.6. When averaged over all other factors, early shading reduced tuber FW yield by c. 12 t/ha and late shading by c. 5 t/ha. The final crop sample was taken on 28 August (106 DAE) when the canopies of all treatments had completely senesced. The overall average total DM yield was 11.8 t/ha and the tuber FW yield was 59.2 t/ha (Table 110). In 2007, the average total DM and tuber FW yields at final harvest were 9.0 and 38.8 t/ha, respectively, showing that yields in 2008 which were much larger than those in 2007 and were broadly similar to those in 2006. In 2008, when averaged over the shade treatments, applying 200 kg N/ha increased total DW yield by 2.4 t/ha and tuber FW yields by 13.6 t/ha. The corresponding increases in yields in 2007 were 5.4 and 23.7 t/ha. These yield data support the earlier ground cover data and show that yields in 2008 were larger than in 2007 but crop responses to N fertilizer were smaller. When averaged over both N treatments, crops that were shaded for most of the growing season (Early-Late) had total DM and tuber FW yields of 9.9 and 49.6 t/ha, respectively, compared with yields in the unshaded (None-None) crops of 13.1 and 64.7 t/ha. Therefore, reductions in incident radiation as a result of 45 % shading for a large part of the season reduced total DW and tuber FW yields by c. 24 %. The effect of shading on total DW and tuber FW yield was larger when 200 kg N/ha had been applied compared with the unfertilized crop. This suggests that when no N had been applied the crops were severely N deficient and were unable to respond to the larger amounts of incident radiation when unshaded. For the majority of crops, productivity is mainly related to the size and duration of ground cover. The results from this experiment suggest that for crops deficient in N the ability of the leaves to use incident radiation may be compromised.

Shading	Total DM yield (t/ha) 0 kg N/ha	200 kg N/ha	Tuber FW yield (t/ha) 0 kg N/ha	200 kg N/ha
None-None	6.13	5.44	25.2	19.9
Early-None	4.01	4.29	14.4	12.9
None-Late	5.30	5.97	20.7	19.3
Early-Late	5.13	3.95	19.3	10.9
Mean	5.14	4.91	19.9	15.8
S.E. (21 D.F.)	N, 0.190; N and Shade, 0.379		N, 0.82; N and Shade, 1.65	

TABLE 108. EFFECT OF N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON 27 JUNE (44 DAE)

Shading	Total DM yield (t/ha) 0 kg N/ha	200 kg N/ha	Tuber FW yield (t/ha) 0 kg N/ha	200 kg N/ha
None-None	12.57	13.12	55.4	60.9
Early-None	11.06	11.67	49.1	51.6
None-Late	11.20	12.41	51.4	61.2
Early-Late	8.66	9.72	38.3	44.4
Mean	10.87	11.73	48.6	54.6
S.E. (21 D.F.)	N, 0.278; N and Shade, 0.557		N, 1.30; N and Shade, 2.59	

TABLE 109. EFFECT OF N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON 30 JULY (77 DAE)

Shading	Total DM yield (t/ha) 0 kg N/ha	200 kg N/ha	Tuber FW yield (t/ha) 0 kg N/ha	200 kg N/ha
None-None	11.42	14.76	55.4	74.0
Early-None	10.81	13.20	53.3	64.6
None-Late	11.25	13.09	56.8	70.5
Early-Late	8.85	10.89	44.2	55.0
Mean	10.58	12.98	52.4	66.0
S.E. (21 D.F.)	N, 0.324; N and Shade, 0.647		N, 1.45; N and Shade, 2.90	

TABLE 110. EFFECT OF N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON 28 AUGUST (106 DAE)

22.1.3. Radiation Use Efficiency

Using data from all three harvests, values of total DM (i.e. tuber and haulm) yield and radiation absorption were analysed using linear regression on a plot-by-plot basis. The regression lines were constrained to pass through the origin and the slopes of the lines (i.e. RUE, as t DM/TJ) were then subjected to analysis of variance. The overall average RUE was 1.45 t DM/TJ (Table 111). The average RUE of the unshaded crops (1.24 TJ/ha) was similar to that found for Estima in the Variety and N Experiment (p. 38) and the Rate and Timing of N Experiment (p.159). Increasing the N application rate from 0 to 200 kg N/ha increased the RUE from 1.38 to 1.52 t DM/TJ. This effect of N was also consistent with the effects seen in other N experiments in 2008. Reducing the amount of incident radiation by shading increased RUE and this effect was particularly noticeable in the early-shaded treatments. The reduced RUE of the unshaded crops explains why they did not give much larger yields than the crops that were shaded for nearly all the season. The differences in final total DW and tuber FW yield are entirely explicable by the effect of N on ground cover persistence and RUE and the effects of shading on the quantity of radiation received by the crop and the efficiency with which the radiation was converted to DM.

	0 kg N/ha	200 kg N/ha	Mean
None-None	1.17	1.31	1.24
Early-None	1.43	1.57	1.50
None-Late	1.35	1.45	1.40
Early Late	1.57	1.74	1.66
Mean	1.38	1.52	1.45

S.E. (21 D.F.) Nitrogen 0.027; Shading 0.038; Nitrogen and Shading 0.054

TABLE 111. EFFECT OF N APPLICATION RATE AND SHADING ON SEASON-LONG RADIATION USE EFFICIENCY (T DM/TJ)

22.1.4. Total and tuber N uptake

Values for tuber and total (tuber and haulm) N uptake at each harvest are shown in Table 112 to Table 114. At the first harvest on the 27 June (44 DAE), increasing the N application rate from 0 to 200 kg N/ha had increased total N uptake from 111 to 152 kg N/ha. There was some evidence that early shading reduced total N uptake but this effect was not significant. Increasing the N application rate from 0 to 200 kg N/ha had no effect on tuber N uptake but early shading reduced tuber N uptake by an average of 13 kg N/ha. The second harvest was taken on 30 July (77 DAE) and the average total N uptake was 168 kg N/ha. Total N uptake increased from 139 to 197 kg N/ha when 200 kg N/ha was applied. When averaged over the treatments, early shading decreased total N uptake from 180 to 155 kg N/ha when compared with treatments that received no early shade. Late shading had no statistically significant effect on either tuber or total N uptake. The final harvest was taken on 28 August (106 DAE) when all crops had senesced. The overall, average N uptake at this time was 176 kg N/ha and when averaged over the other factor, increasing the N application rate from 0 to 200 kg N/ha increased total N uptake from 144 to 207 kg N/ha. On average, early shading reduced total N uptake from 192 to 159 kg N/ha but the effects of late shading were non-significant. At final harvest, tuber N uptake averaged 151 kg N/ha and applying N increased tuber N uptake from 126 to 175 kg N/ha. Similarly, relative to the unshaded controls, early shading reduced N uptake from 168 to 133 kg N/ha. Between the second and third harvest (77 and 106 DAE) average total N uptake increased from 168 to 176 kg N/ha and this supports results from many earlier experiments that show that the bulk of N uptake occurs early in the growing season. In 2007, when averaged across the shading treatments, measured values for total N uptake at final harvest were 75 or 162 kg N/ha when 0 or 200 kg N/ha had been applied, respectively. Thus, as noted in other experiments, total N uptakes in 2008 were larger than those in 2007 and more similar to those in 2006.

Shading	Tuber N uptake (kg N/ha) 0 kg N/ha	Tuber N uptake (kg N/ha) 200 kg N/ha	Total N uptake (kg N/ha) 0 kg N/ha	Total N uptake (kg N/ha) 200 kg N/ha
None-None	51	45	123	150
Early-None	28	30	89	134
None-Late	38	43	105	191
Early-Late	41	25	128	132
Mean	40	36	111	152
S.E. (21 D.F.)	N, 2.2; N and Shade, 4.3		N, 7.8; N and Shade, 15.5	

TABLE 112. EFFECT OF N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON 27 JUNE (44 DAE)

Shading	Tuber N uptake (kg N/ha) 0 kg N/ha	Tuber N uptake (kg N/ha) 200 kg N/ha	Total N uptake (kg N/ha) 0 kg N/ha	Total N uptake (kg N/ha) 200 kg N/ha
None-None	112	153	151	211
Early-None	102	120	143	184
None-Late	110	156	144	215
Early-Late	82	108	117	178
Mean	102	134	139	197
S.E. (21 D.F.)	N, 3.8; N and Shade, 7.5		N, 5.4; N and Shade, 10.9	

TABLE 113. EFFECT OF N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON 30 JULY (77 DAE)

Shading	Tuber N uptake (kg N/ha) 0 kg N/ha	Tuber N uptake (kg N/ha) 200 kg N/ha	Total N uptake (kg N/ha) 0 kg N/ha	Total N uptake (kg N/ha) 200 kg N/ha
None-None	129	202	150	232
Early-None	122	160	138	193
None-Late	144	198	161	227
Early-Late	109	141	127	177
Mean	126	175	144	207
S.E. (21 D.F.)	N, 8.5; N and Shade, 16.9		N, 9.0; N and Shade, 17.9	

TABLE 114. EFFECT OF N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON 28 AUGUST (106 DAE)

22.2. Conclusions

The experiment has provided more useful information on the relationship between the intensity of incident radiation, RUE and yield production. The experiment in 2008 showed that early shade treatments reduced total N uptake and this is in contrast to experiments in 2006 and 2007 where shading (early or late) had little significant effect. The early shading treatment was applied earlier in 2008 than in previous seasons and reduced the ability of the crop to take up N. It is possible that similar effect could occur in commercial crops in dull seasons and thus irrespective of the amount of N applied, yield production may be compromised.

23. CUF 2009

23.1. Results and Discussion

23.1.1. Emergence, ground cover and radiation absorption

The mean date of 50 % plant emergence was 14 May (28 days after planting) and nearly all plots achieved 100 % plant emergence. There was no effect of N application rate on pattern of crop emergence unlike the reductions in plant emergence seen in the 2008 experiment. The development of ground cover is shown in Figure 38 and estimates of canopy persistence (as integrated ground cover) and radiation absorption are shown in Table 115.

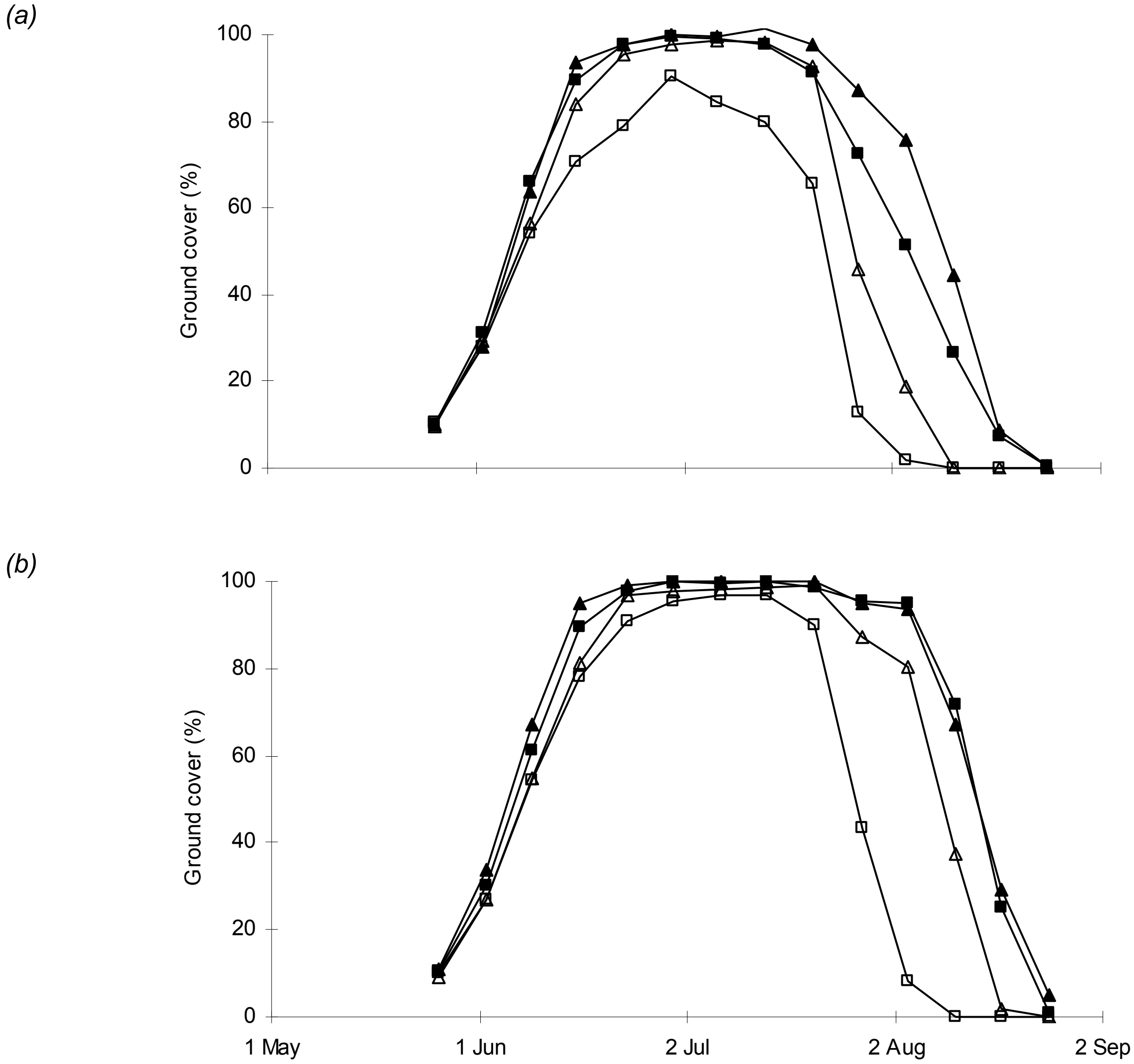


FIGURE 38. GROUND COVER DEVELOPMENT IN ESTIMA. (A) RESTRICTED IRRIGATION AND (B) FULL IRRIGATION. UNSHADED-0 KG N/HA, □; UNSHADED-200 KG N/HA, ■; SHADED-0 KG N/HA, △; SHADED-200 KG N/HA, ▲.

With the exception of the restricted, unshaded and 0N treatment, all plots achieved ground covers in excess of 95 %. The canopies of some crops (i.e. unshaded and receiving no N fertilizer) started to senesce in early to mid-July and this compromised yield potential considerably. When averaged over the shading and N treatments, irrigation had the largest effect on canopy persistence and full irrigation increased integrated ground cover by 900 % days. The effects of shading or applying 200 kg N/ha were +784 and +436 % days, respectively. Previous studies have shown that the shade covers reduce the intensity of incident radiation by c. 45 % and the proportional reduction was not affected by the intensity of the incident radiation. Shading had the largest effect on the amount of radiation absorbed by the crop reducing it by c. 4.5 TJ/ha when compared with unshaded crops. Restricting irrigation reduced radiation absorption by c. 1 TJ/ha and omitting the N application reduced radiation absorption by 1.8 T/ha. There was some indication that applying 200 kg N/ha had a larger effect on ground cover persistence and radiation absorption in the unshaded crops than the shaded crops.

	Integrated ground cover (% days)	**Radiation absorbed (TJ/ha)**
Mean	5760	7.37
Restricted irrigation	5310	6.85
Full irrigation	6210	7.90
0 kg N/ha	5042	6.47
200 kg N/ha	5478	8.28
No shade	5368	9.63
Shade	6152	5.12
S.E. (21 D.F.)	92.5	0.124

TABLE 115. MAIN EFFECTS OF IRRIGATION, N APPLICATION RATE AND SHADING ON INTEGRATED GROUND COVER AND RADIATION ABSORPTION

23.1.2. Yields at the first, second and final harvests

No treatment had any statistically significant effect on the main stem population and this averaged c. 99 000/ha over the three samplings. There were few secondary stems (< 500/ha) and these were not affected by any treatment. Over all three harvests, tuber populations > 10 mm averaged 407 000/ha (Table 116). At the first sampling, tuber populations were not significantly affected by any treatment, although the shaded treatment had a numerically smaller tuber population. At the second sampling, tuber populations were significantly reduced in the shaded plots, whilst at the final harvest tuber populations were significantly smaller in the shaded and in the 0N treatments. In 2008, early shading (starting 16 DAE) also resulted in a significant reduction in tuber population and this was consistent with a reduction in crop growth rate reducing the number of tubers initiated. The 2009 experiment suggested that the number of tubers retained until final harvest may also be affected by shading and N nutrition. There was no evidence that withholding irrigation had any effect on tuber population.

	26 June	28 July	19 August or 4 September
Mean	412	415	393
Restricted irrigation	417	418	383
Full irrigation	408	414	403
0 kg N/ha	421	408	374
200 kg N/ha	404	423	412
No shade	424	443	414
Shade	401	388	372
S.E. (21 D.F.)	11.9	8.2	8.3

TABLE 116. MAIN EFFECTS OF IRRIGATION, N APPLICATION RATE AND SHADE TREATMENTS ON TUBER POPULATION > 10 MM (000/HA)

At the first sampling, the total DW yield was significantly larger in those crops that had been fully irrigated, had received 200 kg N/ha or were unshaded and the size of these treatment effects were similar (Table 117). Increasing the N application rate from 0 to 200 kg N/ha increased tuber FW yield by c. 1.3 t/ha. However, the effects of shading and irrigation were larger (c. 4.0 t/ha in both cases).

		Total DM yield (t/ha)		Tuber FW yield > 10 mm (t/ha)	
Irrigation	Shade	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
Restricted	No Shade	4.42	5.47	15.5	17.4
irrigation	Shade	3.93	4.64	13.0	13.7
Full	No Shade	5.43	5.98	21.5	21.6
irrigation	Shade	3.95	5.73	15.2	17.8
Means for N		4.43	5.45	16.3	17.6
Overall mean		4.94		17.0	
S.E. (21 D.F.)		0.117 (N); 0.233 (N*Shade*Irri)		0.34 (N); 0.69 (N*Shade*Irri)	

TABLE 117. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON 26 JUNE

On 28 July, when averaged over other factors, reducing radiation absorption by 45 % reduced total DW yield from 11.6 to 9.7 t/ha and this equivalent to a 16 % reduction in total DM yield (Table 118). Increasing the N applications from 0 to 200 kg N/ha increased total DW yield by 2.9 t/ha whilst full irrigation increased DW yield by 2.6 t/ha when compared with restricted irrigation. Total DW yield increases resulting from irrigation or N application were larger in the unshaded crops than shaded crops. When compared with unfertilized crops, applying 200 kg N/ha increased tuber FW yield by an average of 13.5 t/ha. The main effects of irrigation and shading were smaller and averaged c. 10 t/ha. The response to irrigation and N were much smaller in the shaded crops than unshaded crops. For example, in the shaded crops, use of irrigation or N increased yield by 4.3 or 6.8 t/ha, respectively whilst in the unshaded crops the corresponding yield increases were 16.3 or 20.1 t/ha. For some treatment combinations at final harvest (i.e. restricted irrigation, unshaded and unfertilized) there was little difference in total DW yield between the second and final harvest and in some cases the yields at the final sample were numerically smaller (Table 119). The main effect of full irrigation was to increase total DW yield by 3.7 t/ha whilst applying 200 kg N/ha increased yield by 4.9 t/ha. Shading reduced total DW yield by 0.7 t/ha. Total DW yield increases resulting from use of irrigation or N were also larger in the unshaded treatments. On average, use of N fertilizer increased tuber FW yield by 24 t/ha whilst use of 144 mm irrigation compared with 44 mm increased yield by 15 t/ha. The main effect of shading was to reduce yields by 6 t/ha. In shaded crops the yield increase from use of N or irrigation was 19 and 9 t/ha, respectively whereas in the unshaded crops the response to these inputs was much larger (30 or 22 t/ha, respectively). The data collected in this experiment, complement those collected in similar experiments in 2006–2008. Collectively, these data show that severe constraints on incident radiation do not incur pro rata reduction in total DW or tuber FW yields. Furthermore, these data also demonstrate that to maximise the potential of a UK environment the crop needs adequate supply of water and N.

		Total DM yield (t/ha)		**Tuber FW yield > 10 mm (t/ha)**	
Irrigation	**Shade**	**0 kg N/ha**	**200 kg N/ha**	**0 kg N/ha**	**200 kg N/ha**
Restricted	No Shade	7.82	11.21	34.5	50.9
irrigation	Shade	8.20	10.30	35.0	43.8
Full	No Shade	11.16	16.22	47.1	71.1
irrigation	Shade	9.70	10.62	41.3	46.0
Means for N		9.22	12.09	39.5	52.9
Overall mean		10.65		46.2	
S.E. (21 D.F.)		0.233 (N); 0.466 (N*Shade*Irri)		0.82 (N); 1.63 (N*Shade*Irri)	

TABLE 118. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON 28 JULY

		Total DM yield (t/ha)		**Tuber FW yield > 10 mm (t/ha)**	
Irrigation	**Shade**	**0 kg N/ha**	**200 kg N/ha**	**0 kg N/ha**	**200 kg N/ha**
Restricted	No Shade	6.90	10.26	33.6	51.2
irrigation	Shade	7.68	10.86	35.3	50.6
Full	No Shade	9.40	18.03	43.0	84.8
irrigation	Shade	9.41	13.69	41.3	63.0
Means for N		8.35	13.21	38.3	62.4
Overall mean		10.78		50.4	
S.E. (21 D.F.)		0.288 (N); 0.576 (N*Shade*Irri)		1.14 (N); 2.27 (N*Shade*Irri)	

TABLE 119. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON 19 AUGUST OR 4 SEPTEMBER

23.1.3. Radiation use efficiency

Analysis of RUE for some treatments was compromised since there was little radiation absorbed and total DM yield produced between the second and third crop samplings. The average RUE of the unshaded crops (1.23 t DM/TJ, Table 120) was similar to that found in a similar experiment in 2008. Use of irrigation increased RUE from 1.54 to 1.79 t DM/TJ and a similar increase resulted from increasing the N application rate from 0 to 200 kg N/ha. Reducing the intensity of incident radiation by 45 % increased RUE from 1.23 to 2.10 t DM/TJ. The increased RUE of the shaded crops explains why total DW and tuber FW yields were not much smaller than crops that were unshaded for most of the season.

Irrigation	**Shade**	**RUE (t DM/TJ)** **0 kg N/ha**	**200 kg N/ha**
Restricted irrigation	No Shade	1.02	1.12
	Shade	1.85	2.16
Full irrigation	No Shade	1.20	1.58
	Shade	2.03	2.37
Means for N		1.53	1.81
Overall mean		1.67	
S.E. (21 D.F.)		0.031 (N); 0.063 (N*Shade*Irri)	

TABLE 120. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON SEASON-LONG RADIATION USE EFFICIENCY (RUE)

23.1.4. Total and tuber N uptake

Values for tuber and total (tuber and haulm) N uptake at each harvest are shown in Table 121 to Table 123. At the first harvest on 26 June, the main effect of increasing the N application rate from 0 to 200 kg N/ha was to increase total N uptake from 79 to 145 kg N/ha. The main effects of irrigation were smaller and full irrigation increased total N uptake from 104 to 119 kg N/ha. Shading reduced total N uptake by c. 10 kg N/ha, but this effect was not statistically significant. Tuber N uptake was significantly larger in unshaded crops and those that had received 200 kg N/ha. At the second harvest total N uptake was increased from 101 to 193 kg N/ha when 200 kg N/ha was applied and from 133 to 161 when crops were fully irrigated. Shading reduced total N uptake by c. 10 kg N/ha but this reduction was not statistically significant. Tuber N uptake was not significantly increased by use of irrigation, but was larger in the unshaded crops and in those crops that received 200 kg N/ha. Final harvest was taken when all the crops had senesced and the average total N uptake was 143 kg N/ha. Since this was similar to the value recorded for the second harvest, on average, there had been little new N uptake. This supports results from many other experiments and observations that show that the bulk of N uptake occurs early in the growing season. Where no N had been applied, total N uptake averaged 96 kg N/ha and this increased to 193 kg N/ha once 200 kg N/ha had been applied. The effect of irrigation on total N uptake was smaller: crops with restricted irrigation had a total N uptake of 126 kg N/ha compared with 160 kg N/ha for crops that received 144 mm irrigation. On average, shading had no significant effect on total N uptake. Increasing the N application rate to shaded crops increased total N uptake by 79 kg N/ha but the increase was 109 kg N/ha for unshaded crops. It would seem that extra solar energy available in the unshaded crops allowed more N to be taken up. The largest total N uptake (241 kg N/ha, from the fully irrigated, unshaded and fertilized crop) was similar to that achieved by Estima crops grown with similar agronomy in nearby experiments.

		Tuber N uptake (kg N/ha)		Total N uptake (kg N/ha)	
Irrigation	**Shade**	**0 kg N/ha**	**200 kg N/ha**	**0 kg N/ha**	**200 kg N/ha**
Restricted	No Shade	32	42	74	143
irrigation	Shade	24	35	76	125
Full	No Shade	34	45	92	159
irrigation	Shade	23	34	73	153
Means for N		28	39	79	145
Overall mean		34		112	
S.E. (21 D.F.)		1.3 (N); 2.6 (N*Shade*Irri)		4.0 (N); 8.0 (N*Shade*Irri)	

TABLE 121. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON TUBER AND TOTAL N UPTAKE ON 26 JUNE

		Tuber N uptake (kg N/ha)		Total N uptake (kg N/ha)	
Irrigation	**Shade**	**0 kg N/ha**	**200 kg N/ha**	**0 kg N/ha**	**200 kg N/ha**
Restricted	No Shade	70	126	85	175
irrigation	Shade	74	107	97	176
Full	No Shade	87	157	115	236
irrigation	Shade	69	103	108	186
Means for N		75	123	101	193
Overall mean		99		147	
S.E. (21 D.F.)		3.5 (N); 7.1 (N*Shade*Irri)		3.9 (N); 8.0 (N*Shade*Irri)	

TABLE 122. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON TUBER AND TOTAL N UPTAKE ON 28 JULY

		Tuber N uptake (kg N/ha)		Total N uptake (kg N/ha)	
Irrigation	**Shade**	**0 kg N/ha**	**200 kg N/ha**	**0 kg N/ha**	**200 kg N/ha**
Restricted	No Shade	73	146	82	156
irrigation	Shade	82	156	94	171
Full	No Shade	85	222	97	241
irrigation	Shade	92	170	110	190
Means for N		83	174	96	190
Overall mean		128		143	
S.E. (21 D.F.)		3.2 (N); 6.3 (N*Shade*Irri)		3.5 (N); 6.9 (N*Shade*Irri)	

TABLE 123. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON TUBER AND TOTAL N UPTAKE ON 19 AUGUST OR 4 SEPTEMBER

23.2. Conclusions

This experiment examined the combined effects of three key factors (radiation, water supply and N supply) on the processes of yield production. In the absence of any apparent restrictions, tuber FW yields in excess of 80 t/ha were achieved but were halved when restriction were applied. Shading reduced incident radiation by c. 45 % but its effects on tuber FW yield were relatively small. Much larger reductions in yield resulted from restricting water or N supply.

24. CUF 2010

24.1. Results and Discussion

24.1.1. Emergence, ground covers and radiation absorption

The mean date of 50 % plant emergence was 19 May (37 days after planting) and nearly all plots achieved 100 % plant emergence. There was no effect of N application rate on pattern of crop emergence. The initial expansion of ground cover was slowed when no N was applied, so that at 25 DAE the ground covers were significantly smaller in the plots that received no N fertilizer (Figure 39 and Table 124). The maximum ground cover was reduced in rainfed crops and also those that were unshaded and received no N. All treatment combinations were at, or close to, complete senescence at final harvest on 8 October. In the 2009 experiment, the integrated ground cover of the fully irrigated Estima was 6210 % days but in 2010, the canopy of the rainfed Desiree was 8093 % days and therefore much more persistent. The main effect of N application rate on integrated ground cover was larger than the main effects of either irrigation or shading. Previous studies have shown that the shade covers reduce the intensity of incident radiation by c. 45 % and the proportional reduction was not affected by the intensity of the incident radiation. Shading had the largest effect on the amount of radiation absorbed by the crop reducing it by c. 6.4 TJ/ha when compared with unshaded crops. Restricting irrigation reduced incident radiation by c. 0.7 TJ/ha and omitting the N application reduced radiation absorption by 2.9 T/ha. As found in 2009, there was some indication that applying 200 kg N/ha had a larger effect on ground cover persistence and radiation absorption in the unshaded crops than the shaded crops.

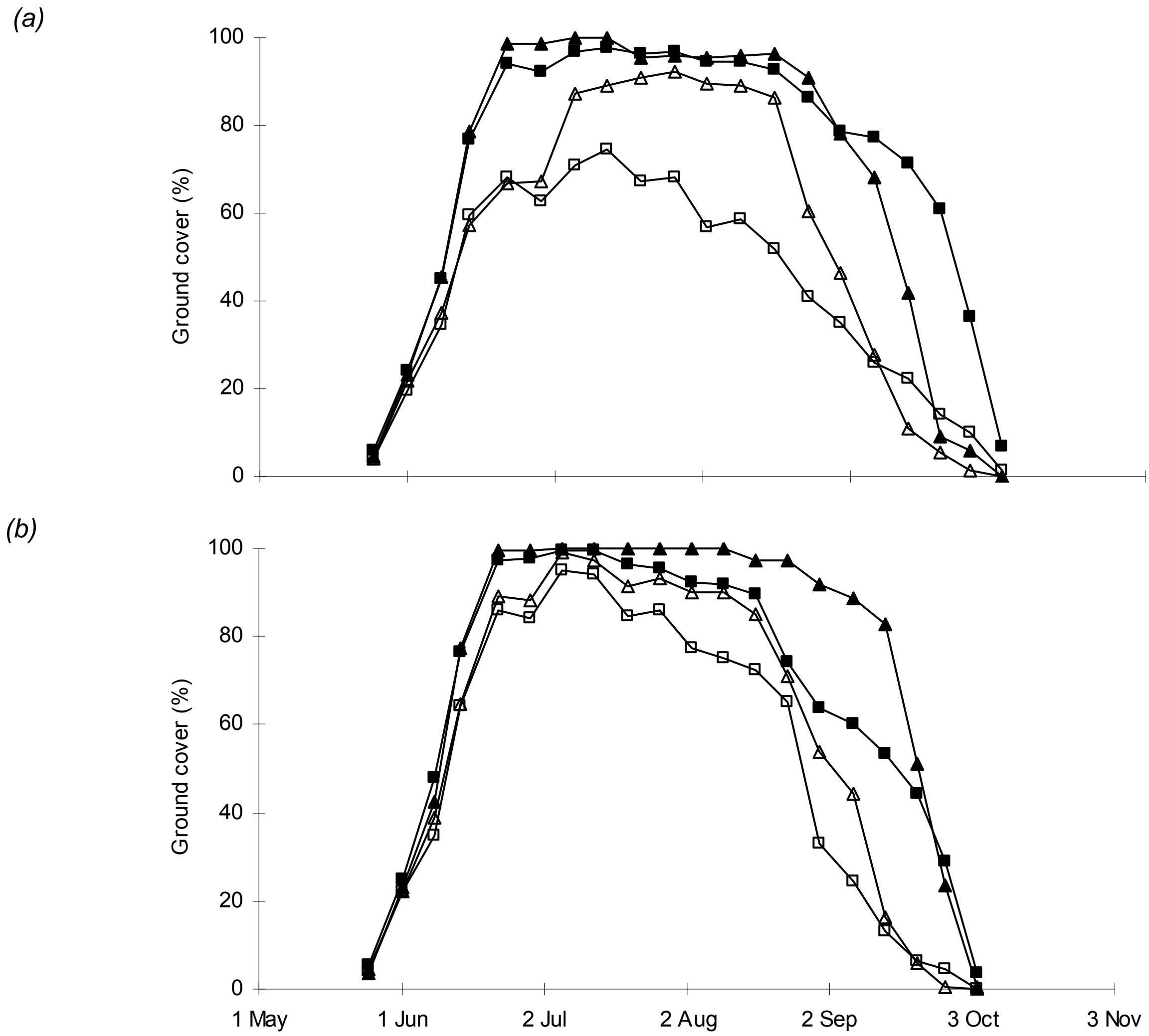


FIGURE 39. GROUND COVER DEVELOPMENT IN DESIREE. (*A*) UNSHADED AND (*B*) SHADED. RAINFED-0 KG N/HA, □; RAINFED-200 KG N/HA, ■; IRRIGATED-0 KG N/HA, △; IRRIIGATED-200 KG N/HA, ▲.

	GC at 25 DAE (%)	**Maximum GC (%)**	**Maximum GC (Ang)**	**Integrated GC (% days)**	**Radiation absorbed (TJ/ha)**
Rainfed	63	92	78	8093	9.55
Full irrigation	64	98	86	8735	10.26
0 kg N/ha	55	91	75	7083	8.44
200 kg N/ha	72	100	88	9745	11.37
No shade	61	92	78	8105	13.09
Shade	66	98	86	8723	6.72
S.E. (21 D.F.)	1.4	-	1.1	136.3	0.140

TABLE 124. MAIN EFFECTS OF IRRIGATION, N APPLICATION RATE AND SHADING ON GROUND COVER AT 25 DAE, PERCENT AND ANGULAR TRANSFORMED (ANG) MAXIMUM GROUND COVER, WHOLE SEASON INTEGRATED GROUND COVER AND RADIATION ABSORPTION

24.1.2. Yields at the first, second and final harvests

When averaged over all treatment combinations and harvests, the mean stem population was 151 000/ha. The effects of shading and irrigation on stem population were mostly small and non-significant. At the final sampling (8 October) the recorded stem population was significantly larger when 200 kg N/ha had been applied, however, the effect was small and was probably a consequence of difficulties in counting small and senesced stems late in the season.

Over all three harvests, tuber populations > 10 mm averaged 476 000/ha (Table 125). At the first sampling, tuber populations were not significantly affected by any treatment, although the shaded treatment had a numerically smaller tuber population. At the second sampling, tuber populations were significantly reduced when no N had been applied, whilst at the final harvest tuber populations were significantly smaller in the shaded and in the N0 treatments. Similar results were also obtained when tuber populations > 20 mm were analysed. This experiment suggests that the number of tubers retained until final harvest may also be affected by shading and N nutrition as was also found in 2009. There was no evidence that withholding irrigation had any effect on tuber population.

	2 July	**30 July**	**8 October**
Rainfed	476	507	441
Full irrigation	477	512	445
0 kg N/ha	467	480	412
200 kg N/ha	486	539	474
No shade	492	526	475
Shade	460	493	411
S.E. (21 D.F.)	14.1	13.1	11.1

TABLE 125. MAIN EFFECTS OF IRRIGATION, N APPLICATION RATE AND SHADE TREATMENTS ON TUBER POPULATION > 10 MM (000/HA), CUF 2010

At the first sampling on 2 July, total DW yields were significantly larger in those crops that received irrigation, were unshaded or had received 200 kg N/ha (Table 126). The magnitude of these effects was similar for the irrigation and N treatments but was slightly smaller for the effects of shading. Increasing the N application rate from 0 to 200 kg N/ha had no statistically significant effect on tuber FW yield but, on average, irrigation increased yield by c. 4.5 t/ha and shading reduced yield by c. 1.1 t/ha. On 30 July, when averaged over the other factors, reducing the amount of incident radiation by 45 % reduced total DW from 9.1 to 8.1 t/ha equivalent to a reduction of c. 11% (Table 126). Increasing the N application rate from 0 to 200 kg N/ha increased total DM yield by 2 t/ha from 7.6 to 9.6 t/ha. When compared to the rainfed plots, full irrigation increased total DM yields by 3.2 t/ha. As found in 2009, the response to N was larger in the unshaded plots than in the shaded. On average, use of irrigation had the largest effect on tuber FW yield and when compared with the rainfed plots, irrigation increased FW yields by c. 13 t/ha. The effects of shading and N on FW yield were similar: shading or withholding N fertilizer reduced yields by c. 5.5 t/ha. The effect of N on tuber FW yield was much larger in the unshaded crops than in the shaded. Applying 200 kg N/ha to the shaded crop increased tuber FW yields from 25.1 to 27.0 t/ha whereas for the unshaded crops the increase was from 27.2 to

36.4 t/ha. At the final harvest on 8 October, irrigation increased total DW yield by 4.9 t/ha, shading reduced yield by 1.8 t/ha and increasing the N application rate from 0 to 200 kg N/ha increased total DM production by 5.4 t/ha (Table 126). The increase in total DM yield resulting from applying N was larger in the unshaded crop than in the shaded. The main effect of N was to increase tuber FW yield by 24.5 t/ha, whereas 173 mm irrigation increased tuber FW yield by 17.3 t/ha. The main effect of season-long shading was to reduce tuber FW yields by 9.6 t/ha. In crops where the amount of incident radiation had been reduced by shading, increasing the N application rate from 0 to 200 kg N/ha increased yield from 38.6 to 55.9 t/ha. For the unshaded crops, the corresponding increase was from 41.1 to 72.7 t/ha. The data collected in this experiment, complement those collected in similar experiments in 2006–2009. Collectively, these data show that severe constraints on incident radiation do not incur pro rata reductions in total DW or tuber FW yields. Furthermore, these data also demonstrate that to maximise the potential of a UK environment the crop needs adequate supply of water and N.

			Total DM yield (t/ha)		**Tuber FW yield > 10 mm (t/ha)**	
Date	Irrigation	Shading	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
2 July	Rainfed	No Shade	3.73	4.53	11.5	12.6
		Shade	3.54	4.11	10.6	11.2
	Irrigated	No Shade	4.50	4.94	16.1	18.5
		Shade	4.53	4.84	15.3	14.2
	Mean for N		4.07	4.86	13.4	14.1
	S.E. (21 D.F.)		0.124 (N); 0.248 (N*Shade*Irri)		0.38 (N); 0.76 (N*Shade*Irri)	
30 July	Rainfed	No Shade	5.84	8.69	19.2	29.1
		Shade	6.06	7.34	18.9	23.0
	Irrigated	No Shade	9.51	12.34	35.2	43.7
		Shade	8.93	10.01	31.3	31.1
	Mean for N		7.58	9.60	26.2	31.7
	S.E. (21 D.F.)		0.247 (N); 0.495 (N*Shade*Irri)		1.04 (N); 2.08 (N*Shade*Irri)	
8 October	Rainfed	No Shade	8.21	13.80	33.4	60.8
		Shade	7.81	11.19	31.3	47.0
	Irrigated	No Shade	12.11	20.27	48.7	84.6
		Shade	11.86	16.17	45.8	64.8
	Mean for N		10.00	15.36	39.8	64.3
	S.E. (21 D.F.)		0.378 (N); 0.756 (N*Shade*Irri)		1.26 (N); 2.52 (N*Shade*Irri)	

TABLE 126. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON TOTAL DRY MATTER (DM) YIELD AND TUBER FRESH WEIGHT (FW) YIELD > 10 MM ON THREE OCCASIONS, CUF 2010

24.1.3. Radiation use efficiency

The average RUE for total DM production of the unshaded crops (1.03 t DM/TJ, Table 127) was somewhat smaller than those found in similar experiments in 2008 and 2009. On average, use of irrigation increased RUE for total production from 1.18 to 1.59 t DM/TJ. Increasing the N application rate from 0 to 200 kg N/ha resulted in a smaller but statistically significant increase in RUE. On average, reducing the intensity of incident radiation by 45 % increased RUE from 1.03 to 1.74 t DM/TJ. The increased RUE of the shaded crops explains why total DW and tuber FW yields were not much smaller than crops that were unshaded for most of the season. The effects of the treatments and treatment combinations on the RUE for tuber DM production were similar to those for total DM production.

		Total RUE (t/TJ)		**Tuber RUE (t/TJ)**	
Irrigation	**Shade**	**0 kg N/ha**	**0 kg N/ha**	**200 kg N/ha**	**200 kg N/ha**
Rainfed	No Shade	0.85	0.89	0.78	0.92
	Shade	1.43	1.54	1.40	1.70
Irrigated	No Shade	1.08	1.30	1.00	1.54
	Shade	1.90	2.07	2.00	2.30
Means for N		1.32	1.45	1.30	1.62
S.E. (21 D.F.)		0.034 (N); 0.069 (N*Shade*Irri)		0.056 (N); 0.113 (N*Shade*Irri)	

TABLE 127. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON SEASON-LONG RADIATION USE EFFICIENCY, (T DM/TJ), CUF 2010

24.1.4. Total and tuber N uptake

At the first harvest on 2 July, the main effect of increasing the N application rate from 0 to 200 kg N/ha was to increase total N uptake from 76 to 141 kg N/ha (Table 128). The main effects of irrigation were smaller and full irrigation increased total N uptake from 99 to 117 kg N/ha. Reducing incident radiation by 45 % had no statistically significant effect on total N uptake. Tuber N uptake was significantly larger in unshaded crops, those that had received 200 kg N/ha and those that were irrigated. At the second harvest (30 July), total N uptake was increased from 98 to 189 kg N/ha when 200 kg N/ha was applied and from 114 kg N/ha for rainfed crops to 173 kg N/ha when crops were irrigated. Shading reduced total N uptake by c. 10 kg N/ha but this reduction was not statistically significant. Tuber N uptake was significantly increased by use of irrigation and was also larger in the unshaded crops and in those crops that received 200 kg N/ha. Final harvest was taken when all the crops had more or less senesced and the majority or N had been transferred from haulm to tubers. The average total N uptake at final harvest was 166 kg N/ha and this indicates that relatively little N was taken up between the second and final harvests. This supports results from many other experiments and observations that show that the bulk of N uptake occurs early in the growing season. Where no N had been applied, total N uptake averaged 115 kg N/ha and this increased to 216 kg N/ha once 200 kg N/ha had been applied. This increase suggests that N fertilizer was, on average, used with an efficiency of c. 50 %. The effect of irrigation on total N uptake was smaller as rainfed crops had a total N uptake of 145 kg N/ha compared with 186 kg N/ha for crops that received 173 mm irrigation. When averaged over the other factors, shading reduced total N uptake by c. 18 kg N/ha. Increasing the N application rate to shaded crops increased total N uptake from 114 to 198 kg N/ha but for the unshaded crops the increase was from 115 to 234 kg N/ha. Similarly, for rainfed crops the application of 200 kg N/ha increased total N uptake from 103 to 187 kg N/ha whilst for fully irrigated crops total N uptake increased from 127 kg N/ha to 246 kg N/ha. It would seem that extra solar energy available in the unshaded crops allowed more N to be taken up. The largest total N uptake (265 kg N/ha, from the fully irrigated, unshaded and fertilized crop) was somewhat larger than obtained by Estima in similar experiment in 2009 but was similar to that achieved by the Estima crops given 250 kg N/ha in a nearby experiment.

			Tuber N uptake (kg N/ha)		**Total N uptake (kg N/ha)**	
Date	**Irrigation**	**Shading**	**0 kg N/ha**	**200 kg N/ha**	**0 kg N/ha**	**200 kg N/ha**
2 July	Rainfed	No Shade	29	43	67	133
		Shade	28	37	72	125
	Irrigated	No Shade	34	55	78	160
		Shade	33	39	86	145
	Mean for N		31	44	76	141
	S.E. (21 D.F.)		1.3 (N); 2.5 (N*Shade*Irri)		3.3 (N); 6.5 (N*Shade*Irri)	
30 July	Rainfed	No Shade	54	100	75	173
		Shade	53	80	76	132
	Irrigated	No Shade	83	139	120	227
		Shade	83	97	122	223
	Mean for N		68	104	98	189
	S.E. (21 D.F.)		3.1 (N); 6.3 (N*Shade*Irri)		4.8 (N); 9.6 (N*Shade*Irri)	
8 October	Rainfed	No Shade	92	178	102	204
		Shade	95	148	104	169
	Irrigated	No Shade	118	247	129	265
		Shade	112	201	125	228
	Mean for N		104	193	115	216
	S.E. (21 D.F.)		4.5 (N); 9.1 (N*Shade*Irri)		5.4 (N); 10.7 (N*Shade*Irri)	

TABLE 128. EFFECT OF IRRIGATION, N APPLICATION RATE AND SHADING ON TUBER AND TOTAL N UPTAKE ON THREE OCCASIONS, CUF 2010

24.1.5. Comparison of estimates of radiation absorption using ground cover or measurement by solarimeter

Using ground cover to estimate radiation absorption resulted in larger values than if measured using solarimeters (Table 129) and over the four treatments compared the average radiation absorption was 10.29 TJ/ha when using solarimeters compared with 13.09 TJ/ha when using the grid. However, the size of the discrepancy varied with treatment and was largest in those plots that had received 200 kg N/ha. The cause of this difference in estimate of radiation absorption can be seen by comparing Figure 37a and Figure 40. When 200 kg N/ha was applied, the ground covers were maintained at 100 % for several weeks and it was assumed that, during this period, radiation absorption was also 100 %. However, the solarimeter data show that, during this period, the maximum proportion of radiation absorbed seldom exceeded 85 %. These differences in estimates of radiation absorption found in this experiment are consistent with those found by Firman & Allen (1989). The differences in estimates of radiation absorption derived from ground cover or solarimeters will also result in differences in the estimates of RUE. When using estimates derived from ground cover, the average RUE was 1.02 t DM/TJ compared with average of 1.31 t DM/TJ when using the solarimeter. Irrespective of the method used, there was some evidence that RUEs were smaller in the rainfed crops and in the crops that received no N. The large difference in the estimate of radiation absorption for the rainfed crop that received 200 kg N/ha may, in part, be a consequence of diurnal changes in ground cover due to drought stress. Ground covers were typically measured in the morning when the crop was rehydrated and the ground covers were recorded at 100 %. However, on days with large evaporative demands the crop would have wilted in the afternoon and, if they had been measured again, they may have been less than 100 %. Since the solarimeters record throughout the day, cycles of wilting/rehydration would be measured. Firman & Allen (1989) showed that at 100 % ground cover the proportion of light absorbed by the crop was variable and therefore, at present, there is unlikely to be a sufficiently robust method of converting percentage ground cover measured by grids to percentage radiation absorption that can be used in models. Thus, whilst the deficiencies of using grids need to be recognized the grid method is still amongst the simplest, fastest and most reproducible methods of describing canopy size. For the foreseeable future the CUF model will continue to use measurements of ground cover data.

	Rainfed		**Irrigated**		
	0 kg N/ha	**200 kg N/ha**	**0 kg N/ha**	**200 kg N/ha**	**S.E. (9 D.F.)**
Ground cover RA (TJ/ha)	9.83	15.54	11.89	15.08	0.309
Solarimeter RA (TJ/ha)	8.76	10.71	8.84	12.84	0.687
Difference in RA (TJ/ha)	1.07	4.83	3.05	2.24	0.790
Ground cover RUE (t DM/TJ)	0.83	0.89	1.02	1.35	0.065
Solarimeter RUE (t DM/TJ)	0.95	1.30	1.40	1.59	0.106

TABLE 129. COMPARISON OF RADIATION ABSORPTION (RA) AND RADIATION USE EFFICIENCY (RUE) ESTIMATED USING 1 : 1 RELATIONSHIP WITH GROUND COVER OR MEASURED WITH TUBE SOLARIMETERS. DATA ARE FROM UNSHADED PLOTS ONLY AND EACH VALUE IS THE MEAN OF FOUR REPLICATES

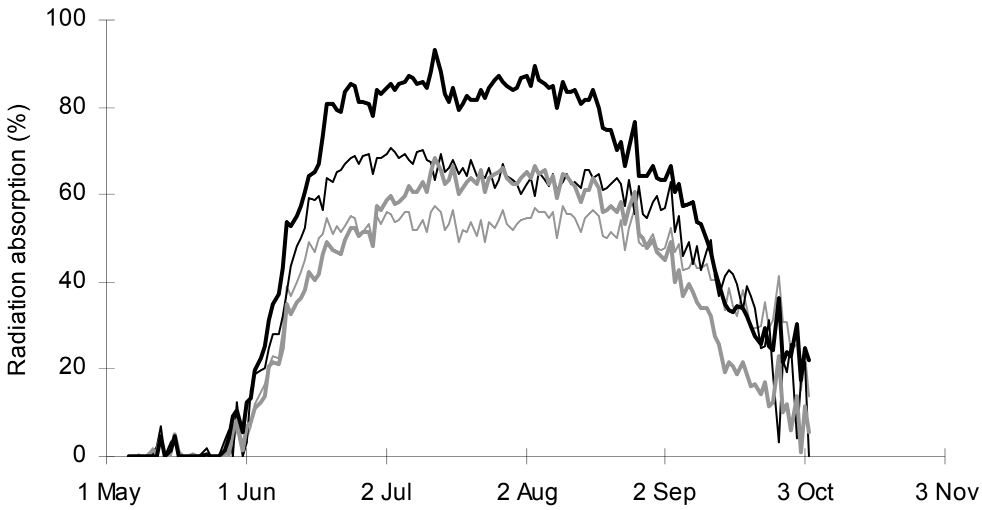


FIGURE 40. EFFECT OF IRRIGATION AND N APPLICATION RATE ON PERCENT RADIATION ABSORPTION MEASURED USING TUBE SOLARIMETERS. IRRIGATED-N0, THIN BLACK LINE; IRRIGATED-N200, THICK BLACK LINE; RAINFED-N0, THIN GREY LINE AND RAINFED-N200, THICK GREY LINE.

24.2. Conclusions for shading experiments 2006-2010

This experiment examined the combined effects of three key factors (radiation, water supply and N supply) on the processes of yield production. In the absence of any apparent restrictions, tuber FW yields in excess of 80 t/ha were achieved but were halved when restrictions were applied. Shading reduced incident radiation by c. 45 % but its effects on tuber FW yield were relatively small. Much larger reductions in yield resulted from restricting water or N supply than from shading. The data collected between 2007-2010 shows that for irrigated crops given 200 kg N/ha, the total N uptake of crops shaded for the majority of the season was c. 175 kg N/ha compared with 213 kg N/ha for unshaded. For crops receiving no N, the difference was 108 kg N/ha (shaded) and 113 kg N/ha (unshaded). The reduction in incident radiation due to shading (45 %) was extreme and for a particular location (e.g. CUF) the difference in incident radiation is far larger than is seen from season-to-season. However, the relative differences in incident radiation are similar to those seen in different locations (e.g. CUF and Dalhart, Texas). These data suggest that in bright environments potato crops have a greater capacity to utilise N and to make full use of the radiation environment, more N may be required. The solarimeter data show that there are discrepancies between estimates of radiation absorption derived from ground covers and those from use of solarimeters and these differences may result in differences in RUE.

25. Effects of timing and rate of N applications on yields

25.1. Introduction

This experiment was part of a series of experiments that investigated factors that affect nitrogen uptake by the potato crop and, in turn, yield formation. The main objective of this experiment was to investigate the effects of varying the time and rate of N applications on total and tuber N uptake and thus test the possibility of materially altering the yield potential of a crop by changing its N uptake with late-season N applications. A parallel objective was to help define the latest date at which N applied to the potato crop will be utilised and could reasonably be expected to increase yield.

25.2. Materials and Methods

The experiment was done in Osier Field, Cambridge University Farm. Estima seed (SE2, 30-35 mm, 25.0 g) was manually planted at 25 cm spacing into pre-formed ridges with 76.2 cm centres on 10 April. The experiment tested all combinations of two N application rates and four timings of N application. Details of the N treatments are given in Table 130. Each treatment combination was replicated four times and allocated at random to blocks. Each plot was four rows (3.05 m) wide and 9 m long. Nitrogen applications at planting were made using ammonium nitrate broadcast by hand onto the ridges and then incorporated by raking. Within-season N applications were made using a urea and ammonium nitrate solution applied using a hand-held Azo type sprayer. The sprayer was calibrated to apply 15 kg N/ha in 421 l/ha water per pass and two passes were used to apply 30 kg N/ha.

	Summary of N application rate (kg N/ha) and timings							
Date (DAE)	**T1-60**	**T2-60**	**T3-60**	**T4-60**	**T1-120**	**T2-120**	**T3-120**	**T4-120**
10 April (-)	60	45	30	15	120	90	60	30
2 June (20)	0	15	15	15	0	30	30	30
23 June (41)	0	0	15	15	0	0	30	30
14 July (62)	0	0	0	15	0	0	0	30
Total applied	60	60	60	60	120	120	120	120

TABLE 130. SUMMARY OF N APPLICATION TIMINGS AND RATES

Plant emergence was measured in each plot every 3-4 days until complete and ground covers were measured weekly using a grid. The crop was sampled on four occasions (12 June (30 DAE), 3 July (51 DAE), 31 July (79 DAE) and 27 August (106 DAE)). At each sampling, 10 plants (area = 1.91 m2) were removed from the centre two rows of the four-row plot leaving 0.5 m discard between plot ends or previously-sampled areas. The number of plants and stems was recorded and all tubers > 10 mm were collected. The total fresh weight of haulm was recorded in the field using a portable electronic balance and a representative sub-sample of haulm (c. 1 kg) was taken. The tubers were graded in 10 mm increments and the number and weight of tubers in each grade was recorded. A sub-sample of tubers (c. 1 kg) was taken, washed, chipped and then dried, together with the haulm, to constant weight at 90 °C. The dried haulm and tubers were sent to a commercial laboratory for measurement of total N concentration. The crop received a total of 143 mm irrigation and agrochemicals were applied according to standard farm practice.

25.3. Results and Discussion

25.3.1. Emergence, ground cover development and radiation absorption

The average date of 50 % plant emergence was 13 May (33 days after planting) and complete emergence was obtained in nearly all plots. The effects of the N treatments on the date of 50 % plant emergence were small and, generally, non-significant. The development of ground cover for selected treatments are shown in Figure 41 and summarised in Table 131. When averaged over all treatments, canopy persistence was 6283 % days and 10.89 TJ/ha of solar energy was absorbed. In 2007, the values for a similar experiment were 5138 % days and 8.62 TJ/ha, respectively. Increasing the total amount of N applied from 60 to 120 kg N/ha had no statistically significant effect on canopy persistence or on radiation absorption however applying the N in several splits caused a small but statistically significant decrease in canopy persistence and radiation absorption.

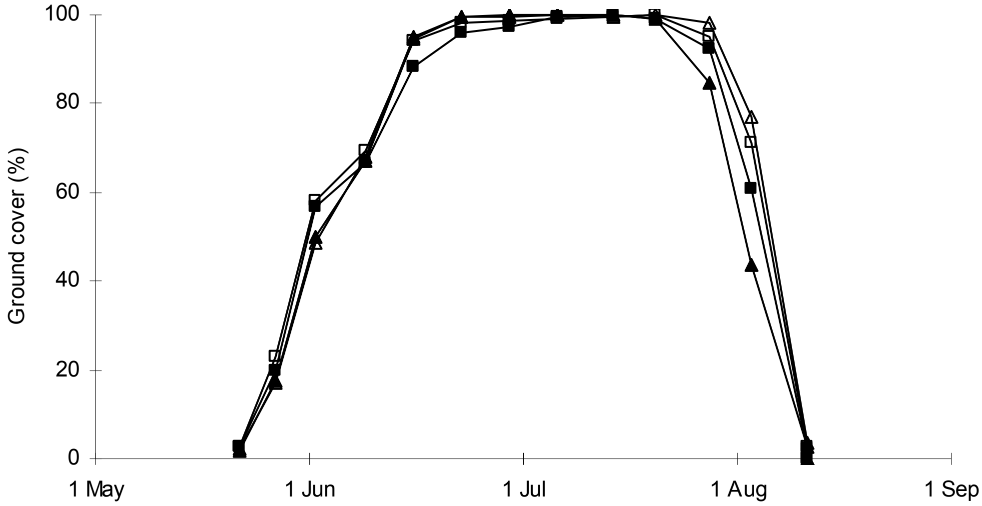


FIGURE 41. EFFECT OF TIME AND RATE OF N APPLICATION ON GROUND COVER DEVELOPMENT. T1-60, □; T4-60, ■; T1-120, △ AND T4-120, ▲.

Timing	Integrated ground cover (% days) 60 kg N/ha	120 kg N/ha	Mean	Radiation absorbed (TJ/ha) 60 kg N/ha	120 kg N/ha	Mean
T1	6371	6375	6373	11.00	11.04	11.02
T2	6400	6298	6349	11.07	10.87	10.97
T3	6352	6270	6311	11.00	10.91	10.96
T4	6169	6029	6099	10.69	10.56	10.62
Mean	6323	6243	6283	10.94	10.84	10.89
S.E. (21 D.F.)	44.8 (N); 63.3 (Timing); 89.6 (Timing and N)			0.067 (N); 0.095 (Timing); 0.134 (Timing and N)		

TABLE 131. EFFECT OF TIME AND RATE OF N APPLICATION ON SEASON-LONG INTEGRATED GROUND COVER AND RADIATION ABSORPTION

25.3.2. Tuber fresh weight yields

Timing of N application had no statistically significant effect on either the number of above-ground stems or tubers >10 mm at any harvest. Increasing the total amount of N applied from 60 to 120 kg N/ha tended to decrease the number of stems and, in consequence, the number of tubers was also smaller at the larger N rate but this effect was not always statistically significant (Table 132).

	Total N applied (kg /ha)	**Harvest 1 (12 June)**	**Harvest 2 (3 July)**	**Harvest 3 (31 July)**	**Harvest 4 (27 August)**
Total number of stems (000/ha)	60	107	115	107	106
	120	98	101	102	100
	S.E. (21 D.F)	3.3	3.8	3.4	2.5
Number of tubers > 10 mm (000/ha)	60	486	585	514	493
	120	430	524	508	459
	S.E. (21 D.F.)	14.3	15.3	14.7	11.0

TABLE 132. MEAN NUMBER OF ABOVE-GROUND STEMS AND TUBERS AT EACH HARVEST

At the first harvest (12 June, 30 DAE) the mean tuber FW yield was 4.0 t/ha and whilst yields were not affected by the total N application rate they were significantly larger where the N was applied as multiple splits (Table 133). This suggests that very early yield production was increased due to improved DM partitioning as a consequence of a reduction in available N. At the second harvest (3 July, 51 DAE), the average tuber FW yield had increased to 36.2 t/ha and was not significantly affected by either total N application rate or the timing of application. There was some indication, however, that yields were larger for the smaller N application rate and where multiple splits were used. The third harvest was taken on 31 July (79 DAE), when all treatments had received their N applications. At this time, tuber FW yield averaged 61.7 t/ha (Table 134) and yields were numerically larger when 120 kg N/ha had been applied and, although the effect was not statistically significant, yields were larger when the entire N dose had been applied at planting. The final harvest was taken 106 DAE (27 August) after the canopies had completely senesced. Between the third and final harvests, average yield had increased by c. 2.5 t/ha to 64.2 t/ha. Yield were slightly (but not significantly) larger when 120 kg N/ha had been applied and there was also significant benefit from applying the entire N at planting or 75 % at planting and the remaining 25 % at 20 DAE (i.e. at about the time of tuber initiation).

Timing	Harvest 1 (12 June)			Harvest 2 (3 July)		
	60 kg N/ha	120 kg N/ha	Mean	60 kg N/ha	120 kg N/ha	Mean
T1	4.0	3.2	3.6	35.8	35.0	35.4
T2	4.0	3.8	3.9	37.5	34.4	36.0
T3	4.4	3.4	3.9	37.5	36.2	36.9
T4	4.7	4.7	4.7	35.7	37.9	36.8
Mean	4.3	3.8	4.0	36.6	35.9	36.2
S.E. (21 D.F.)	0.19 (N); 0.27 (Timing); 0.38 (Timing and N)			0.77 (N); 1.09 (Timing); 1.55 (Timing and N)		

TABLE 133. EFFECT OF TIME AND RATE OF N APPLICATION ON TUBER FW YIELD > 10 MM (T/HA) AT HARVEST 1 AND HARVEST 2

Timing	Harvest 3 (31 July)			Harvest 4 (27 August)		
	60 kg N/ha	120 kg N/ha	Mean	60 kg N/ha	120 kg N/ha	Mean
T1	61.4	65.6	63.5	63.7	68.5	66.1
T2	58.5	65.7	62.1	68.0	70.7	69.4
T3	61.3	60.3	60.8	61.0	60.1	60.5
T4	56.6	64.2	60.4	63.0	58.8	60.9
Mean	59.5	63.9	61.7	63.9	64.6	64.2
S.E. (21 D.F.)	1.17 (N); 1.66 (Timing); 2.35 (Timing and N)			1.39 (N); 1.97 (Timing); 2.79 (Timing and N)		

TABLE 134. EFFECT OF TIME AND RATE OF N APPLICATION ON TUBER FW YIELD > 10 MM (T/HA) AT HARVEST 3 AND HARVEST 4

25.3.3. Radiation use efficiency

Using data from all four harvests, values of total (i.e. haulm and tuber) DM yield were regressed against radiation absorption. These regressions were done on a plot-by-plot basis and the fitted parameters were then tested using analysis of variance. The slope of the regression line is an estimate of season-long RUE. When averaged over all treatments, whole season RUE was 1.24 (± 0.073) t DM/TJ. Increasing the N application rate from 60 to 120 kg N/ha had no statistically significant effect on RUE but the RUE was significantly larger when the N was either applied at planting or with most at planting and some at tuber initiation.

25.3.4. Nitrogen uptake

The effect of the rate and timing of N applications on total N uptake for the second and third harvests are shown in Table 135. The second harvest was taken c. 51 DAE, 11 days before the final application of N at 62 DAE. The third harvest was taken c. 79 DAE when all plots had received their entire N application. The overall, mean total N uptake was 173 kg N/ha at the second harvest and 175 kg N/ha at the third. These results suggest that there was little N uptake between these two harvests and the bulk of N uptake had occurred before 51 DAE. For both harvests, increasing the total N application rate from 60 to 120 kg N/ha increased total N uptake by c. 20 kg N/ha. Timing of N application rate had no effect on total N uptake and there was no evidence that the late applications of N (T4) resulted in an increase in N uptake between the second and third harvests.

Timing	Harvest 2 (3 July) 60 kg N/ha	120 kg N/ha	Mean	Harvest 3 (31 July) 60 kg N/ha	120 kg N/ha	Mean
T1	159	176	167	162	191	177
T2	180	189	180	169	192	180
T3	169	188	178	167	176	172
T4	150	186	168	150	193	171
Mean	165	182	173	162	188	175
S.E. (21 D.F.)	4.3 (N); 6.0 (Timing); 8.5 (Timing and N)			5.3 (N); 7.4 (Timing); 10.5 (Timing and N)		

TABLE 135. EFFECT OF TIME AND RATE OF N APPLICATION ON TOTAL (TUBER AND HAULM) N UPTAKE (KG N/HA) AT HARVEST 2 AND HARVEST 3

Regression analysis of individual plot data showed that the average rate of tuber N uptake was 12.7 kg N/TJ and increasing the total amount of N applied from 60 to 120 kg N/TJ increased the rate of tuber N uptake from 12.0 to 13.4 kg N/TJ (Table 136). In 2007, in a similar experiment, the increase in tuber N uptake rate was from 10.9 and 13.4 kg N/TJ. The timing of N application had no statistically significant effect on the rate at which tubers took up N. Maximum total N uptake was estimated by fitting an exponential curve to values of total N uptake measured at the first three harvests. The fourth harvest was omitted since there was loss of haulm DM between the third and fourth harvests. Using this method, maximum total N uptake averaged 184 kg N/ha and was significantly increased from 172 to 196 kg N/ha when the total amount of N applied was increased from 60 to 120 kg N/ha. In 2007, the average maximum total N uptake was only 130 kg N/ha but there was a relatively larger increase in total N uptake (from 114 to 145 kg N/ha). These results suggest that soil supply and the crop's ability to access soil N was larger in 2008 than in 2007. The timing of N application had no effect on the total N uptake of the crop.

Timing	Rate of tuber N uptake (kg N/TJ) 60 kg N/ha	120 kg N/ha	Mean	Maximum total N uptake (kg N/ha) 60 kg N/ha	120 kg N/ha	Mean
T1	11.6	13.8	12.7	169	196	183
T2	12.3	14.3	13.3	179	196	188
T3	11.6	12.9	12.3	178	188	183
T4	12.4	12.7	12.5	160	204	182
Mean	12.0	13.4	12.7	172	196	184
S.E. (21 D.F.)	0.34 (N); 0.48 (Timing); 0.68 (Timing and N)			4.6 (N); 6.5 (Timing); 9.2 (Timing and N)		

TABLE 136. EFFECT OF RATE AND TIMING OF N APPLICATION ON THE RATE OF TUBER N UPTAKE AND MAXIMUM TOTAL N UPTAKE

25.4. Conclusions

Increasing the total N application rate from 60 to 120 kg N/ha had no statistically significant effect on yield and suggests that this crop was adequately supplied with N from other sources. Nitrogen uptake data showed that late applications of N (i.e. after c. 50 DAE) were not used very efficiently by the crop and yield formation was compromised resulting in a yield penalty. Since multiple-splits appeared to reduce N supply to the crop, their use will tend to increase yields at early harvests due to more favourable DM partitioning from haulm to tubers. Furthermore, in situations where crops are receiving total N application in excess of their requirements, splitting will tend to mask some of the negative effects of over-application by reducing the efficiency with which the crop takes up N.

26. Nitrogen requirements of potatoes grown on silt textured soils

26.1. Introduction

These experiments also form part of the Grower Collaboration Project (Project No R295) and were designed to complement the comparisons of “grower” and “CUF Modified” N application rates in a crops grown A H Worth, Holbeach Hurn, Lincolnshire. They are reported here due to synergies between certain aspects of the Grower Collaboration project and the current N nutrition project.

26.2. Materials and Methods

Key details of each experiment are shown in Table 137. Each treatment was replicated five times and allocated at random to blocks. Each plot was c. 5 m long and 4 rows (3.66 m) wide and potato seed was planted by hand-dibbing into pre-formed ridges. Nitrogen was applied as ammonium nitrate (34.5 % N) in a single dose at planting and was then shallowly incorporated into the soil by raking. Emergence and ground covers were measured intermittently by CUF staff during the course of the season and a single harvest was taken manually in the autumn. At this harvest, 10 plants were dug from the two centre rows of each four-row plot leaving a minimum of 1 m discard at the ends of each harvested area The number of stems was counted and all tubers > 10 mm were collected and returned to CUF. The number and weight of tubers in each 10 mm size grade was recorded. A 1 kg sample of tubers was removed from the 50-60 mm size grade, washed, chipped and then dried to constant weight at 90 °C to measure tuber DM concentration.

	2008	**2009**	**2010**
Field	Field 13	Field 38	Field 26/27
OS grid reference	TF405275	TF408295	TF407281
Variety (average seed weight, g)	Maris Piper (39.4)	Maris Piper (73.7)	Marfona (39.4)
N rates tested (kg N/ha)	0, 50, 100, 150, 200, 250 & 300	0, 50, 100, 150, 200, 250 & 300	0, 50, 100, 150, 200, 250 & 300
P application rate (kg P2O5/ha)	180	100	0
K application rate (kg K2O/ha)	240	490	240
Planting date	29 April	9 April	27 April
Within-row spacing (cm)	28	40	35
Plant population (000/ha)	39 100	27 340	31 250
Date of final harvest	18 September	10 September	4 August
Harvest areas (m2)	2.56	3.66	3.20

Table 137. Treatment details of N response experiment at A H Worth, Holbeach Hurn, 2008-2010

27. HOLBEACH 2008, MARIS PIPER

27.1. Results and Discussion

27.1.1. Emergence and ground covers

Plant emergence was rapid and 50 % plant emergence was achieved on c. 16 May (17 days after planting) and all treatments achieved complete or near-complete emergence. The effects of N application rate on ground cover are shown in Table 138. Ground covers were significantly smaller when no N or 50 kg N/ha had been applied, however increasing the N application rate beyond 100-150 kg N/ha had relatively little effect on ground cover.

N application (kg N/ha)	Ground cover on 13 August %	Ground cover on 13 August Ang	Ground cover on 11 September %	Ground cover on 11 September Ang
0	78	63	59	50
50	84	67	68	56
100	92	74	85	68
150	90	72	80	65
200	93	76	89	73
250	93	75	92	74
300	92	74	94	76
Mean	89	72	81	66
S.E. (24 D.F.)	-	2.5	-	2.7

TABLE 138. EFFECT OF N APPLICATION RATE ON GROUND COVER, AS PERCENT AND ANGULAR TRANSFORMED PERCENT (ANG), OF MARIS PIPER MEASURED ON TWO OCCASIONS

27.1.2. Components of yields on 18 September

Nitrogen application rate had no statistically significant effect on the number of mainstems, the number of tubers > 10 mm per stem or, in consequence, the tuber population > 10 mm (Table 139). When the size of the standard error for yield is considered, increasing the N application rate to c. 100 to 150 kg N/ha resulted in a statistically significant increase in tuber FW yield whilst N applications in excess of 150 kg N/ha had little or no effect (Table 140). The effects of N on tuber DM were relatively small and erratic although omitting N resulted in the largest tuber DM concentration. Since N had no effect on tuber population, mean tuber size (μ) was related to tuber FW yield. In consequence, mean tuber size tended to increase when the N application rate was increased from 0 to 150 kg N/ha but N had little effect thereafter. The coefficient of variation (COV) of mean tuber size was not affected by N application rate.

	Number of mainstems (000/ha)	Number of tubers > 10 mm per stem	Number of tubers > 10 mm (000/ha)
Mean	103	4.1	420
S.E. (24 D.F.)	6.8	0.22	25.3

TABLE 139. MEAN VALUES FOR STEM AND TUBER POPULATION FOR MARIS PIPER ON 18 SEPTEMBER

Application rate (kg N/ha)	Tuber FW yield (t/ha)	Tuber DM concentration (%)	Mean tuber size (mm)	COV (%)
0	46.6	25.3	54.6	18.8
50	52.1	24.7	56.0	19.5
100	54.6	24.9	55.4	19.6
150	57.6	24.2	58.6	19.9
200	58.5	24.6	59.4	19.8
250	60.2	23.8	60.4	19.8
300	56.1	24.5	60.6	19.3
Mean	55.1	24.6	57.9	19.5
S.E. (24 D.F.)	2.05	0.20	1.08	0.49

TABLE 140. EFFECT OF N APPLICATION RATE ON TUBER FW YIELD > 10 MM, TUBER DRY MATTER (DM) CONCENTRATION, MEAN TUBER SIZE AND COEFFICIENT OF VARIATION (COV) OF TUBER SIZE DISTRIBUTION FOR MARIS PIPER, HOLBEACH 1998

27.1.3. Optimum N application rate and yield at optimum

Examination of treatment means and standard errors suggest that the optimum N application rate for this crop was c. 150 kg N/ha resulting in a tuber yield > 10 mm of c. 58 t/ha. The optimum N application rate was also estimated using the “bent-stick” approach of Boyd (1972). Fitting this model explained 87.7 % of the variation in yield and gave an optimum N application rate of 138 (± 29.2) kg N/ha (Figure 42). The yield at the optimum was estimated to be 58.1 (± 0.81) t/ha.

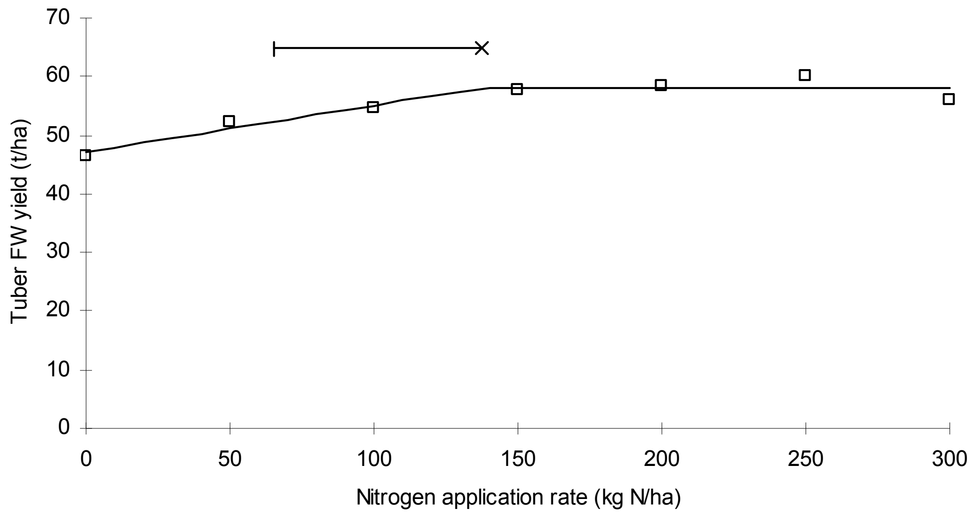


FIGURE 42. RELATIONSHIP BETWEEN N APPLICATION RATE AND YIELD OF MARIS PIPER. MEASURED YIELD (□), FITTED LINE (—), ESTIMATE OF OPTIMUM N APPLICATION RATE (×) AND 95 % CONFIDENCE INTERVAL, HOLBEACH 2008.

27.2. Conclusions

The commercial N application rate for this field was 180 kg N/ha compared with 140 kg N/ha for the CUF modified N application rate. Due to the limitations of split-field experiments the effects of the modified N rate on yield cannot be accurately assessed due to the absence of randomisation and replication. However, this replicated and randomised experiment supports the hypothesis that N application rate can be reduced without compromising yield production.

28. HOLBEACH 2009, MARIS PIPER

28.1. Results and Discussion

28.1.1. Emergence and ground covers

Plant emergence was rapid and 50 % plant emergence was achieved on c. 4-6 May (c. 25 days after planting) and all treatments achieved complete or near-complete emergence. With the exception of plots that received 0 or 50 kg N/ha, all treatments had achieved near-complete ground cover by the end of June (Figure 43). Assessment of ground cover at final harvest showed that canopies were more persistent with increase in N application rate.

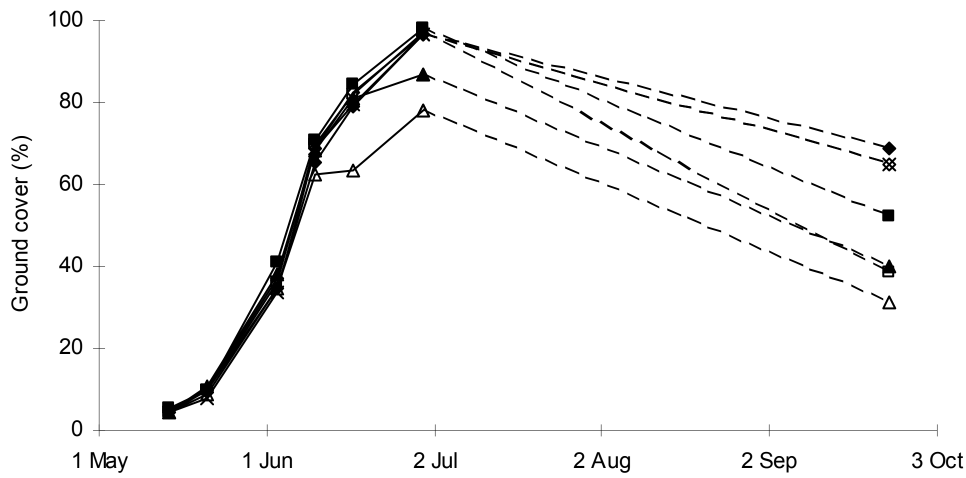


FIGURE 43. EFFECT OF N APPLICATION RATE ON GROUND COVER OF MARIS PIPER IN FIELD 38, A H WORTH, 2009. 0, △; 50, ▲; 100, □; 150, ■; 200, ◊; 250, ♦ AND 300 KG N/HA, ×.

28.1.2. Components of yields on 10 September

Nitrogen application rate had no statistically significant effect on the number of mainstems (which averaged 108 000 ± 5 400/ha) or the tuber population > 10 mm (327 000 ± 13 700/ha). The overall average tuber yield was 63.2 t/ha and when the size of the standard error for yield is considered, increasing the N application rate to c. 150 kg N/ha resulted in a statistically significant increase in tuber FW yield but N applications in excess of c. 150 kg N/ha had little or no effect (Table 141). There was no effect of N application rate on tuber DM concentration. Since N had no effect on tuber population, mean tuber size (μ) was related to tuber FW yield and mean tuber size tended to increase when the N application rate was increased from 0 to c. 150 kg N/ha but N had little effect thereafter. The coefficient of variation (COV) of mean tuber size was not affected by N application rate.

Application rate (kg N/ha)	**Tuber FW yield (t/ha)**	**Tuber DM concentration (%)**	**Mean tuber size (mm)**	**COV (%)**
0	54.6	26.6	59.8	19.0
50	59.7	27.9	61.5	18.7
100	63.8	27.3	62.9	18.9
150	64.4	27.1	64.0	18.6
200	65.9	26.9	64.7	19.1
250	67.2	26.3	68.7	20.9
300	67.2	26.0	66.3	19.1
Mean	63.2	26.9	64.0	19.2
S.E. (24 D.F.)	1.38	0.48	0.98	0.57

TABLE 141. EFFECT OF N APPLICATION RATE ON TUBER FW YIELD > 10 MM, TUBER DRY MATTER (DM) CONCENTRATION, MEAN TUBER SIZE AND COEFFICIENT OF VARIATION (COV) OF TUBER SIZE DISTRIBUTION FOR MARIS PIPER, HOLBEACH 2009

28.1.3. Optimum N application rate and yield at optimum

Examination of treatment means and standard errors suggest that the optimum N application rate for this crop was c. 150-200 kg N/ha resulting in a tuber yield > 10 mm of c. 65 t/ha. The optimum N application rate was also estimated using the “bent-stick” approach of Boyd (1972). Fitting this model explained 93.5 % of the variation in yield and gave an optimum N application rate of 124 (± 16.4) kg N/ha (Figure 44). The yield at the optimum was estimated to be 66.2 (± 0.59) t/ha.

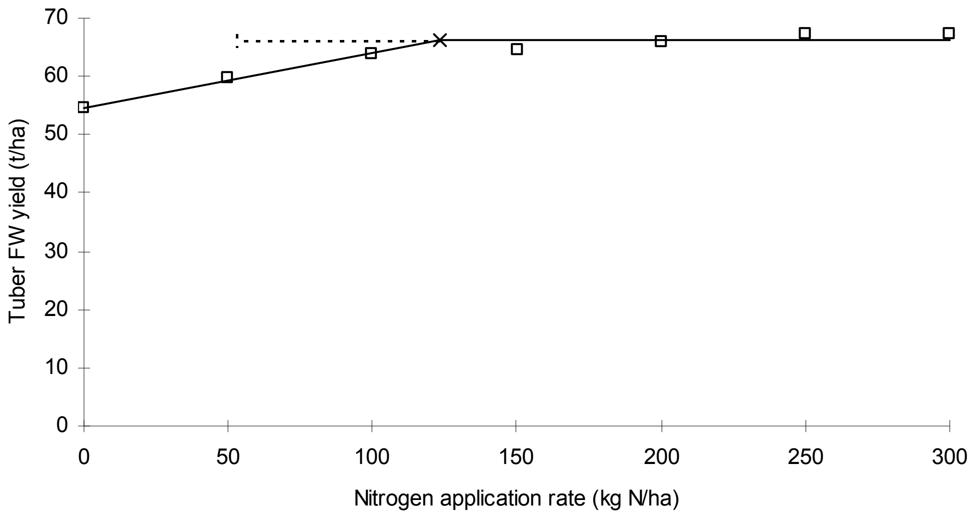


FIGURE 44. RELATIONSHIP BETWEEN N APPLICATION RATE AND YIELD OF MARIS PIPER. MEASURED YIELD (□), FITTED LINE (—), ESTIMATE OF OPTIMUM N APPLICATION RATE (×) AND 95 % CONFIDENCE INTERVAL, HOLBEACH 2009.

28.2. Conclusions

The commercial N application rate for this field was 180 kg N/ha compared with 155 kg N/ha for the CUF modified N application rate. Due to the limitations of split-field experiments the effects of the modified N rate on yield cannot be accurately assessed due to the absence of randomisation and replication. However, this replicated and randomised experiment indicates the modified N application rate calculated for this site would have reduced costs without compromising yield.

29. HOLBEACH 2010, MARFONA

29.1. Results and Discussion

29.1.1. Components of yields on 4 August

Nitrogen application rate had no statistically significant effect on the number of mainstems (which averaged 125 000 ± 3 710/ha) or the tuber population > 10 mm (415 000 ± 8 290/ha). The overall average tuber yield was 48.0 t/ha and when the size of the standard error for yield is considered, increasing the N application rate to c. 50 kg N/ha resulted in a statistically significant increase in tuber FW yield but N applications in excess of c. 50 kg N/ha had no significant effect (Table 142). Increasing the N application rate from 0 to 200 kg N/ha decreased tuber DM concentration from 20.0 to 18.6 % but there was little affect on tuber DM thereafter. Since N had little effect on tuber population, mean tuber size (µ) was related to tuber FW yield however the coefficient of variation (COV) of mean tuber size was not affected by N application rate.

Application rate (kg N/ha)	Tuber FW yield (t/ha)	Tuber DM concentration (%)	Mean tuber size (mm)	COV (%)
0	38.5	20.0	58.4	21.7
50	51.9	19.3	60.4	20.5
100	49.4	19.5	60.1	19.7
150	48.1	19.1	61.0	18.5
200	48.3	18.6	61.2	19.6
250	50.4	18.5	63.4	19.9
300	49.3	18.7	62.2	21.1
Mean	48.0	19.1	61.0	20.1
S.E. (24 D.F.)	2.04	0.30	0.97	0.74

TABLE 142. EFFECT OF N APPLICATION RATE ON TUBER FW YIELD > 10 MM, TUBER DRY MATTER (DM) CONCENTRATION, MEAN TUBER SIZE AND COEFFICIENT OF VARIATION (COV) OF TUBER SIZE DISTRIBUTION FOR MARFONA, HOLBEACH 2010

29.2. Conclusions

The commercial N application rate for this field was 180 kg N/ha compared with 150 kg N/ha for the CUF modified N application rate. Due to the limitations of split-field experiments the effects of the modified N rate on yield cannot be accurately assessed due to the absence of randomisation and replication. However, this replicated and randomised experiment indicated the modified N application rate calculated for this site (150 kg N/ha) would have reduced costs without compromising yield and they may have been further opportunities for reducing inputs of N fertilizer.

30. FACTORS AFFECTING AMINO-ACID CONCENTRATION IN POTATO TUBERS; M F ALLISON & M SMALLWOOD (CYGNET PB).

30.1. Introduction

In 2002, acrylamide was discovered in a range of cooked foods (Tareke et al. 2002). Further work by Mottram et al. (2002) showed that acrylamide was formed in Maillard reactions between free amino acids and reducing sugars and that asparagine was the principal amino acid involved. A strategy to reduce acrylamide levels in cooked potato products would be to select potato varieties with inherently low asparagine levels. The purpose of this preliminary study was to measure the concentration of free amino acids in a range of potato varieties grown under experimental conditions and also to investigate the influence of N application rate and timing of sampling on amino acid concentration.

30.2. Materials and Methods

This study used material generated from the N and variety trial done at Babraham in 2010 (page 27). Due to the costs associated with amino acid analysis it was not possible to sample all treatment combinations at each sampling occasion and the sampling scheme shown in Table 143 was used. At each sampling c. 500 g of tuber (c. three 50-60 mm tubers) were taken from each replicate of the designated treatments. These tubers were then stored at 8 °C for a maximum of 48 hours during transit to Reading University for analysis. The tubers were chipped and weighed, blast-frozen and then freeze-dried for 72 hours. The dry chips were re-weighed to determine the moisture content of the fresh material. The frozen potato chips were milled to a coarse flour and the free-amino acids were extracted from the flour with 0.01 M HCl. The amino acids asparagine and glutamine were quantified by gas chromatography–mass spectrometry and their concentrations expressed as mmol/100 g tuber DW.

Sample date	N application rate (kg N/ha)	Varieties
13 July	200	Chicago, Hermes, Markies
9 August	200	Chicago, Hermes, Markies
16 September	100, 200	Cabaret, Casablanca, Chicago, Hermes, Lady Rosetta, Maris Piper, Markies

TABLE 143. SAMPLING SCHEME FOR ANALYSIS OF FREE AMINO ACIDS

30.3. Results, Discussion and Conclusions

The effect of variety, N application rate and time of sampling on the concentration of asparagine and glutamine are shown in Figure 45. For glutamine, the concentration was generally greater in Markies and least in Chicago with Hermes intermediate. As the season progressed the concentration of glutamine decreased, so that for Markies the concentration of glutamine on 16 September was c. half that on 13 July. At final harvest, increasing the N application rate from 100 to 200 kg N/ha increased glutamine concentration in all three varieties. The concentration of asparagine was consistently greater in Hermes than in Markies or Chicago and increasing the N application rate increased the concentration of asparagine in all three varieties. However, in contrast to glutamine, the concentration of free-asparagine increased as the season progressed.

Burch et al. (2008), regressed acrylamide concentration in French fries against asparagine concentration in raw potato and, dependent on the variety, found R2 values of between 40 and 79 %. These data suggest that whilst the concentration of asparagine in raw potato affects the concentration of acrylamide within the cooked product, it is not the only determinant. The preliminary study reported here indicates that for varieties grown under similar conditions, the concentration of asparagine can vary widely and this is likely to have some effect on the concentration of acrylamide in the cooked product. The increase in asparagine concentration with time in all varieties is also of interest and the effects of storage time and regime on asparagine concentration also warrants further attention. Whilst the effects of variety were larger, N application rate also had a significant effect on amino acid concentration and indicate that crop management may influence concentrations of amino acids in fresh tuber and acrylamide concentration in cooked products.

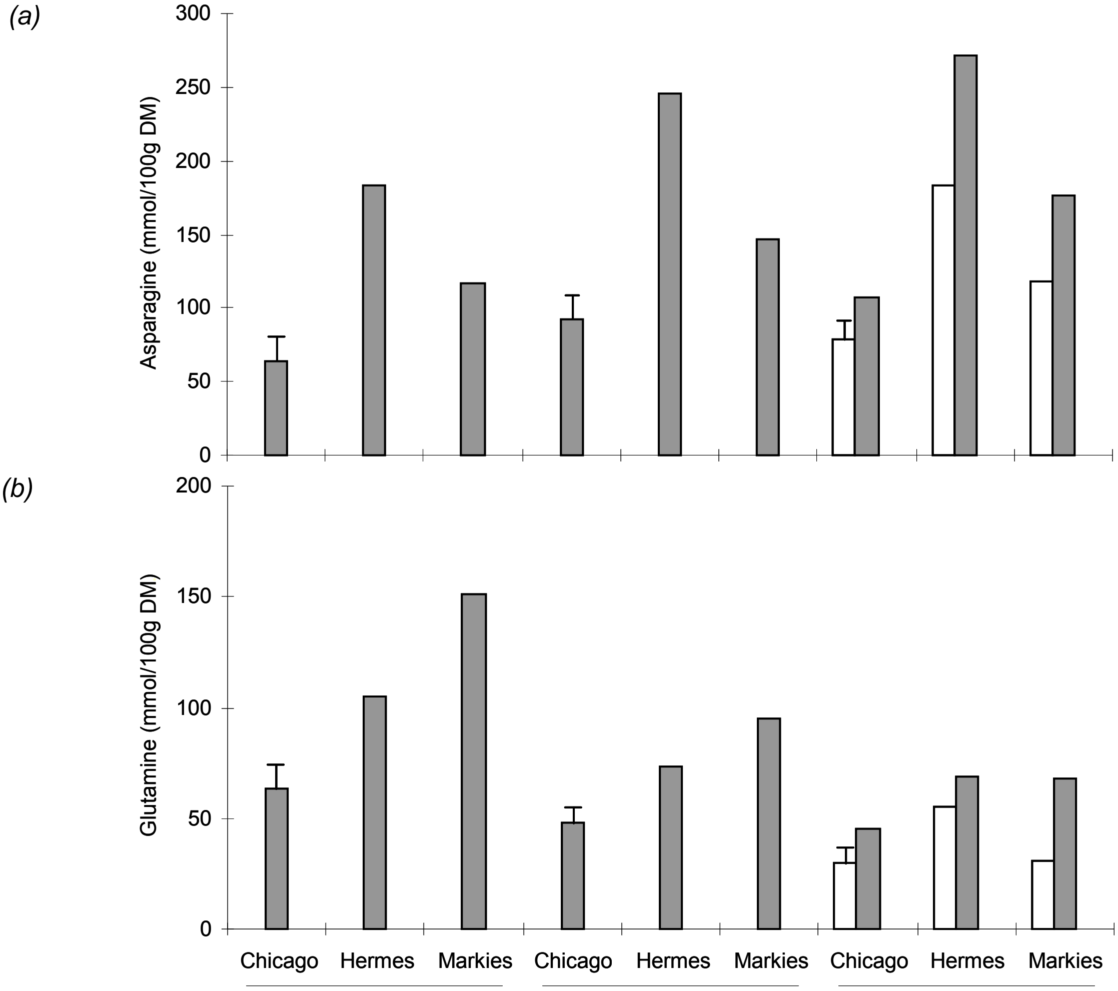


FIGURE 45. EFFECT OF VARIETY, DATE OF SAMPLING AND N APPLICATION RATE ON TUBER CONCENTRATION OF *(A)* ASPARAGINE AND *(B)* GLUTAMINE. OPEN SYMBOLS, 100 KG N/HA, SHADED SYMBOLS, 200 KG N/HA. BARS ARE 1 S.E.. EACH VALUE IF THE MEAN OF FOUR-REPLICATE SAMPLES.

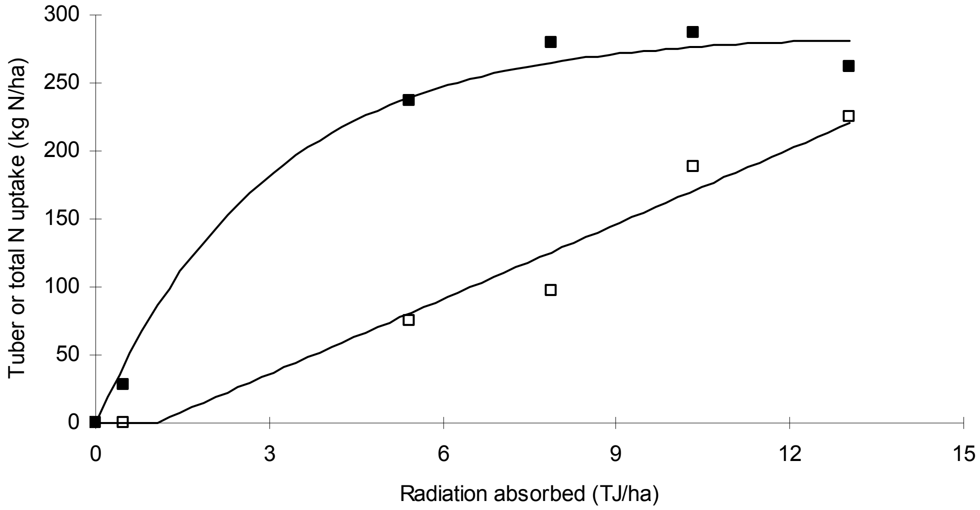
31. A TEST OF THE CUF N MODEL

31.1. Introduction

The Cambridge University Farm (CUF) nitrogen management model makes several assumptions about how N is taken up by the potato crop and how it is then redistributed between haulm and tubers. The first assumption is that radiation absorption by the crop is the key determinant of both total and tuber N uptake. Following from this, the second assumption is that tuber N uptake is approximated by a linear relationship with radiation absorption. The third assumption is that the relationship between total N uptake and radiation absorption is asymptotic and can be approximated by an exponential relationship, constrained to pass the through the origin. This section of the report is concerned with testing the validity of these assumptions.

31.2. Material and Methods

The first assumption was tested using data collected from the variety and N experiment done at Cambridge University Farm in 2010 (page 63). To test the second and third assumptions, N uptake and radiation data from many experiments and commercial crops were collated (Table 144). Data were included only if there were at least three occasions at which total (haulm and tuber) N uptake was measured and these comprised 1472 plots For each plot, daily values of ground cover were calculated by linear interpolation of weekly observations. Estimates of daily radiation absorption were calculated as the product of daily estimates of ground cover and daily incident radiation. Cumulative absorbed radiation was calculated for each harvest in each plot. Total N uptake was analysed by fitting an exponential curve to value of total N uptake (kg N/ha) at each sampling against the cumulative radiation absorbed (TJ/ha). It was assumed that at crop emergence, total N uptake and radiation absorption were zero and, in consequence, the exponential curve was constrained to pass through the origin. Total N uptake was described in terms of two parameters; r, the shape of the curve and b, the asymptotic value of total N uptake. Tuber N uptake was analysed by linear regression of tuber N uptake against radiation absorption and tuber N uptake was also described in terms of two parameters; m, the rate of tuber N uptake (kg N/TJ) and d, the intercept of the fitted line with the x-axis which is an estimate of when tuber N uptake started (as TJ/ha). Goodness of fit of the linear and exponential regressions was assessed using several parameters: examination of the proportion of variance explained by the regression (R2, adjusted for total and residual degrees of freedom in each regression); examination of the statistical significance of the regression (F ratio) and by comparing predicted values for tuber and total N uptake at the final sampling made using the fitted parameters with those observed. Examples of a linear regression of tuber N uptake and an exponential regression of total N uptake are shown in Figure 46.



Parameters of tuber N uptake	Parameters of total N uptake
Slope (m, kg N/TJ) = 18.43 ± 2.16	Shape (r) = 0.71 ± 0.056
Constant (kg N/ha) = 19.6 ± 18.5	Asymptotic value of N uptake (r, kg N/ha) = 285 ± 14.0
Adjusted R^2 = 0.947	Adjusted R^2 = 0.986
Fprob = 0.003	Fprob = < 0.001
Observed tuber N uptake at 13.02 TJ/ha = 225.5 kg N/ha	Observed total N uptake at 13.02 TJ/ha = 261.9 kg N/ha
Predicted tuber N uptake at 13.02 TJ/ha = 220.3 kg N/ha	Predicted total N uptake at 13.02 TJ/ha = 281.6 kg N/ha
Difference in observed and predicted = 5.3 kg N/ha	Difference in observed and predicted = -19.7 kg N/ha

FIGURE 46. EXAMPLE OF LINEAR AND EXPONENTIAL REGRESSION FITTED TO TUBER (OPEN SYMBOLS) AND TOTAL (CLOSED SYMBOLS) N UPTAKE IN RELATION TO RADIATION ABSORPTION. DATA ARE FROM PLOT 14 OF THE VARIETY AND N EXPERIMENT IN 2010.

Due to methodological difficulties in recovering all the haulm at the final harvest it is probable that not all DM is recovered and measurements of total N may be less than that measured at the penultimate harvest (e.g. Figure 46). A consequence of fitting the exponential curve to all data is that the asymptotic value for N uptake is likely to be underestimated.

Year	Location	Varieties	N applied (kg N/ha)	Replicates	Other factors tested	Total number of plots
2010	CUF	Crisps4all, Estima & Russet Burbank	0, 125, 250 & 375	4	None	48
2010	Babraham	Cabaret, Casablanca, Chicago, Estima, Hermes, Lady Rosetta, Markies & Maris Piper	100 & 200	4	None	64
2010	CUF	Desiree	0 & 200	4	Shading and water supply	32
2010	CUF	Lady Rosetta & Maris Piper	0 & 180	3	Soil conditions	48
2009	CUF	Maris Piper	180	3	Soil conditions	48
2009	CUF	Estima	0 & 200	4	Shading and water supply	32
2009	CUF	Brooke, Estima & Russet Burbank	0, 125, 250 & 375	4	None	48
2009	CUF	Bonnie, Chopin, Crisps4all, Estima, Markies, Maris Piper, Vales Sovereign	0 & 180	4	None	56
2009	Babraham	Bonnie, Casablanca, Chicago, Estima, Lionheart & Maris Piper	200	4	None	24
2008	CUF	Maris Piper	0 & 200	4	Soil conditions	48
2008	CUF	Estima	0 & 200	4	Shading	32
2008	CUF	Estima	60 & 120	4	Timing of N	32
2008	CUF	Brooke, Estima & Russet Burbank	0, 125, 250 & 375	4	None	48
2007	CUF	Maris Piper	0, 150 & 300	4	Soil conditions	48
2007	CUF	Brooke, Estima & Russet Burbank	0, 125, 250 & 375	4	None	48
2007	CUF	Estima	60 & 120	4	Timing of N	32
2006	CUF	Maris Piper	0, 100, 200 & 300	3	Soil conditions	48
2006	CUF	Estima & Russet Burbank	0, 125, 250, & 375	4	None	32
2006	CUF	Maris Piper	165 & 330	4	Water supply and seed stock	32
2006	CUF	Estima	0 & 120	4		32

TABLE 144. DETAILS OF EXPERIMENTAL AND COMMERCIAL CROPS USED IN TEST OF CAMBRIDGE UNIVERSITY FARM N MODEL (CONTINUED OVERLEAF)

Table 144. (continued)

Year	Location	Varieties	N applied (kg N/ha)	Replicates	Other factors tested	Total number of plots
2005	CUF	Maris Piper	0, 100, 200 & 300	3	Soil conditions	48
2005	CUF	Estima & Courlan	100	4	Timing of N	32
2005	CUF	Estima, Hermes, Maris Piper & Russet Burbank	0, 100 & 200	4	None	48
2004	CUF	Estima	100 & 200	4		32
2004	CUF	Cara, Estima, Maris Piper & Russet Burbank	0, 100 & 200	4	None	48
2004	Abbot's Ripton	Estima	0 & 200	4	None	8
2004	Wrentham	Estima	0 & 200	4	None	8
2004	Yeovil	Estima	0 & 200	4	None	8
2003	CUF	Estima & Cara	0 & 300	4	Planting density	32
2003	CUF	Estima	0, 120 & 240	3	Date of planting	36
2002	CUF	Estima & Cara	0 & 300	4	Planting density	32
2001	CUF	Estima & Cara	0 & 300	4	Planting density	32
1999	CUF	Estima	0, 150 & 300	3	K and Mg applications	54
1998	CUF	Estima	0, 150 & 300	3	K and Mg applications	54
1997	CUF	Estima	0, 150 & 300	3	K and Mg applications	54
2006	Colorado	Agria, Asterix, Bildstar, Centennial, Innovator, Island Sunshine, Miriam, Norkotah, Rio Grande, Satina Vokal & Yukon Gold	180 to 220	3	Commercial crop	75
2007	Colorado	Agria & Satina	180 to 220	3	Commercial crop	9
2008	Colorado	Bildstar, Fabula, Mozart, Norkotah, Red Star, Satina & Yukon Gold	180 to 220	3	Commercial crop	30

TABLE 145. (CONTINUED) DETAILS OF EXPERIMENTAL AND COMMERCIAL CROPS USED IN TEST OF CAMBRIDGE UNIVERSITY FARM N MODEL

31.3. Results and Discussion

Figure 47a shows the relationship between cumulative incident radiation and the amount of this incident radiation absorbed by crops of Estima that had received either 0 or 375 kg N/ha. Between crop emergence (23 May) and final harvest (7 October) a total of 20.8 TJ/ha was incident upon the crop. However, due to the pattern of ground cover development only 9.33 TJ/ha was absorbed by the unfertilized Estima and 12.86 TJ/ha by the crop that received 375 kg N/ha. Due to canopy senescence between the penultimate and final harvest, relatively little of the incident radiation was absorbed and this was particularly noticeable in the unfertilized crop. The pattern of tuber N uptake with time from emergence is shown in Figure 47b. From c. 20 DAE (i.e. from tuber initiation) until the penultimate harvest at 85 DAE, tuber N uptake in both fertilized and unfertilized crops was well described by a linear relationship. When no N was applied the slope of the relationship was 1.8 kg N/ha/day (R2 = 0.99) and when 375 kg N was applied the slope was increased to 3.3 kg N/ha/day (R2 = 0.98). Between 85 DAE and the final sampling at 137 DAE, there was little increase in tuber N uptake in either crop. However, when tuber N uptake was plotted against radiation absorption (Figure 47c), the relationship was approximately linear over all harvests and for the unfertilized crop the slope of the relation was 13.2 kg N/TJ (R2=0.98) compared with 19.2 kg N/TJ (R2=0.98) when 375 kg N/ha had been applied. For some periods within the season, when incident radiation and ground cover are relatively constant then tuber N uptake will be closely related to time. However, these data show that due to variations in ground cover, and to a lesser extent variation in incident radiation, tuber N uptake over the entire growing season is better described by a linear relationship against radiation absorption than by a linear relationship with time and suggest that tuber N uptake is largely an energy dependent process.

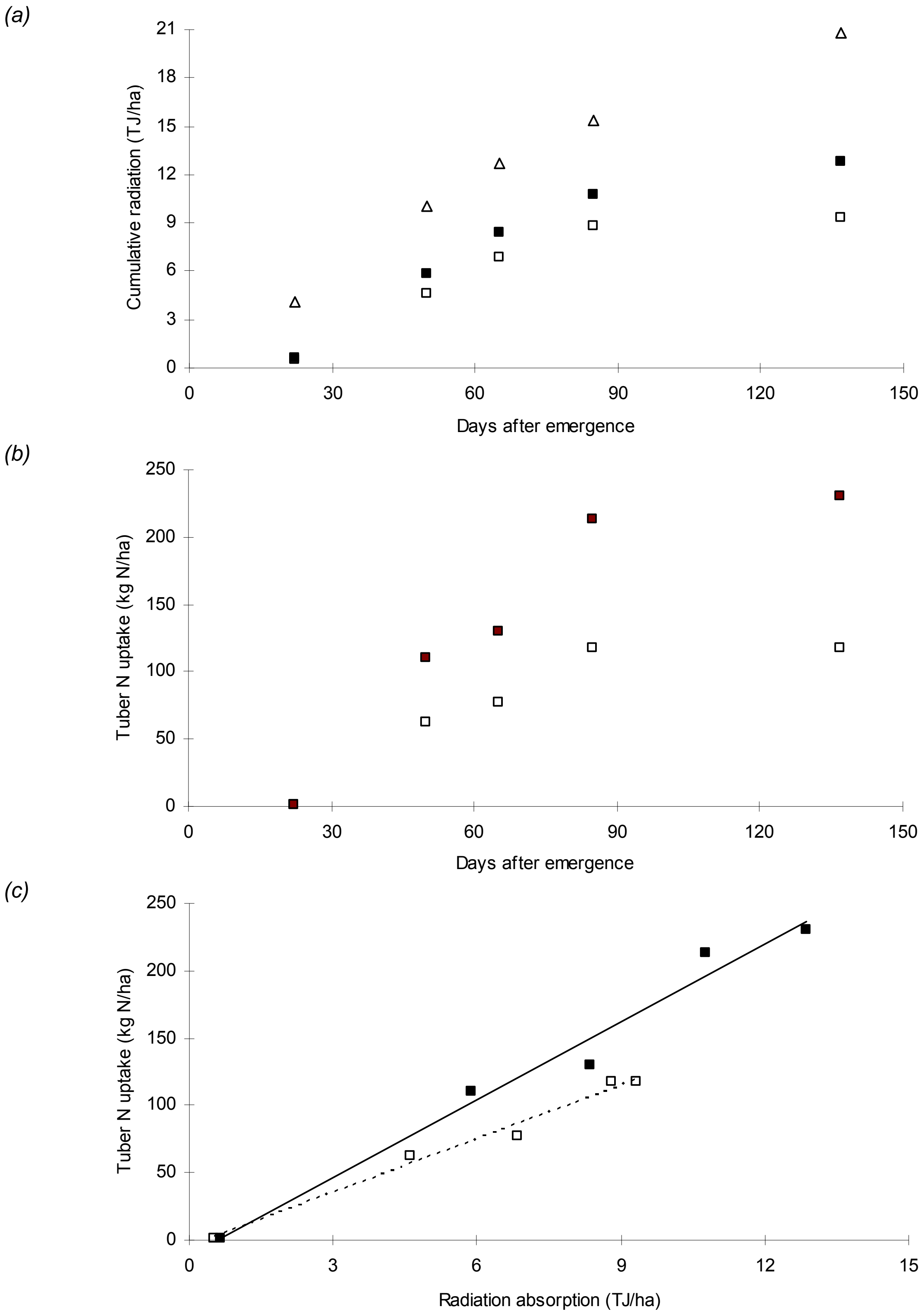


FIGURE 47. (A), RELATIONSHIP BETWEEN CUMULATIVE INCIDENT RADIATION (△) AND CUMULATIVE RADIATION ABSORPTION (SQUARES); (B), RELATIONSHIP BETWEEN TUBER N UPTAKE AND TIME FROM EMERGENCE AND (C) RELATIONSHIP BETWEEN TUBER N UPTAKE AND RADIATION ABSORPTION IN ESTIMA RECEIVING NO N (□) OR 375 KG N/HA (■). SEE TEXT FOR DETAILS OF REGRESSION LINES.

Of the 1472 plots analysed, fits of linear regressions to tuber N uptake and exponential curves to total N uptake were successful in 1467 plots. Summary statistics for tuber N and total N uptake are shown in Table 146 and Table 147 and distributions of goodness of fit parameters are shown in Figure 48. On average 96 % of the variation in tuber N uptake was explained by a linear relationship with the quantity of radiation absorbed by the crop and, on average, the regressions were statistically significant with a median F ratio of 0.015. When the parameters from each regression were used to predict tuber N uptake at the final sampling the median difference between observed and predicted values were c. 2 kg N/ha. Since the median difference between observed and predicted tuber N uptake was small and the distribution of differences appeared to be normally distributed, the linear model used to describe tuber N uptake in relation to radiation absorption appears to be adequate. The interquartile range in the difference between observed and predicted tuber N uptake was 13 kg N/ha. The median rate of tuber N uptake was 14.5 kg N/TJ and thus the interquartile range in the prediction of tuber N uptake was equivalent to c. 1 TJ/ha of energy. Assuming a RUE of 1.25 t/TJ, a harvest index of 0.80 and tuber DM concentration of 20 %, then the yield potential estimated by modelling of tuber N uptake might therefore be expected to be within ± 2.5 t/ha in half of all crops. On the basis of measures of goodness of fit, the exponential model of total N uptake was more satisfactory than the linear model of tuber N uptake although this may have been partly associated with constraining the curve to pass through the origin. On average, 97 % of the variation in total N uptake was explained by an exponential relationship with radiation absorption. The median F ratio for the regressions was 0.001. On average, observed values for total N uptake at the final sampling were c. 6 kg N/ha smaller than those predicted using the parameters from the fitted curves, but the distribution of deviation about the mean value appeared to be symmetrical. The interquartile range of the deviation of observed and modelled total N uptake was 22 kg N/ha. As shown in the materials and methods, the exponential model might be expected to overestimate N at final harvest but analysis of the statistical parameters suggests that the exponential curve is a reasonable model of total N uptake in relation to radiation absorption.

The analysis above was performed on values from 1467 individual plots, however all of these data were derived from replicated observations in either experiments or commercial fields. When averaged by treatment (n=410), the median deviation of total N uptake was 5.1 kg N/ha (with an interquartile range of 14.6 kg N/ha) and the median deviation for tuber N uptake was 2.0 kg N/ha with an interquartile range of 9.0 kg N/ha. These data show that using replicate measurements of N uptake parameters will improve the precision of the CUF N model.

In conclusion, these data suggest that these simple empirical models of tuber and total N uptake should be sufficiently reliable to be used to interpret growth and yield of crops in both experiments and in commercial crops.

	Lower quartile	Median	Upper quartile
Rate of tuber N uptake (kg N/TJ)	11.9	14.6	17.6
Start of tuber N uptake (TJ/ha)	0.30	0.85	1.54
F ratio of regression	0.005	0.015	0.057
Proportion of variation explained by regression	0.92	0.96	0.99
Difference between observed and modelled N uptake at final harvest (kg N/ha)	-4.0	2.2	9.1

TABLE 146. SUMMARY STATISTICS FOR TUBER N UPTAKE (SAMPLE SIZE = 1467 PLOTS)

	Lower quartile	Median	Upper quartile
Asymptotic value of total N uptake (kg N/ha)	154	198	244
Shape of total N uptake curve, r	0.586	0.688	0.770
F ratio of regression	<0.001	0.001	0.006
Proportion of variation explained by regression	0.93	0.97	0.99
Difference between observed and modelled N uptake at final harvest (kg N/ha)	-18.1	-5.6	3.9

TABLE 147. SUMMARY STATISTICS FOR TOTAL N UPTAKE (SAMPLE SIZE = 1467 PLOTS)

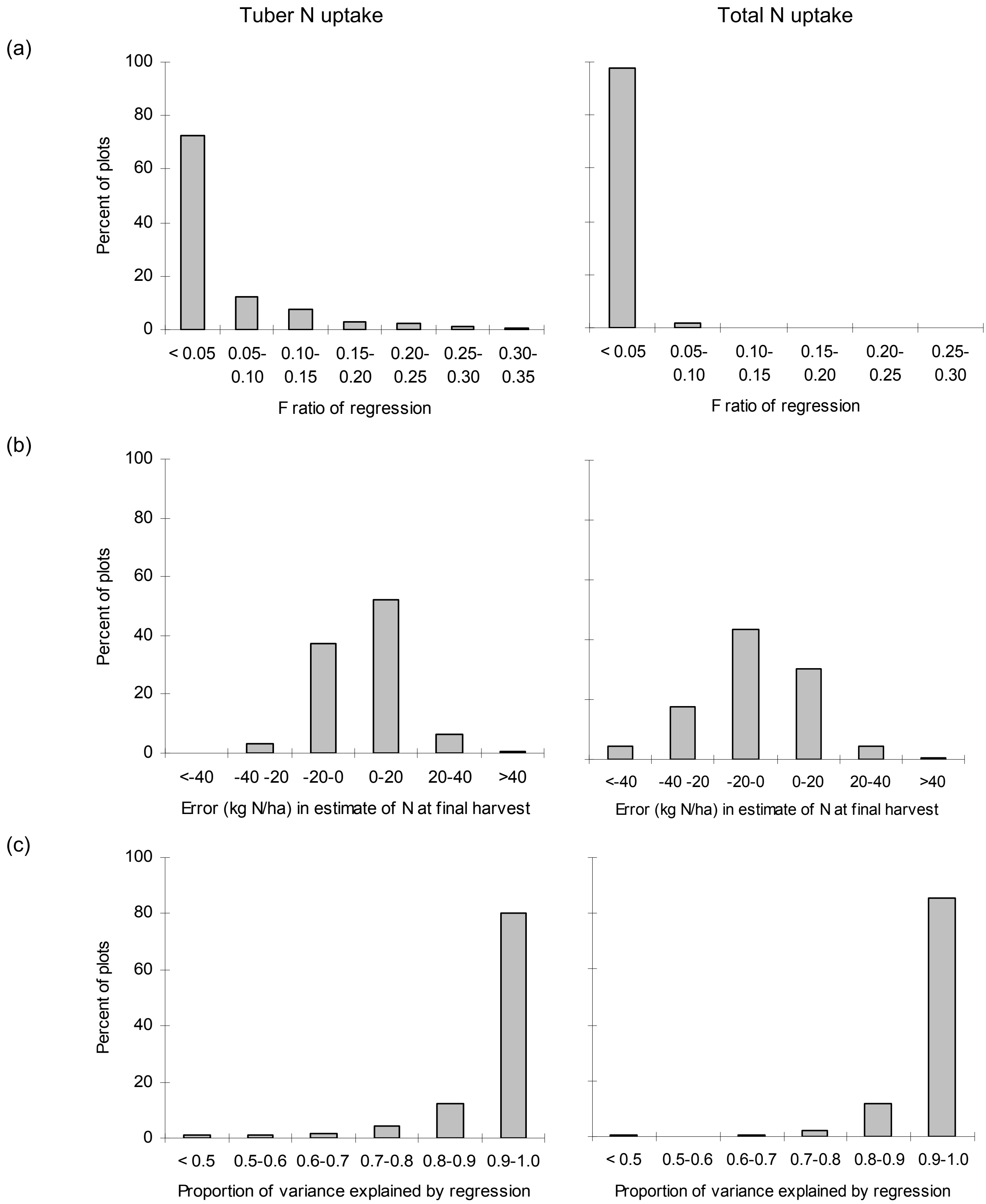


FIGURE 48. ASSESSMENT OF LINEAR MODEL OF TUBER N UPTAKE AND EXPONENTIAL MODEL OF TOTAL N UPTAKE IN RELATION TO RADIATION ABSORPTION. TESTS ARE (A) F RATIO OF REGRESSION, (B) DIFFERENCE BETWEEN OBSERVED N UPTAKE AT FINAL HARVEST AND MODELLED N UPTAKE AND (C) PROPORTION OF VARIANCE EXPLAINED BY REGRESSION.

32. OVERALL CONCLUSIONS

The purpose of this project was to validate the principles underpinning the CUF N model and then use the model to interpret the growth and yield of experimental and commercial crops as well as improving the understanding of varietal differences in N nutrition and fertilizer use efficiency.

The validation showed that simple relationships with radiation absorption explained much of the variation in total and tuber N uptake by potato crops and that these simple relationships could then be used to make inferences about canopy persistence and yield potential. Similarly experiments at CUF and elsewhere showed that differences in a variety's response to N fertilizer can be explained by an understanding of how increasing the N supply affects total N uptake and the rate at which N is transferred from the haulm. This understanding can be used to rank varieties in their response to N and will thus help provide an objective basis for future N recommendations. This study has demonstrated the importance of total N uptake in determining canopy persistence and since most N uptake occurs within the first half of the growing season, yield potential is also determined early in the season. This knowledge has led to practical recommendations involving the timing of N applications. Detailed measurements in commercial crops have also shown that due to spatial heterogeneity of root systems in ridge planted potato crops, N falling into the wheeling is unlikely to be recovered efficiently. Minimising the loss of basal and top-dressings of N into wheelings will increase N use efficiency and enable reductions in the overall N application rate. Several experiments tested the effects of poor soil conditions (e.g. compaction or cloddiness) on the N uptake and yield of crops. In many of these experiments the effects of poor soil conditions on yield were surprisingly small, but in all cases the effects were explicable in terms of the dynamics of N uptake and redistribution. These experiments also showed that the yield penalty associated with poor soil conditions could not be removed by applying extra N (or water) but in those crops receiving no or small amounts of N, the effects of poor soil conditions tended to be more severe. Experiments also showed that when compared to rain-fed crops, irrigation increased the apparent efficiency with which crops recovered both soil and fertilizer derived N. This increase in efficiency showed why the larger yield associated with use of irrigation could be achieved without use of more N fertilizer.

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34. ACKNOWLEDGEMENTS

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