Evaluation of an N management and yield prediction model developed by Cambridge University Farm

Potato Council Project R273

Final Report

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Summary

This report describes a British Potato Council Project R273 that funded work at Cambridge University Farm (CUF) to evaluate a nitrogen (N) management model. This model relates crop N uptake and redistribution from haulm to tubers to the amount of solar energy absorbed by the crop. The model can be used to estimate the yield potential of the crop at final harvest on the basis of crop samples taken 45-50 days after crop emergence. The three-year programme (2005-2007) was designed to test specific components of the model and also to develop crop recording protocols and data transfer systems that would allow commercialisation of the model.

In total, crop yield, N uptake and radiation absorption data were collected from 211 experimental or commercial crops in the UK and in the USA. The purpose of the work in the USA was to test the N model in commercial crops using varieties and environmental conditions that contrasted to those in UK. The key findings from this programme were that crop yield potential was closely associated with total N uptake and that the majority of total N uptake occurred within *c.* seven weeks from crop emergence. Factors that reduced early N uptake, (e.g. insufficient N, water stress or compaction) reduced N uptake and, in turn, reduced yield potential. In some crops, yield potential was not realised and this may be attributed to the effects of heat or water stress or disease. Since the yield potential of crops was set early in the season, where late applications of N were made, these had little effect on N uptake, canopy persistence or yield.

Varietal differences in total N uptake and partitioning between haulm and tubers were consistent with differences in N fertilizer requirement and the N model can be used to rapidly assess the likely N requirement of new varieties. The N model has also proved useful in identifying factors that may be limiting the formation of crop yield and could be a useful management tool. A crop recording system originally developed at CUF has been adapted in collaboration with growers and agronomists in the UK and USA to facilitate the rapid collection of key crop data, the transfer of these data to CUF for processing and interpretation and the subsequent return of advice and recommendations.

SECTION 1

Structure of this report

This report is split into four main sections. Section 1 contains a listing of key data and conclusions from work done in 2005-2007. In addition, Section 1 includes a brief introduction to Project R273 and a summary of the theory behind the Cambridge University Farm (CUF) N management model. Finally, Section 1 also includes two tables that show the extent of work done in 2005-2007 and acknowledgments to the sponsors who funded this work and the many growers in the UK and abroad who provided crops and invaluable assistance during the course of the project. Section 2, gives detailed reports for work done in 2006 and 2007. Details of the work done in 2005 are given in an earlier report (Allison & Allen, 2006). The purpose of Section 3 is to examine in more detail certain aspects of the CUF N management and yield prediction model. These include: varietal differences in N uptake and consequences for N requirement; the importance of the correct timing of crop sampling; use of the N management system in commercial UK crops and the identification of factors that may be limiting yield formation. Finally, Section 4 presents conclusions, areas where further work is needed and areas for possible commercial exploitation of the model.

Key data and conclusions from nutrition programme in 2005-2007

1. The main activities in 2005-2007 were the evaluation of components of the CUF N management model in both the UK and USA.

2. In 2005, CUF was contacted by Irish Potato Marketing Ltd to compare their variety Orla with Estima. An N response experiment at CUF showed that Orla had a smaller N requirement than Estima (*c.* 160 kg N/ha compared with 160-240, respectively). At the optimum N application rates, both varieties produced yields in excess of 85 t/ha. These large yields were a consequence of persistent canopies and were explicable in terms of total N uptake by the crop and the rate of redistribution of N from the haulm to the tubers.

3. At CUF, experiments in 2006 and 2007 with Estima used shading and N treatments to investigate the effects of the intensity of incident radiation and N supply on crop productivity, N uptake and N redistribution. The experiments support observations made in commercial crops grown in California that radiation use efficiency decreases as the intensity of incident radiation increases.

4. An experiment at CUF in 2005 tested the effects of applying 0, 100 and 200 kg N/ha on the growth and yield of Estima, Hermes, Maris Piper and Russet Burbank. For Hermes, Maris Piper and Russet Burbank the optimum N application rate was *c.* 100 kg N/ha (giving an average tuber yield of *c.* 58 t/ha), but for Estima the optimum was closer to 200 kg N/ha resulting in a yield of 55 t/ha. Experiments at CUF in 2006 and 2007 tested the effects of applying 0, 125, 250 or 375 kg N/ha on the yield and N uptake of Russet Burbank and Estima. In 2006, the optimum N application rate for both varieties was *c*. 125 kg N/ha and the tuber fresh weight (FW) yield at the optimum N application rate was 56.3 and 57.8 t/ha for Estima and Russet Burbank, respectively. For Russet Burbank, the onset of the linear phase of tuber bulking occurred several days after tuber initiation (TI) and the length of the delay was increased by N. Analysis of tuber and haulm N uptake suggested radiation absorption potentials that were larger than actually achieved. The reason for this discrepancy is not certain but may

have been due to a combination of heat/water stress and disease. In 2007, the optimum N application rate for both varieties was *c.* 250 kg N/ha and the yield at the optimum averaged 53.6 t/ha. Thus, in 2007 the response to N fertilizer was larger but yields were smaller than in 2006. These differences were explicable in terms of total N uptake but it is not known whether the restricted uptakes in 2007 were caused by reduced soil N supply or the crop's inability to access these reserves.

5. In 2005, two experiments on Starveacre field at CUF tested the effects of contrasting soil conditions (achieved by timing of cultivations) on the N requirement of Maris Piper. These two experiments had similar experimental designs but were done on soils with contrasting soil textures. The average yield on the heavy-textured soil was 57.6 t/ha compared with 62.1 t/ha on the lighter-textured soil. On the lighter-textured soils responses to N were small irrespective of cultivation treatment. In contrast, on the heavier-textured soils, yields were reduced when no N was applied to plots that had been worked whilst wet. Experiments at CUF in 2006 and 2007 continued to investigate the effects of contrasting soil conditions (caused by ridging wet or dry soils), irrigation and N application rate on the yield and N uptake of Maris Piper. In 2006, the overall average tuber FW yield at final harvest was 52.0 t/ha compared with 58.1 t/ha in 2007. In 2006, crops grown in Cultivated-wet soils had yields *c.* 10 t/ha less than those grown in the Cultivated-dry soils and the Irrigated crops had yields *c.* 12 t/ha larger than the Unirrigated. Irrespective of cultivation or irrigation treatment, the optimal N application rate was zero. In 2007, cultivating the soils whilst wet or dry had no effect on tuber FW yield, however, the yield of the irrigated crop was 65.1 t/ha compared with only 51.0 t/ha for the unirrigated. In 2007, increasing the N application rate from 0 to 300 kg N/ha increased yields from 46.8 to 67.6 t/ha. In both seasons the effects of the treatments on tuber yield were explicable in terms of their effects on total N uptake. Despite some extreme experimental treatments, the N management model still predicted potential radiation absorption to within 1 TJ/ha.

6. In 2005, an experiment tested the effect of applying 100 kg N/ha as two 50 kg N/ha splits with one applied at planting and the other at 19, 26, 37 or 58 days after 50 % plant emergence (DAE) on the growth and yield of Estima and Courlan. The main feature of this experiment was the small tuber yield of Courlan compared with Estima (35.2 and 54.8 t/ha, respectively) and this was probably due to the sensitivity of Courlan to cool temperatures early in the season and poor soil conditions. These differences in yield were consistent with differences in crop N uptake early in the season. The experiment showed that timing of N application had no statistically significant effect on yield.
   In 2007, a similar experiment with Estima, investigated the effect of timing and rate of N application on growth, N uptake and yield. Tuber FW yield increased from 42.2 to 48.0 t/ha when the total amount of N applied was increased from 60 to 120 kg N/ha. This increase in yield was explicable in terms of increased N uptake, canopy persistence and radiation absorption. There was no statistically significant yield benefit from applying the N in multiple splits.

7. In 2005 and 2006, data collected from the Size and Uniformity Project (BPC R257) were used to test aspects of the N management model. This experiment compared in factorial combination two stocks of Maris Piper, two N application rates (165 or 330 kg N/ha) and two irrigation regimes (scheduled and variable). In 2005, the average yields were large (71.5 t/ha) and were not significantly affected by seed stock, N application rate or irrigation regime.
   In 2006, increasing the N application rate from 165 to 330 kg N/ha increased total and haulm N uptake and thereby increased yield potential. Haulm N uptake was also increased by scheduling irrigation when compared with variable applications. On average, estimates of potential radiation absorption were 3 TJ/ha larger than those actually achieved and this suggests that there was a tuber yield loss of 15-18 t FW/ha. The causes for the yield loss are not known but may have been due to the effects of heat stress or early blight.

8. In 2007, data collected from the Scab project (SA-LINK LK0989) was used to test aspects of the N management model. In this experiment irrigation water was

applied by drip or sprinkler. When water had been applied frequently by sprinkler the crop canopy was much paler, suggesting that N uptake had been impaired. However, despite marked visual differences between the two irrigation methods there were no significant effects on N uptake, canopy persistence, dry matter production or tuber FW yield.

9. Work in the USA allowed various components of models to be tested under commercial conditions and relied on data collection by third parties (i.e. non CUF staff). The work in the US also allowed the model to be tested in environments that were much warmer and brighter than those for which the model was created. A key objective of the studies in the USA was to set up systems for efficient data recording in the USA, the transfer of these data to the UK for processing and the return of predictions and recommendation to the USA. In general this objective has been achieved, with the time difference between the UK and USA enabling rapid turn around of data. Crop recording and reporting sheets have been developed to facilitate information transfer between CUF, farm managers and agronomists. The data collected provided insights into some limitations of current models and how these limitations may be avoided by careful crop sampling and data processing.

10. Testing of the CUF N management model on commercial crops within the UK was hampered by the availability of reliable meteorological data. However, when suitable data were available the model performed well and made reliable predictions of potential radiation absorption.

11. Work in 2007 showed that the CUF N management model could be used as a rapid method to determine the determinacy of new varieties and therefore estimate their likely fertilizer N requirement. This work could be extended to use the model to identify varietal characteristics that confer efficient N use within breeding programs

12. When used as part of a crop monitoring program (for example within the CUF/BPC Grower Collaboration Project R295) the N management model provides a framework within which the performance of commercial crops can be

analysed. This analysis highlights where limitations to yield production exist and how they may be alleviated.

Introduction

Ongoing work at CUF has established relationships between N uptake and redistribution and the amount of radiation absorbed by the crop. These relationships can be used to predict canopy persistence, potential radiation absorption and yield. The components of this system are illustrated in Figure 1 and Figure 2. The system assumes that, when plotted against absorbed radiation, the rate of tuber N uptake (blue line) is constant whereas the rate of total N uptake (red line) decreases as the season progresses. A consequence of these contrasting rates of N uptake is that at a point in the season (4.1 TJ/ha in this example), the rate of tuber N uptake must exceed the rate of total N uptake and this can only be achieved by the remobilization of N from the haulm and its transport to the tubers. This process will deplete the canopy of N and will eventually result in complete canopy senescence. Since total DM and tuber FW yield can be linked to radiation absorption, knowledge of the pattern of total and tuber N uptake in relation to radiation absorption can be used to predict potential tuber FW yield.

Figure 1. Example of total (△), tuber (◊) and haulm N uptake (□) in relation to the amount of radiation absorbed by the crop.

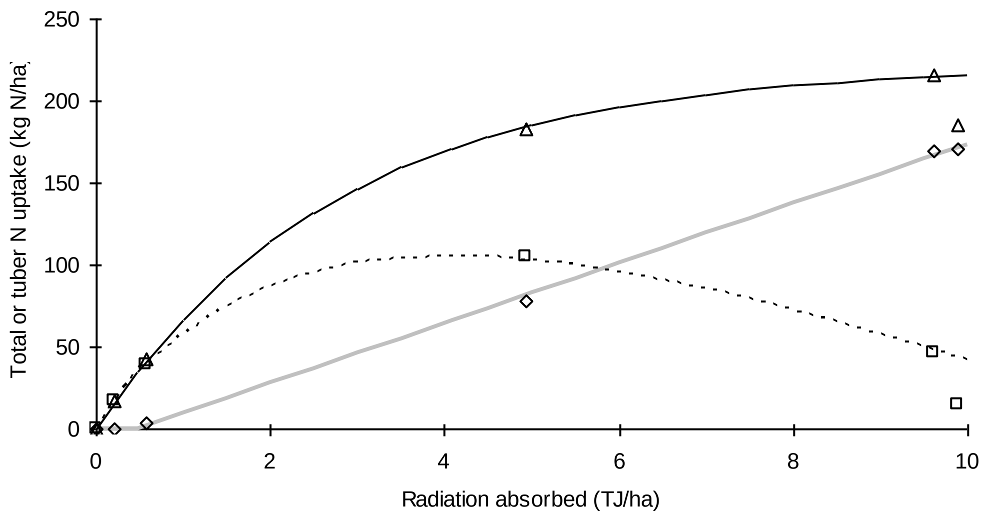
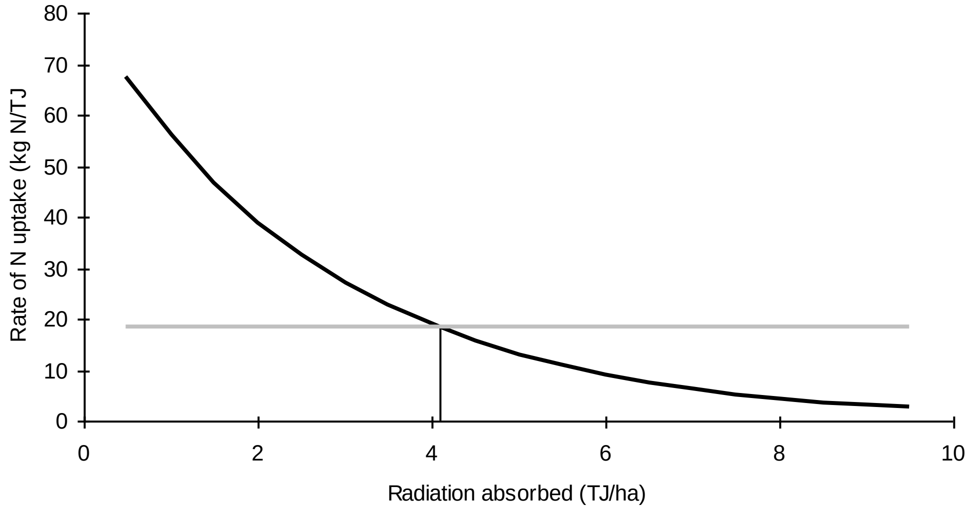


Figure 2. Example of the change in rate of total (—) and tuber N uptake (—) in relation to the amount of radiation absorbed by the crop. Values are based on example in Figure 1.



Experimental program in 2005-2007

A summary of the experimental program for 2005 is shown in Table 1 and, as noted earlier, full details of the experiments are given in an earlier report. An outline of the experimental program for 2006 and 2007 is shown in Table 2 and more details are contained within this report for each experiment. One experiment (Maris Piper stock × Irrigation Regime × N application rate) was part of the BPC-funded Size and Uniformity project (R257) and one experiment (Precision Irrigation and Non-Water Based Suppression of Potato Common Scab) was part of a LINK project. All of the work done within the USA was on commercial farms.

Acknowledgments

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Incorporated). The experimental program within the UK was completed with help from many growers and their agronomists and the Agronomy Centre staff at CUF.

Table 1. **Selected details of programme of work in the USA and UK in 2005. For more details see report for 2005**

Location	Season	Grower	Sector	Fields	Varieties and other treatments
CUF	2005	CUF	Table	1	Orla and Estima (5N rates)
CUF	2005	CUF	Table/Crisping/ French Fries	1	Estima, Hermes, Maris Piper and Russet Burbank (3N rates)
CUF	2005	CUF	Table/Crisping	1	Estima and Courlan
CUF	2005	CUF	Table/French Fries	1	Maris Piper (4N rates × 2 cultivations)
CUF	2005	CUF	Table French Fries	1	Maris Piper (4N rates × 2 cultivations)
CUF	2005	CUF	Table/French Fries	1	Maris Piper
California	2004-05	FTC	Table	6	Asterix, Innovator, Island Sunshine and Satina
Colorado	2005	FTC	Table	33	Agria, Asterix, Bildstar, Centennial, Innovator, Island Sunshine, Norkotah, Rio Grande, Satina & Yukon Gold
Texas	2005	CSS Farms	Crisping	3	FL1291, FL1833 & FL1867
Texas	2005	CSS Farms	Crisping	1	FL1833 (5N rates)
Nebraska	2005	CSS Farms	Crisping	3	FL1833, FL1845 & FL1867
Minnesota	2005	R D Offut	French Fries	3	Russet Burbank (2N rates)
Minnesota	2005	R D Offut	French Fries	1	Russet Burbank (4N rates)

Table 2. Selected details of programme of work in the USA and UK in 2006 and 2007

Location	Season	Grower	Sector	Fields	Varieties and other treatments
California	2005-06	FTC	Table	17	Asterix, Innovator, Russet Norkotah, Red Lasoda and Satina
Colorado	2006	FTC	Table	25	Agria, Asterix, Bildstar, Centennial Russet, Innovator, Island Sunshine, Miriam, Rio Grande, Russet Norkotah, Satina, Vokal and Yukon Gold
Texas	2006	CSS Farms	Crisping	6	FL 1833, FL 1867, FL 1921, Snowden and White Pearl
Nebraska	2006	CSS Farms	Crisping	3	FL 1833, FL 1867 and FL 1845
Minnesota	2006	R D Offut	French Fries	1	Russet Burbank (4 N rates)
CUF	2006	CUF	Table	1	Estima (Shading × 2 N rates)
CUF	2006	CUF	Table/French Fries	1	Estima and Russet Burbank (4 N rates)
CUF	2006	CUF	Table	1	Maris Piper (Soil conditions × 2 Irrigation regimes × 4 N rates)
CUF	2006	CUF	Table	1	Maris Piper (2 stocks × 2 Irrigation regimes × 2 N rates)
Norfolk	2006	B & C Farming	French Fries	2	Russet Burbank
Suffolk	2006	Greens of Soham	Crisping	3	Lady Rosetta
Somerset	2006	B & B Farming	Table	1	Sante
Suffolk	2006	Greenvale AP	Table	3	Maris Piper and Marfona
California	2006-07	FTC	Table	26	Asterix, Innovator, Russet Norkotah, Red Lasoda, Satina and Yukon Gold
Colorado	2007	FTC	Table	52	Agria, Asterix, Bildstar, Canela, Centennial Russet, Fabula, Innovator, Island Sunshine, Rio Grande, Russet Norkotah, Satina, Vokal and Yukon Gold
CUF	2007	CUF	Table	1	Estima (Shading × 2 N rates)
CUF	2007	CUF	Table	1	Estima and Russet Burbank (4 N rates)
CUF	2007	CUF	Table/French Fries	1	Maris Piper (Soil conditions × 2 Irrigation regimes ×3 N rates)
CUF	2007	CUF	Table	1	Estima
CUF	2007	CUF	Table	1	Maris Piper (2 × irrigation method)
Norfolk	2007	B & C Farming	French Fries	2	Russet Burbank
Norfolk	2007	B & C Farming	Seed	1	Maris Peer
Norfolk	2007	Greens of Soham	Crisping	2	Lady Rosetta
Somerset	2007	B & B Farming	Table	1	Estima
Somerset	2007	Perrins Hill Partnership	Table	1	Estima

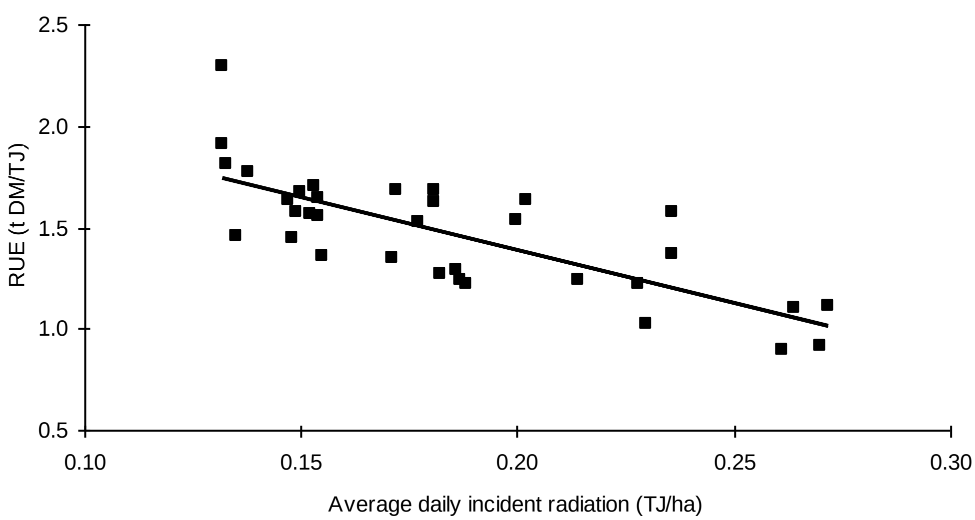
SECTION 2

Effect of shading and N application rate on N uptake and yield of Estima in 2006

Introduction

In early 2006, CUF was involved with studies on commercial crops grown by Farming Technologies in Kern County, California. The planting dates for these crops ranged from 13 December 2005 to 1 March 2006 and the dates of 50 % plant emergence ranged from to 24 January to 8 April. In consequence, these crops emerged and grew in contrasting radiation environments. As part of these studies, the crops were sampled on several occasions during their growing season and the radiation use efficiency (RUE) was calculated from estimates of radiation absorption and total dry matter yield. It was noticed that the early-planted crops used radiation more efficiently than later-planted crops. Further analysis of these data showed that radiation use efficiency was inversely related to average daily incident radiation (Figure 3). Thus, early-planted crops, growing in relatively dull conditions used radiation more efficiently than the later-planted crops that grew in very bright conditions.

Figure 3. Relationship between radiation use efficiency (RUE) and average daily incident radiation for crops grown in Kern County, California 2006. The regression equation is RUE = 2.43 – 5.21IR; R^2 = 0.57; P < 0.001.



As a result of these observations an experiment was done at CUF to investigate the effects of variation in incident radiation on radiation use efficiency, yield production and N uptake and redistribution.

Materials and Methods

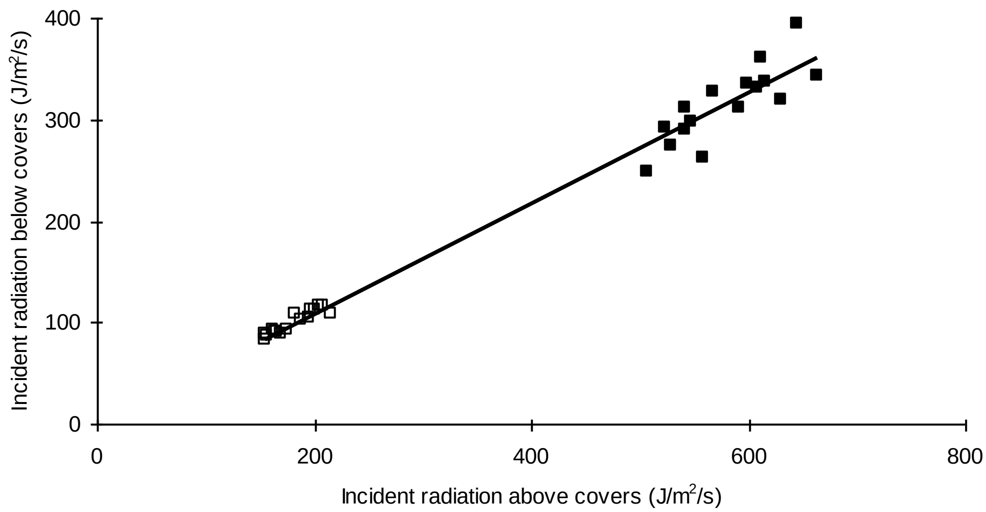
Estima seed (SE1; 25-30 mm; count 2291/50 kg) was planted by hand at 25 cm spacing into pre-formed ridges with 76.2 cm centres on 13 April. The experiment tested all combinations of two N application rates (0 or 200 kg N/ha), early shading (none or shaded) and late shading (none or shaded). The early-shaded treatments lasted from 31 May to 5 July (13–48 DAE) and the late-shaded treatments lasted from 7 July to 12 September (50–117 DAE). Each treatment combination was replicated four times and each plot was four rows wide (3.05 m) and 6 m long. Nitrogen fertilizer, as ammonium nitrate, was applied by hand in a single application at planting and then shallowly incorporated by raking. The crop was sampled on 6 July, 3 August and on 15 September when the canopies had completely senesced. At each harvest, ten plants (area = 1.91 m^2) were taken from the central two rows of each plot. The total number of stems was recorded and all tubers > 10 mm collected. The haulm was weighed in the field and a representative sub-sample (*c*. 1 kg) was taken and then dried at 90 °C to constant weight (*c*. 48 hours). The tubers were graded in 10 mm increments and the number and weight of tubers were recorded. A sub-sample of tubers (*c*. 1 kg) was taken from the 50-60 mm grade, chipped and then dried to constant weight at 90 °C. The dried haulm and tubers were then sent for measurement of total N content at a commercial laboratory. The crop received a total of 222 mm irrigation.

Results and Discussion

Shading

On average, the shade material reduced the amount of radiation underneath the covers by *c*. 45 % and this reduction was not affected by the intensity of the incident radiation (Figure 4).

Figure 4. **Effect of shade covers on radiation below cover on a dull day (5 July; □) and a bright day (28 June; ■). Note values for incident radiation are approximate conversions from instrumentation. Each point is the mean of twenty paired readings. The regression equation is BC = 0.54AC; R^2 = 0.98; P < 0.001.**

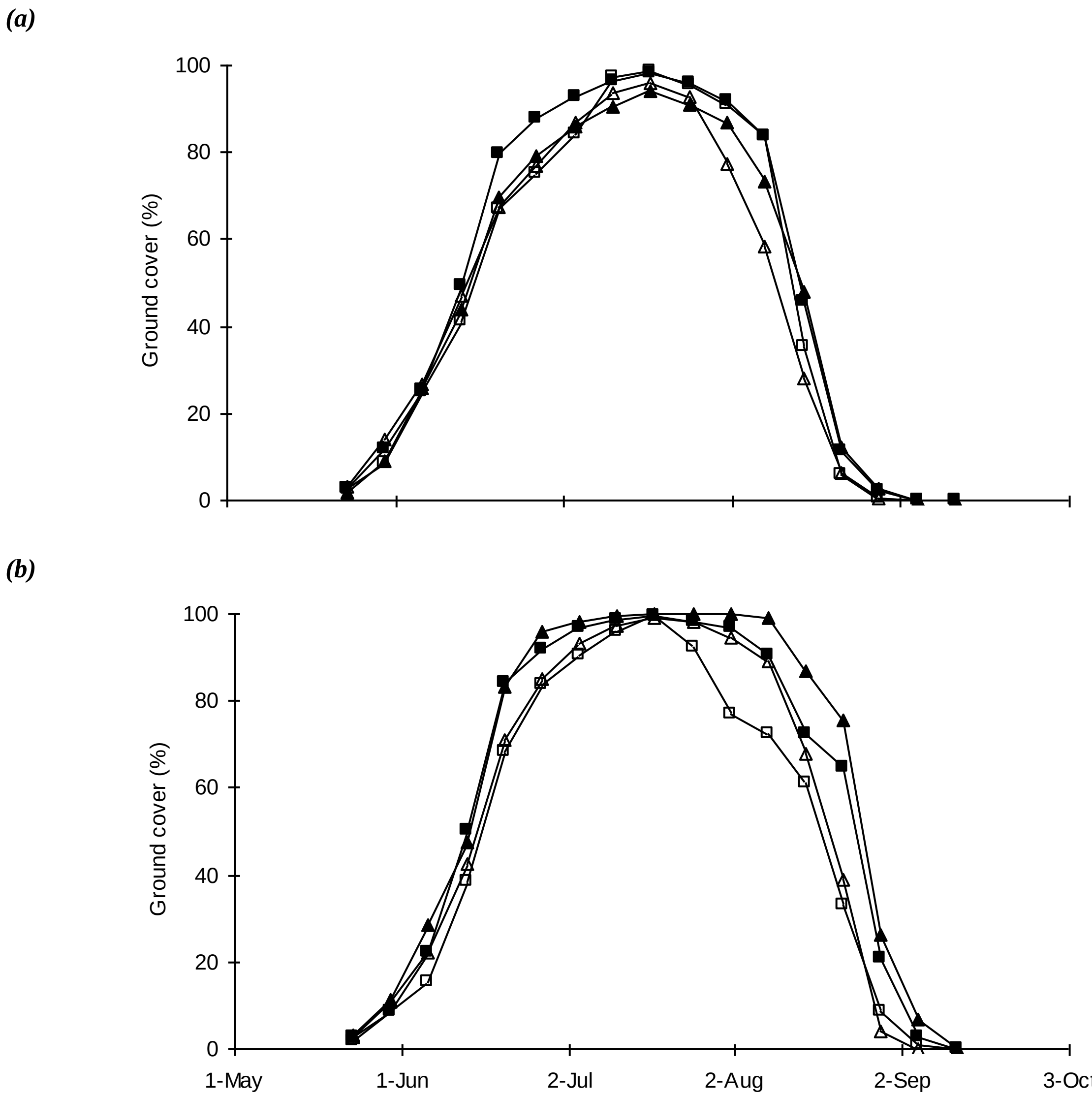


Emergence, ground cover and radiation absorption

The mean date of 50 % plant emergence was 18 May (25 days after planting). Crops that had received no N emerged *c.* 2 days before those that had received 200 kg N/ha. The final plant stand was only 92.7 % of intended and the loss of plants was mainly due to soil-borne *Rhizoctonia* and some plants (< 1 %) were also killed during the season by blackleg. In addition, one plot (200 kg N/ha and unshaded) was badly affected by early blight (*Alternaria solani*). The first symptoms were first noticed on 18 July but for simplicity all data from this plot have been omitted from analyses.

The development of ground cover is shown in Figure 5 and is summarised in Table 3. Applying 200 kg N/ha increased integrated ground cover by *c.* 1100 % days (equivalent to an extra 11 days at 100 % ground cover). Although the effects were relatively small, the early-shaded treatments had more persistent ground covers than the unshaded.

Figure 5. 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, ▲.



Using values for the percentage reduction in incident radiation due to shading it is possible to estimate the amount of radiation absorbed by shaded crops. Irrespective of the shading treatment, applying 200 kg N/ha increased radiation absorption by *c.* 1 TJ/ha (Table 3). When averaged over the N treatments, the early shading treatment decreased radiation absorption by c. 1.3 TJ/ha and the late shading treatment by c. 3.2 TJ/ha. The effect of early and late shading was to reduce radiation absorption by *c.* 4.6 TJ/ha when compared with the unshaded treatment.

Table 3. **Effect of N application rate and shading on integrated ground cover and radiation absorption**

	Integrated ground cover (% days)		Radiation absorption (TJ/ha)	
Shading	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
None-None	5674	6467	10.70	11.75
Early-None	6124	7007	9.45	10.46
None-Late	5430	6428	7.70	8.36
Early-Late	5700	7437	5.95	7.26
Mean	5732	6835	8.45	9.46
S.E. (20 D.F.)	141.4 (N); 282.7 (N and shade)		0.176 (N); 0.352 (N and shade)	

Yields at first, second and third samplings

At the first sampling (6 July, 49 DAE), the overall mean total DW and tuber FW yield were 6.7 and 25.7 t/ha, respectively and these were not affected by N application rate (Table 4). When averaged over the other factors, the early shading treatment reduced total DW yield from 7.4 t/ha to 5.9 t/ha and tuber FW from 29.2 to 22.2 t/ha. Thus, reducing the amount of radiation received by the crop by 45 % resulted in modest reductions in both total DM yield and tuber FW yield production.

Table 4. **Effect of N application rate and shading on total dry matter (DM) and tuber fresh weight (FW) yields on 6 July (49 DAE)**

	Total DM yield (t/ha)		Tuber FW yield (t/ha)	
Shading	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
None-None	7.54	7.44	30.3	28.9
Early-None	5.51	5.64	22.3	19.4
None-Late	6.86	7.94	28.1	29.4
Early-Late	5.57	6.75	23.2	23.9
Mean	6.37	6.94	26.0	25.4
S.E. (20 D.F.)	0.230 (N); 0.461 (N and Shade)		1.08 (N); 2.16 (N and Shade)	

The second crop sample was taken on 3 August (77 DAE) and total DW and tuber FW yields had increased to 12.5 and 51.5 t/ha, respectively (Table 5). Applying 200 kg N/ha resulted in a small, but statistically significant increase in both total DW and tuber FW yield. Shading had no significant effect on either total DM yield or tuber FW yield but this may be have been a consequence of the relatively large standard error.

Table 5. **Effect of N application rate and shading on total dry matter (DM) and tuber fresh weight (FW) yields on 3 August (77 DAE)**

	Total DM yield (t/ha)		Tuber FW yield (t/ha)	
Shading	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
None-None	12.86	14.35	53.6	58.4
Early-None	12.34	12.74	49.6	51.1
None-Late	10.82	12.85	47.1	54.2
Early-Late	11.39	12.95	46.0	52.2
Mean	11.85	13.22	49.1	54.0
S.E. (20 D.F.)	0.376 (N); 0.752 (N and Shade)		1.64 (N); 3.28 (N and Shade)	

The final sampling was taken on 15 September (120 DAE) once the canopies had completely senesced. The overall average total DM yield was 13.12 t/ha and the fresh weight yield was 59.6 t/ha (Table 6). Applying 200 kg N/ha increased total yield by 3.6 t DM/ha and tuber FW yield by 16 t/ha. Numerically total DW and tuber FW yield were reduced by the late shading treatment however, due to the large S.E., these differences were not statistically different.

Table 6. **Effect of N application rate and shading on total dry matter (DM) and tuber fresh weight (FW) yields on 15 September (120 DAE)**

	Total DM yield (t/ha)		Tuber FW yield (t/ha)	
Shading	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
None-None	12.40	15.68	56.2	72.3
Early-None	11.91	15.88	52.5	71.7
None-Late	9.70	13.08	47.5	60.1
Early-Late	11.30	15.05	50.8	65.3
Mean	11.33	14.92	51.7	67.4
S.E. (20 D.F.)	0.676 (N); 1.351 (N and Shade)		2.74 (N); 5.47 (N and Shade)	

Previous studies at CUF have shown that, in general, more tubers were initiated per stem when conditions were bright and the crop was growing rapidly. Thus, it might be expected that crops that were shaded during initiation would set fewer tubers than unshaded crops. Table 7 shows the effects of shading on the number of stems and tubers at each harvest and supports this hypothesis. At each harvest the number of stems was not affected by the early shade treatment but for the first and second samplings the number of tubers > 10 mm was significantly smaller in the shaded treatments. However, by the final harvest this effect had disappeared and this was due to a reduction in the number of tubers retained by the unshaded crops.

Table 7. Main effect of early shade treatment on the total number of stems and tubers > 10 mm (000/ha)

	Harvest 1 (49 DAE)		Harvest 2 (77 DAE)		Harvest 3 (120 DAE)	
	Stems	Tubers	Stems	Tubers	Stems	Tubers
None	84.7	397	85.4	401	76.8	363
Early	83.8	350	83.1	363	83.0	365
Mean	84.2	373	84.2	382	79.9	364
S.E. (20 D.F.)	2.08	11.4	3.09	20.8	4.32	18.1

Radiation Use Efficiency

Using data from all harvests, values of total DM production 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. radiation use efficiency as t DM/TJ) were then subjected to analysis of variance. The overall, average radiation use efficiency was 1.62 t DM/TJ and increasing the N application rate from 0 to 200 kg N/ha resulted in a small but statistically significant increase in radiation use efficiency (Table 8). Shading had a much larger effect on radiation use efficiency than N and in the unshaded crops, each TJ of energy was converted to *c.* 1.3 t DM/ha compared with 2.1 t DM/ha for those crops that were shaded for most of the season. For comparison the Estima grown in the Variety and N experiment had a season-long radiation use efficiency of 1.2 t DM/ha (p. 37). The reduced efficiency of the unshaded crops explains why they did not give much larger yields than the crops that were shaded for nearly all the season.

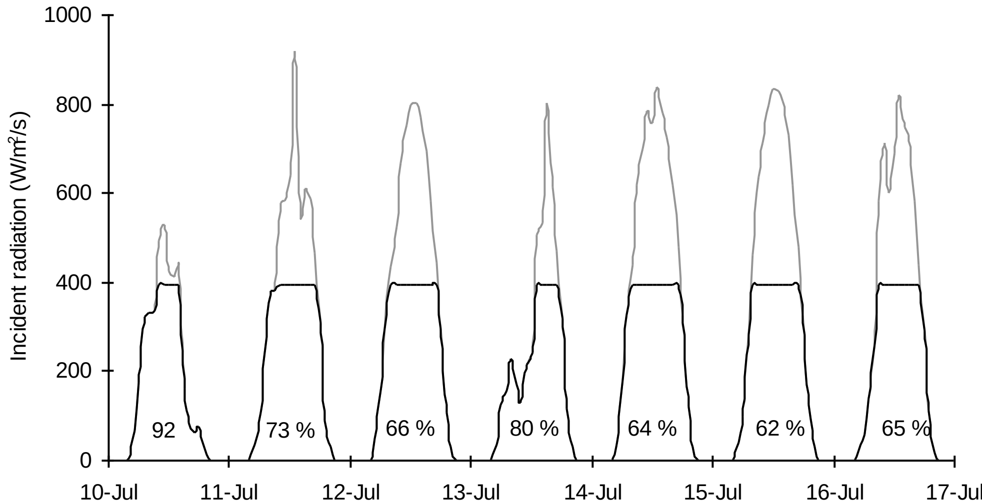
Table 8. **Effect of N application rate and shading on season-long radiation use efficiency (t DM/TJ)**

Shading	0 kg N/ha	200 kg N/ha	Mean
None-None	1.30	1.35	1.32
Early-None	1.41	1.55	1.48
None-Late	1.40	1.68	1.54
Early-Late	2.10	2.16	2.13
Mean	1.55	1.69	1.62

S.E. (20 D.F.) Nitrogen, 0.042; Shading, 0.060; Nitrogen and Shading, 0.084

These data suggest that the unshaded crops could only use a proportion of the incident radiation and on very bright days a substantial proportion of the incident radiation may be wasted. Using relationships first derived for Russet Burbank grown in a glasshouse experiment (Dwelle *et al.* 1981) and the hourly values of incident radiation for a week at CUF in July 2006, it is possible to estimate the amount of incident radiation that the crop cannot use (Figure 6). For example, the total incident radiation on 10 July was 14.21 MJ/m^2 (the area underneath the grey line) and of this the crop was able to use 13.26 MJ/m^2 (the area underneath the black line). However, 15 July was much brighter and the total incident radiation was 28.12 MJ/m^2 and of this the crop was only able to use 17.87 MJ/m^2. These relationships (and similar ones now incorporated into the CUF yield model) explain the decrease in radiation use efficiency found in California and shown in Figure 3. Furthermore, the shading experiment has shown that even under temperate UK conditions, the potato crop cannot use all the incident radiation it receives and this wastage must be taken account of in growth models if they are to be accurate.

Figure 6. **Comparison of total incident radiation (grey line), amount useable by a potato crop (black line) and percent of daily incident radiation used by the crop. Meteorological data from CUF 2006 and modified using relationship described by Dwelle *et al.* (1981).**



Nitrogen uptake and redistribution

The CUF N management model assumes that tuber N uptake is linear with respect to the amount of radiation absorbed by the crop. An objective of this experiment was to investigate the effect of changing the radiation environment (by shading) on tuber N uptake. At each harvest, N uptake by haulm and tubers was measured in each plot. Using data from each harvest, values of tuber N uptake were related to radiation absorption on a plot-by-plot basis using linear regression and the fitted parameters were tested by analysis of variance. In most cases, a linear fit against radiation absorption explained > 95 % of the variation in tuber N uptake and the regressions were always highly significant and thus, the assumption of linearity appears valid. The effects of N application rate and shading treatments on the rate of tuber N uptake are shown in Table 9. The overall average rate of tuber N uptake was 21.8 kg N/TJ and increasing the N application rate from 0 to 200 kg N/ha increased the rate of tuber N uptake from 17.7 to 25.8 kg N/TJ. The slowest rate of tuber N uptake was in the crop that was unshaded for the whole of the season and the fastest rates were associated with the late-shaded treatments. The effect of shading on the rate of tuber N uptake is explicable by considering the amount of radiation received by the crops and how efficiently it was used. For example, the unshaded crops absorbed more radiation (Table 3) but used this energy less efficiently (Table 8) and in consequence had a slower rate of N uptake per unit of energy absorbed. When combined, the net effect of the differences in radiation and radiation use efficiency on tuber N uptake at final harvest was non-significant (Table 10) and therefore these crops achieved very similar tuber N uptakes but by very different routes.

Table 9. Effect of N application rate and shading on the rate of tuber N uptake in relation to energy absorption (kg N/TJ)

Shading	0 kg N/ha	200 kg N/ha	Mean
None-None	11.4	16.6	14.0
Early-None	13.6	20.9	17.3
None-Late	21.3	34.0	27.6
Early-Late	24.6	31.7	28.1
Mean	17.7	25.8	21.8

S.E. (20 D.F.) Nitrogen, 1.07; Shading, 1.51; Nitrogen and Shading, 2.14

Table 10. Effect of N application rate and shading on tuber N uptake on 15 September (kg N/ha)

Shading	0 kg N/ha	200 kg N/ha	Mean
None-None	142	224	183
Early-None	138	220	179
None-Late	125	211	168
Early-Late	135	196	165
Mean	135	213	174

S.E. (20 D.F.) Nitrogen, 10.3; Shading, 14.5; Nitrogen and Shading, 20.5

If the amount of energy used by the crop is the key driver of N uptake and redistribution then, in principle, the relationship between the rate of tuber N uptake and energy usage should be similar irrespective of shading. Using relationships similar to those described by Dwelle *et al*. (1981), it is possible to investigate how tuber N uptake is related to energy usage by the crop (as distinct from energy absorption) and these are shown in Table 11. The rate of tuber N uptake with respect to utilized radiation was increased by applying 200 kg N/ha as was found with absorbed radiation (Table 9). However, when related to utilized radiation, the effects of shading on the rate of tuber N uptake were much smaller. These results support the hypothesis that N uptake and redistribution are largely controlled by the amount of energy used by the crop. Studies in 2007 were done to further understand these relationships to help improve our predictive systems.

Table 11. Effect of N application rate and shading on the rate of tuber N uptake in relation to energy usage (kg N/TJ)

Shading	0 kg N/ha	200 kg N/ha	Mean
None-None	19.5	28.2	23.8
Early-None	23.1	34.9	29.0
None-Late	25.0	39.1	32.1
Early-Late	27.6	36.3	32.0
Mean	23.8	34.6	29.2

S.E. (20 D.F.) Nitrogen, 1.48; Shading, 2.10; Nitrogen and Shading, 2.97

A key component of the CUF N management and yield prediction model is an accurate description of the pattern of total (haulm and tuber) N uptake. Total N uptake was analysed by fitting an exponential curve on a plot-by-plot basis of total N uptake measured at each harvest against measured radiation absorption. The fitted exponential curve was constrained to pass through the origin and the fitted parameters were then tested by analysis of variance. The overall average total N uptake was 191 kg N/ha (Table 12) and applying 200 kg N/ha increased N uptake from 148 to 235 kg N/ha. However, shading had no statistically significant effect on the estimate of the maximum amount of N taken up by the crop.

Table 12. Effect of N rate and shading on the asymptotic value of total N uptake

Shading	0 kg N/ha	200 kg N/ha	Mean
None-None	149	214	182
Early-None	150	273	212
None-Late	137	227	182
Early-Late	155	225	190
Mean	148	235	191

S.E. (20 D.F.) Nitrogen, 14.2; Shading, 20.1; Nitrogen and Shading, 28.4

Using information on the rate of tuber N uptake and the pattern of total N uptake in relation to radiation utilisation (as opposed to absorption) it is possible to estimate the point at which the rate of tuber N uptake exceeds the rate of total N uptake. At this point N starts to be withdrawn from the crop canopy, ultimately resulting in senescence. These values, as TJ/ha, can then be converted into values of DAE and these are shown in Table 13. On average, N started to be withdrawn from the canopy at *c.* 43 DAE and applying 200 kg N/ha had no significant effect on this date. The effects of shading were also small and non-significant and this lends support to the hypothesis that N uptake and redistribution is driven by the amount of energy used by the crop as opposed to the amount absorbed. Work in 2007 continued to investigate these relationships.

Table 13. Effect of N rate and shading on date (DAE) when rate of tuber N uptake exceeded rate of total N uptake (i.e. onset of senescence)

Shading	0 kg N/ha	200 kg N/ha	Mean
None-None	42	44	43
Early-None	49	42	46
None-Late	42	36	39
Early-Late	47	40	43
Mean	45	41	43

S.E. (20 D.F.) Nitrogen, 2.0; Shading, 2.8; Nitrogen and Shading, 4.0

Conclusions

This experiment has provided useful information on the inverse relationship between radiation use efficiency and the intensity of the incident radiation. The radiation use efficiency data collected in this experiment at CUF were consistent with the data collected from commercial crops grown in California and with the published work of Dwelle *et al*. (1981). This consistency implies that it is possible to accurately model crop growth in a range of environments. The N uptake and redistribution data showed that shading had little effect on the final values of tuber and total N uptake but did have an effect on the rates at which the processes of N uptake and redistribution occur. These data suggest that some of the variation in the relationships between N uptake and redistribution and radiation absorption may be removed by assessing them in terms of radiation usage.

Effect of shading and N application rate on yield and N uptake of Estima in 2007

Introduction

The shading experiment at CUF in 2006 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 2007 experiment was to gather further data on the relationship between incident radiation, radiation absorption, dry matter production and N uptake.

Materials and Methods

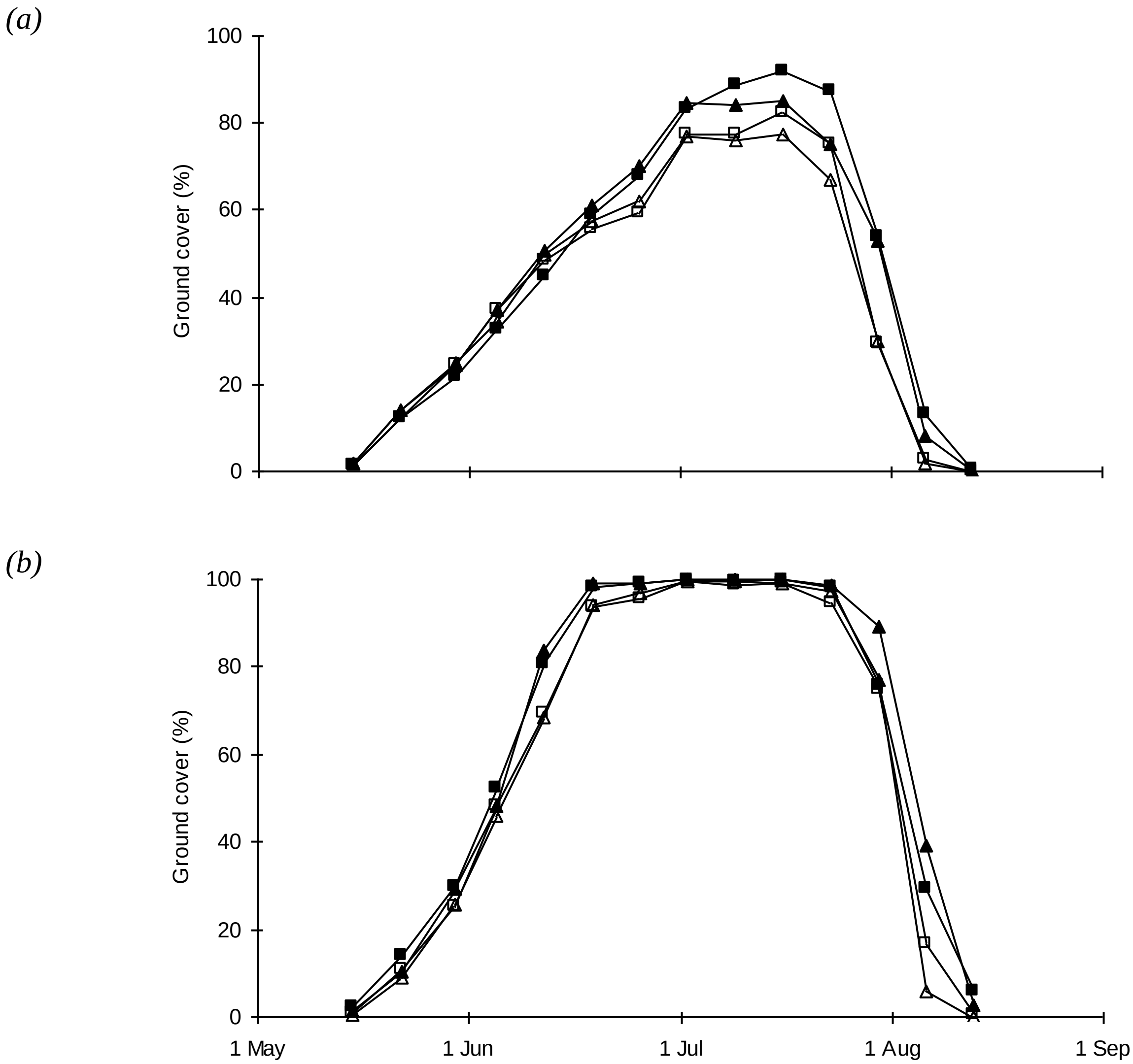
Estima seed (E1; 30-35 mm; mean weight 23.5 g) was planted by hand at 25 cm spacing into pre-formed ridges with 76.2 cm centres on 5 April. The experiment tested all combinations of early shading (none or shaded), late shading (none or shaded) and two N application rates (0 or 200 kg N/ha). Each treatment combination was replicated four times and allocated at random to blocks. Each plot was four rows (3.05 m) wide and 6 m long. Nitrogen fertilizer was applied manually in a single application of ammonium nitrate at planting which was incorporated in to the top 5 cm of soil by raking. The early shading treatments started on 6 June (*c.* 30 DAE) and the late shading treatments started on 18 July (*c.* 72 DAE). The crop was sampled on 6 July (60 DAE) and 15 August (100 DAE). A total of 98 mm of irrigation was applied. Plant emergence was recorded every 2-3 days until complete and ground covers were recorded weekly from 50 % plant emergence until complete senescence. At each harvest, ten plants (area = 1.91 m^2) were taken from the central two rows of each plot leaving a discard of at least 0.5 m from plot ends or adjacent harvested areas. The number of plants and stems was recorded and all tubers > 10 mm were collected. The weight of the haulm was recorded and a representative sub-sample (*c.* 1 kg) was removed for drying. The tubers were graded in 10 mm increments and the number and weight of tubers in each size grade was recorded. A sub-sample of tubers (*c.* 1 kg) was taken from the 50-60 mm grade, chipped and dried, together with the haulm sub-sample, at 90 °C to constant weight. The dried haulm and tubers were then sent for measurement of total N concentration at a commercial laboratory.

Results and Discussion

Emergence, ground covers and radiation absorption

The mean date of 50 % plant emergence was 7 May (32 days after planting) and nearly all plots achieved 100 % plant emergence   Nitrogen application rate had no effect on the date of 50 % emergence or percentage final emergence. The development of ground cover is shown in Figure 7 and summarised in Table 14.

Figure 7. 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, ▲.



Where no N was applied, ground cover expansion was slow and crops failed to achieve complete ground cover. Where 200 kg N/ha was applied, expansion of ground cover was much more rapid and all crops attained 100 % ground cover and maintained it for several weeks. When averaged over the shading treatments, 200 kg N/ha increased integrated ground cover by 1700 %days (equivalent to an extra 17 days at complete ground cover). The early-shaded treatments had significantly more persistent canopies than the unshaded as was found in 2006. 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 5.64 to 7.87 TJ/ha (Table 14). On average, early shading reduced the amount of radiation absorbed by the crop by 1.79 TJ/ha and late shading by 1.10 TJ/ha. Early and late shading reduced the amount of radiation absorbed by 2.90 TJ/ha when compared with crops that were unshaded through the season.

Table 14. Effect of N application rate and shading on integrated ground cover and radiation absorption

	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	4074	5774	6.71	9.65
Early-None	4604	6162	5.50	7.38
None-Late	4011	5724	5.93	8.34
Early-Late	4538	6286	4.40	6.12
Mean	4307	5987	5.64	7.87
S.E. (21 D.F.)	N, 81.0; N and Shade, 162.0		N, 0.117; N and Shade, 0.235	

Yields at the first and second harvests

The number of stems was not affected by N application rate at either harvest (Table 15). However, at both harvests, increasing the N application rate from 0 to 200 kg N/ha increased the number of tubers set and retained per stem and this caused a significant increase in the tuber population. Shading had no statistically significant effect on stem or tuber populations. The increase in the number of tubers set and retained per stem when 200 kg N/ha had been applied is consistent with a larger canopy and growth rate at the time of tuber initiation (*c.* 21-28 DAE).

Table 15. Main effect of N fertilizer on number of stems, tubers > 10 mm per stem and number of tubers > 10 mm

	Harvest 6 July			Harvest 15 August		
	0 kg N/ha	200 kg N/ha	S.E.	0 kg N/ha	200 kg N/ha	S.E.
Above–ground stems (000/ha)	105	108	4.0	98	103	3.4
Tuber per stem	3.71	3.98	0.131	3.81	4.13	0.154
Tubers > 10 mm (000/ha)	385	426	12.0	371	418	13.6

At the first sampling (6 July, 60 DAE), the mean total DW and tuber FW yields were 6.62 and 27.5 t/ha, respectively (Table 16). Total dry weight and tuber yields were significantly increased by the application of 200 kg N/ha. When averaged over all other factors, early shading reduced total DW yield from 7.22 to 6.01 t/ha and tuber FW yield from 30.3 to 24.8 t/ha. The final crop sample was taken on 15 August (100 DAE) when the canopies of all treatments had completely senesced. The overall average total DM yield was 8.99 t/ha and the tuber FW yield was 38.8 t/ha (Table 17). In 2006, the average total DM and tuber FW yields at final harvest were 13.12 and 59.6 t/ha, respectively, showing that yields in 2007 which were much smaller than those in 2006. In 2007, when averaged over the shade treatments, applying 200 kg N/ha increased total DW yield by 5.44 t/ha and tuber FW yields by 23.7 t/ha. The corresponding increases in yields in 2006 were 3.59 and 15.7 t/ha, respectively. 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 8.99 and 38.6 t/ha, respectively, compared with yields in the unshaded (None-None) crops of 10.42 and 44.0 t/ha. Therefore, reductions in incident radiation as a result of 45 % shading reduced total DW and tuber FW yield by less than 15 %. At both harvests, 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 severely N deficient crops the ability of the leaves to use incident radiation is compromised.

Table 16. Effect of N application rate and shading on total dry matter (DM) yield and tuber fresh weight (FW) yield > 10 mm on 6 July (60 DAE)

	Total DM yield (t/ha)		Tuber FW yield (t/ha)	
Shading	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
None-None	5.62	8.93	23.3	38.6
Early-None	5.17	7.15	21.6	29.2
None-Late	5.68	8.67	23.2	36.2
Early-Late	4.99	6.73	20.6	27.7
Mean	5.37	7.87	22.2	32.9
S.E. (21 D.F.)	N, 0.135; N and Shade, 0.269		N, 0.69; N and Shade, 1.38	

Table 17. Effect of N application rate and shading on total dry matter (DM) yield and tuber fresh weight (FW) yield > 10 mm on 15 August (100 DAE)

	Total DM yield (t/ha)		Tuber FW yield (t/ha)	
Shading	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
None-None	6.84	12.86	29.8	54.6
Early-None	6.21	10.45	25.9	44.8
None-Late	5.97	12.13	25.9	53.9
Early-Late	6.05	10.27	26.1	45.5
Mean	6.27	11.43	26.9	49.7
S.E. (20 D.F.)	N, 0.182; N and Shade, 0.364		N, 0.87; N and Shade, 1.73	

Radiation Use Efficiency (RUE)

Using data from both harvests, values of total DM 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. radiation used efficiency, RUE, as t DM/TJ) were then subjected to analysis of variance. The accuracy of the estimates of RUE was compromised by there being only two harvests instead of the intended three. The overall, average RUE was 1.43 t DM/TJ (Table 18). The average RUE of the unshaded crop (1.32 TJ/ha) was similar to that found for Estima in the Variety and N Experiment (p. 49) and the Rate and Timing of N Experiment (p. 59). Increasing the N application rate from 0 to 200 kg N/ha increased the RUE from 1.28 to 1.58 t DM/TJ. This effect of N was also consistent with the effects seen in other N experiments in this season. Reducing the amount of incident radiation by shading increased RUE and this effect was particularly noticeable in the early-shaded treatments and also in those crops receiving no N fertilizer. 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.

Table 18. Effect of N application rate and shading on season-long radiation use efficiency (t DM/TJ)

	0 kg N/ha	200 kg N/ha	Mean
None-None	1.15	1.48	1.32
Early-None	1.30	1.54	1.42
None-Late	1.16	1.53	1.34
Early Late	1.52	1.76	1.64
Mean	1.28	1.58	1.43

S.E. (20 D.F.) Nitrogen 0.029; Shading 0.041; Nitrogen and Shading 0.058

Total and tuber N uptake

Values for total (tuber and haulm) N uptake at the first and second harvests are shown in Table 19. At the first harvest on the 6 July (60 DAE), increasing the N application rate from 0 to 200 kg N/ha had increased total N uptake from 68 to 141 kg N/ha. Shading had no statistically significant effect on total uptake. At the second harvest, total N uptake averaged 75 or 162 kg N/ha when 0 or 200 kg N/ha was applied, respectively. Shading had no effect on total N uptake when no N had been applied but there was some evidence that when 200 kg N/ha had been applied the unshaded crop (None-None) had a larger total N uptake than shaded crops. When averaged over the shading treatments, the increase in total N uptake between the two harvests was 7 and 21 kg N/ha where 0 or 200 kg N/ha had been applied. This supports results from many earlier experiments that show that the bulk of N uptake occurs early in the growing season. In 2006, when averaged across the shading treatments, measured values for total N uptake at final harvest were 142 or 231 kg N/ha when 0 or 200 kg N/ha had been applied, respectively. Thus, as noted in other experiments, total N uptakes in 2007 were smaller than those in 2006. The effects of N application rate on tuber N uptake at final harvest are shown in

Table 20. When averaged over all treatments the mean tuber N uptake was 94 kg N/ha (compared with 174 kg N/ha in 2006). Tuber N uptake was increased by applying N but the effects of shading were smaller and generally non-significant. Although these crops absorbed different amounts of energy and used this energy with different efficiencies, the net effect of shading on tuber N uptake was relatively small.

Table 19. Effect of N application rate and shading on total N uptake (kg N/ha) at the first and second harvests

	Harvest 1 6 July		Harvest 2 15 August	
Shading	0 kg N/ha	200 kg N/ha	0 kg N/ha	200 kg N/ha
None-None	68	142	77	174
Early-None	69	142	75	148
None-Late	66	145	79	160
Early-Late	67	134	70	164
Mean	68	141	75	162
S.E.	(21 D.F) N, 2.9; N and Shade, 5.8		(20 D.F.) N, 3.6; N and Shade, 7.1	

Table 20. Effect of N application rate and shading on tuber N uptake (kg N/ha) on 15 August (100 DAE)

	0 kg N/ha	200 kg N/ha	Mean
None-None	58	143	100
Early-None	55	113	84
None-Late	58	131	94
Early Late	53	125	89
Mean	56	128	92

S.E. (20 D.F.) Nitrogen 3.1; Shading 4.3; Nitrogen and Shading 6.1

Conclusions

The experiment has provided useful information on the relationship between the intensity of incident radiation, radiation use efficiency and yield production. Collectively, the data from experiments in 2006 and 2007 suggest that N uptake, and therefore yield potential, was not greatly affected by shading during the course of the season. It is possible that the absence of any effect due to shading is a consequence of the "early" shading treatments being applied too late. An experiment planned for 2008 will impose shading treatments much earlier in the season (from emergence) because observations made in other experiments suggest that differences in N uptake and thus canopy potentials are set much earlier in the season.

Effect of N application rate on yield and N uptake of Estima and Russet Burbank in 2006

Introduction

This experiment was similar to those done in 2004 and 2005 and had the objective of providing data with which to test the CUF N management and yield prediction models.

Material and Methods

The experiment was done at CUF. The experiment tested all combinations of two contrasting varieties (Estima and Russet Burbank) and four N application rates (0, 125, 250 and 375 kg N/ha). Each treatment combination was replicated four times and allocated at random to blocks. The experiment was planted by hand at 25 cm spacing into pre-formed ridges with 76.2 cm centres on 12 April. All seed was 25-30 mm and had counts/50 kg of 2291 for Estima (SE1) and 2549 for Russet Burbank (SE). The N fertilizer was applied by hand in one application of ammonium nitrate immediately after planting and was incorporated by raking. Each plot was four rows (3.05 m) wide and 10 m long. Plant emergence was recorded every 2-3 days until complete and ground covers were recorded weekly using a grid. The crop received a total of 155 mm irrigation. During the season five harvests (12 June, 29 June, 25 July, 11 August and 21 September) each of 10 plants (1.91 m^2) were taken to measure yield and N uptake. At each harvest, the number of stems was recorded and all tubers > 10 mm collected. The haulm was weighed in the field and a representative sub-sample (*c*. 1 kg) was taken and then dried at 90 °C to constant weight (*c*. 48 hours). The tubers were graded in 10 mm increments and the number and weight of tubers was recorded. A sub-sample of tubers (*c*. 1 kg) was taken from the 50-60 mm grade, chipped and then dried at 90 °C. The dried haulm and tubers were then sent for measurement of total N content at a commercial laboratory.

Results and Discussion

Emergence and ground covers

Both varieties achieved 50 % plant emergence on 17 May (*c*. 35 days after planting). Increasing the N application rate from 0 to 375 kg N/ha delayed the date of 50 % emergence by *c*. 3 days. With the exception of Estima receiving no N, all crops achieved ground covers in excess of 95 % (Figure 8). For both varieties, the main effect of increasing the N application rate was to delay the onset of senescence, although this effect was not very large and all canopies started to senesce by late July or early August.

The effects of variety and N application rate on season-long integrated ground cover are shown in Table 21. As might be expected from an indeterminate variety, Russet Burbank had a more persistent canopy than Estima, however the difference was not large. Increasing the amount of N applied from 0 to 325 kg N/ha increased canopy persistence by a similar amount in both varieties. The amount of radiation absorbed by the crop was related to canopy persistence (Table 22). On average, Russet Burbank absorbed *c.* 1.8 TJ/ha more than Estima, and the amount of radiation absorbed was increased by *c.* 1.9 TJ/ha by increasing the N application rate from 0 to 375 kg N/ha.

Figure 8. Ground cover development in *(a)* Estima and *(b)* Russet Burbank given 0, □; 125, ■; 250, △ or 375, ▲ kg N/ha.

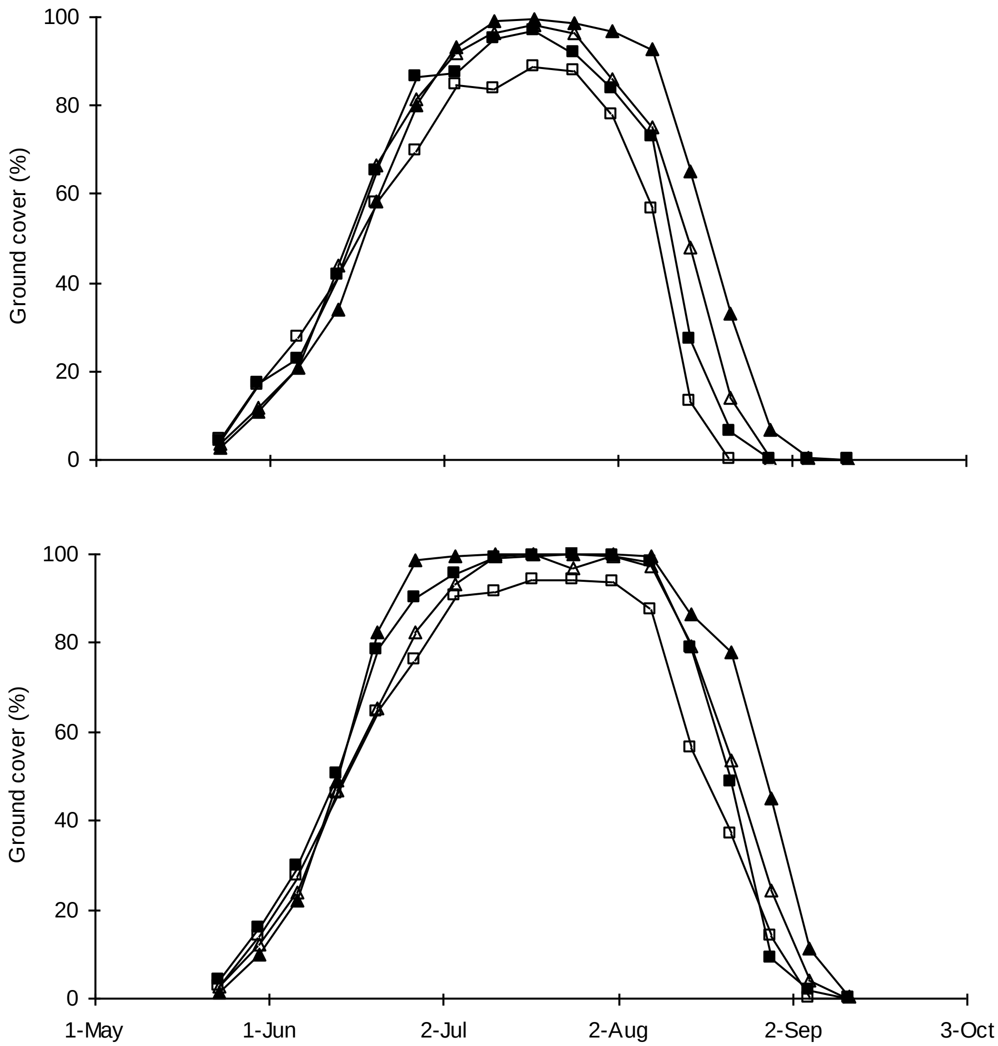


Table 21. Effects of variety and N application rate on season-long integrated ground cover (% days)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	4978	5593	5833	6243	5662
Russet Burbank	6228	6995	6876	7586	6291
Mean	5603	6294	6355	6914	6292

S.E. (21 D.F.) Variety, 167; N rate, 237; Variety and N rate, 335

Table 22. Effect of variety and N application rate on season-long radiation absorption (TJ/ha)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	9.59	10.62	10.92	11.37	10.63
Russet Burbank	11.35	12.65	12.26	13.31	12.39
Mean	10.47	11.64	11.59	12.34	11.51

S.E. (21 D.F.) Variety, 0.270; N rate, 0.382; Variety and N rate, 0.540

Yield at final harvest (21 September)

A final yield assessment was made on the 21 September (127 DAE) when all the canopies were completely senesced. The main effect of variety on the number of stems, tubers > 10 mm per stem and the number of tubers > 10 mm is shown in Table 23. The effect of N application rate on these variates was not statistically significant.

Table 23. Main effect of variety on number of stems and tubers > 10 mm and tubers per stem

	Number of stems (000/ha)	Number of tubers > 10 mm per stem	Number of tubers > 10 mm (000/ha)
Estima	83.7	4.56	379.9
Russet Burbank	77.9	3.54	274.2
Mean	80.8	4.06	327.0
S.E. (21 D.F.)	2.37	0.114	9.30

The average tuber FW yield for both varieties was 51.8 t/ha (Table 24) and for both varieties the optimum N application rate was no more than 125 kg N/ha. For Russet Burbank there was some evidence of a yield reduction when 250 or 375 kg N/ha was applied.

Table 24. Effect of variety and N application rate on tuber fresh weight yield > 10 mm (t/ha)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	46.6	56.3	53.6	56.6	53.3
Russet Burbank	41.5	57.8	49.2	52.7	50.3
Mean	44.0	57.0	51.4	54.7	51.8

S.E. (21 D.F.) Variety, 2.10; N rate, 2.98; Variety and N rate, 4.21

Efficiency of total and tuber dry matter production

Using data from the first four harvests, values of total (haulm and tuber) DM were linearly regressed against absorbed radiation on a plot-by-plot basis. The fitted line was constrained to pass through the origin and the fitted parameters were tested by analysis of variance. The overall average radiation use efficiency was 1.19 t DM/TJ and there were no statistically significant differences due to variety or N application rate (Table 25). The radiation use efficiency of these crops was very similar to the unshaded Estima in the Shade and N experiment (p. 16).

Table 25. Effect of variety and N application rate on season-long radiation use efficiency (t DM/TJ)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	1.23	1.28	1.15	1.21	1.22
Russet Burbank	1.11	1.26	1.15	1.12	1.16
Mean	1.17	1.27	1.15	1.16	1.19

S.E. (21 D.F.) Variety, 0.031; N rate, 0.044; Variety and N rate, 0.062

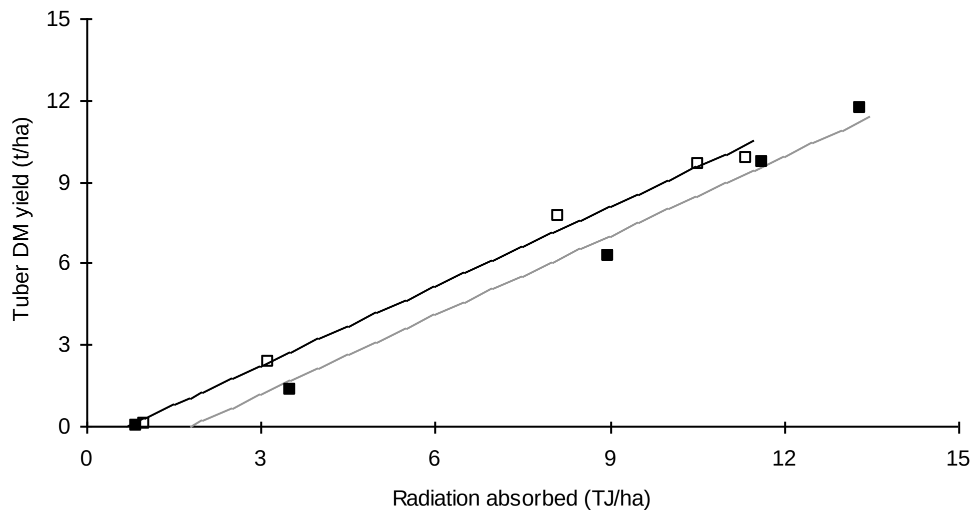
A similar process was used to study the efficiency of tuber DM production except the regression lines were not constrained to pass through the origin and values of tuber DM yield from the final harvest were also included. The efficiency of tuber DM production was not affected by either variety or N application and averaged 1.05 t tuber DM/TJ. However, the intersect of the fitted line with the x-axis (the apparent start date of tuber bulking) was significantly affected by both variety and N application rate. Thus, on average, Estima started it's linear phase of bulking once it had absorbed 0.40 TJ/ha of energy compared with 1.36 TJ/ha for Russet Burbank. Similarly, for Russet Burbank, increasing the N application rate from 0 to 375 kg N/ha delayed the onset of tuber bulking from 0.70 to 1.78 TJ/ha (Figure 9). These values for energy absorption were converted to DAE and Table 26 shows the effect of variety and N application rate on the onset of tuber bulking. For both varieties, the start of the linear phase of tuber bulking was earliest when no N had been applied and as soon as any N was applied the onset of tuber bulking was delayed by *c.* 1 week. This delay represents a significant proportion of the growing season during which the tubers are not bulking and is therefore a loss of yield potential. For some crops, the loss of one week of bulking at the start of the season can be recouped by a delay in haulm destruction at the end of the season but due to the reduction in incident radiation in the autumn, the crop may need more than an extra week of growth. This may incur increased costs due to extra blight sprays and may also push harvesting dates into increasingly cold and wet conditions. However, for relatively short season crops (salads, seed etc.) this delay may represent a significant loss of yield potential. This problem was particularly noticeable in Colorado where the growing season (emergence to haulm destruction) is curtailed by the risk of severe frosts and is only 95-100 days. Studies on tuber bulking showed that in some indeterminate varieties the delay from TI to the onset of tuber bulking with excess N was *c.* three weeks and in these cases tuber yield was undoubtedly reduced. At present we do not know what factors influence the size of this delay although variety and N application rate appear to be important. Studies continued in 2007 to improve our understanding of the relationship between TI and the onset of tuber bulking.

Table 26. Effect of variety and N application rate on estimated start date of tuber bulking (DAE)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	11.6	18.4	16.1	20.8	16.7
Russet Burbank	22.6	30.4	29.0	31.3	28.3
Mean	17.1	24.4	22.6	26.0	22.5

S.E. (21 D.F.) Variety, 1.23; N rate, 1.75; Variety and N rate, 2.47

Figure 9. Relationship between tuber DM yield and radiation absorption in Russet Burbank given 0, □ or 375, ■ kg N/ha. Black line is 0, grey line is 375 kg N/ha.



Nitrogen uptake and redistribution in relation to radiation absorption

The relationship between tuber N uptake and radiation absorption is integral to the CUF N management and yield prediction model. Nitrogen uptake data from all five harvests were analysed as described in the previous sections. In almost all cases, the linear regressions against radiation absorption were close and explained > 95 % of the variation in tuber N uptake. Increasing the N application rate from 0 to 125 kg N/ha increased the rate of tuber N uptake from 12.9 to 16.7 kg N/TJ (Table 27). Applying more N had no significant effect on the rate of tuber N uptake. When averaged over N treatments, varietal differences in the rate of tuber N uptake were small and non significant. In a similar experiment in 2005, the average rate of N uptake by Estima was 13.3 kg N/TJ compared with 11.1 for Russet Burbank. These large seasonal differences in the rate of tuber N uptake illustrate the need for field-specific measurements of tuber N uptake rather than using average values in order to estimate canopy persistence.

Table 27. Effect of variety and N application rate on rate of tuber N uptake (kg N/TJ) in relation to radiation absorption

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	14.2	16.5	16.0	17.5	16.0
Russet Burbank	11.6	16.8	15.8	15.8	15.0
Mean	12.9	16.7	15.9	16.7	15.5

S.E. (21 D.F.) Variety, 0.45; N rate, 0.63; Variety and N rate, 0.89

Using estimates of slopes and intercepts from the linear regressions, the quantity of N taken up by tubers after the crop had absorbed an arbitrary 10 TJ/ha of energy was calculated for each plot and then tested by analysis of variance. The overall, mean tuber N uptake was 140 kg N/ha (Table 28). The Estima tubers took up *c.* 20 kg/ha more N than those of Russet Burbank. Applying the first increment of N increased tuber N uptake but there were no further increases in tuber N uptake when more N was applied. For comparison, in 2005, tuber N uptake for unfertilized Estima and Russet Burbank after they had absorbed 10 TJ/ha was 119 and 87 kg N/ha, respectively, and thus there is considerable seasonal variation.

Table 28. Effect of variety and N application rate on estimated tuber N uptake (kg N/ha) after the crop has absorbed 10 TJ/ha of radiation

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	138	156	151	162	152
Russet Burbank	106	141	135	132	129
Mean	122	149	143	147	140

S.E. (21 D.F.) Variety, 3.78; N rate, 5.35; Variety and N rate, 7.57

Another key component of the CUF N management and yield model is an estimate of the maximum amount of N taken up by the haulm and tubers. As before, this was estimated by fitting an exponential curve on a plot-by-plot basis to total N uptake at each harvest. The exponential curve was constrained to pass through the origin and data from the final harvest was omitted since there was poor recovery of haulm DM resulting in an underestimate of haulm (and therefore total) N uptake. The overall, average total N uptake was 235 kg N/ha (Table 29) and increasing the N application from 0 to 375 kg N/ha increased total N uptake from 165 to 287 kg N/ha.

Table 29. Effect of variety and N application rate on estimated maximum total N uptake (kg N/ha)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	168	222	231	257	220
Russet Burbank	162	245	282	317	251
Mean	165	234	257	287	235

S.E. (21 D.F.) Variety, 7.0; N rate, 9.9; Variety and N rate, 14.0

The CUF N management and yield prediction model uses information on the rate of tuber N uptake and on total N uptake, in relation to radiation absorption, to predict canopy duration and thereby potential radiation absorption. Table 30 compares values of predicted potential radiation absorption (based on tuber and haulm N) and observed season-long radiation absorption. For Estima, the predictions are within 1 TJ/ha of observed radiation absorption and the N management model also gave an accurate description of the response to N fertilizer in this variety. For Russet Burbank, the predicted values of potential radiation absorption were similar to those observed when 0 or 125 kg N/ha were applied. However, when 250 or 375 kg N/ha were applied the N management model overestimated the capacity of the crop to absorb solar energy.

Table 30. Effect of variety and N application rate on predicted potential and observed radiation absorption (TJ/ha)

N applied	Estima		Russet Burbank	
(kg N/ha)	Predicted	Observed	Predicted	Observed
0	9.91	9.59	12.10	11.35
125	11.33	10.62	13.30	12.65
250	12.02	10.92	15.83	12.26
375	12.48	11.37	17.84	13.31
Mean	11.43	10.63	14.77	12.39

S.E. (21 D.F.) for predicted radiation absorption: Variety, 0.360; Variety and N rate 0.721
S.E. (21 D.F.) for observed radiation absorption: Variety, 0.270; Variety and N rate 0.540

The CUF yield model can be used to investigate why the N management model overestimated radiation absorption. Figure 10 and Figure 11 compare measured tuber FW yields of Russet Burbank with predictions from the CUF yield model. In all cases, yields predicted by the model were indistinguishable from the measured yields once the standard errors of the measured yields were taken into account. The achieved yields were therefore, entirely predictable on the basis of ground cover, incident radiation and radiation use efficiency. In consequence, since these crops were successfully modelled, it would seem that they did not suffer unduly from poor soil conditions or drought stress, factors that may have affected radiation use efficiency and are not explicitly accounted for within the yield model. Thus, the cause of the over-estimation has to be sought elsewhere.

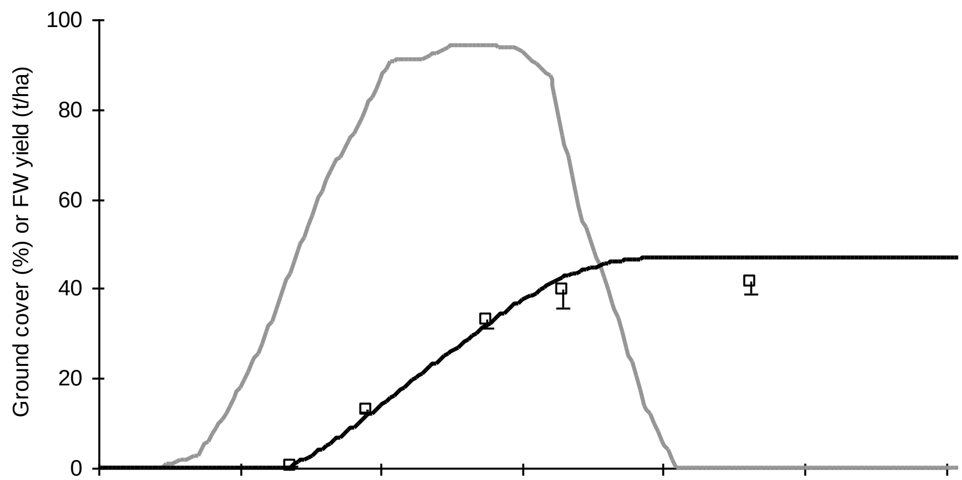
The N management model assumes that radiation absorption drives the transfer of N from the canopy to the tubers until there is no more labile N left within the canopy (i.e. it is totally senesced). The N management system will overestimate potential radiation absorption if this smooth transfer of N is disrupted. Examples of this disruption would include chemical or mechanical defoliation that control tuber size by stopping radiation absorption and, in turn, yield production. Similarly, defoliation by hail would also disrupt N transfer and result in the observed radiation absorption being less than that predicted. Studies within the US have also shown that early blight (*Alternaria solani*) can rapidly defoliate crops, disrupt N transfer and radiation absorption and may result in large yield penalties (Table 31). We are far from certain whether early blight was the cause of the overestimate of potential radiation absorption within the Variety and N experiment. However, early blight was first noted in an adjacent experiment on 18 July resulting in rapid defoliation (Shade and N Experiment, p. 16) and was also noted in other experiments in the same field at CUF. It is probable that it was also present in the Variety and N experiment. For all the Estima crops and the Russet Burbank crops receiving 0 or 125 kg N/ha, the presence of early blight appeared to have little impact on N transfer from haulm to tubers since much of it would have been transferred and the crops were already approaching complete senescence. However, for the Russet Burbank crops that received 250 or 375 kg N/ha, the arrival of early blight in late July/early August would have meant that a larger proportion of their canopy N would not have been transferred to the tubers resulting in a loss of yield potential. The onset of senescence in late July and early August followed a protracted period of high temperatures (the average maximum air temperature from 16 to 31 July was 30 °C). These high temperatures, possibly in conjunction with early blight, may also have contributed to premature canopy senescence.

Conclusions

This experiment has again shown that for many crops the optimum N application rate is relatively modest. For both Estima and Russet Burbank, the optimum N application rate was no more than 125 kg N/ha. The experiment has also provided further evidence of a delay between tuber initiation and the onset of a linear phase of tuber bulking. This delay is of agronomic significance since it may represent a significant loss of yield potential. Work continued in 2007 to understand the factors which control the extent of this delay.

Figure 10. Comparison of modelled yield (black line) and measured yield (□ and 1 S.E.) for Russet Burbank given *(a)* 0 kg N/ha *(b)* 125 kg N/ha. Grey line is ground cover.

(a)



(b)

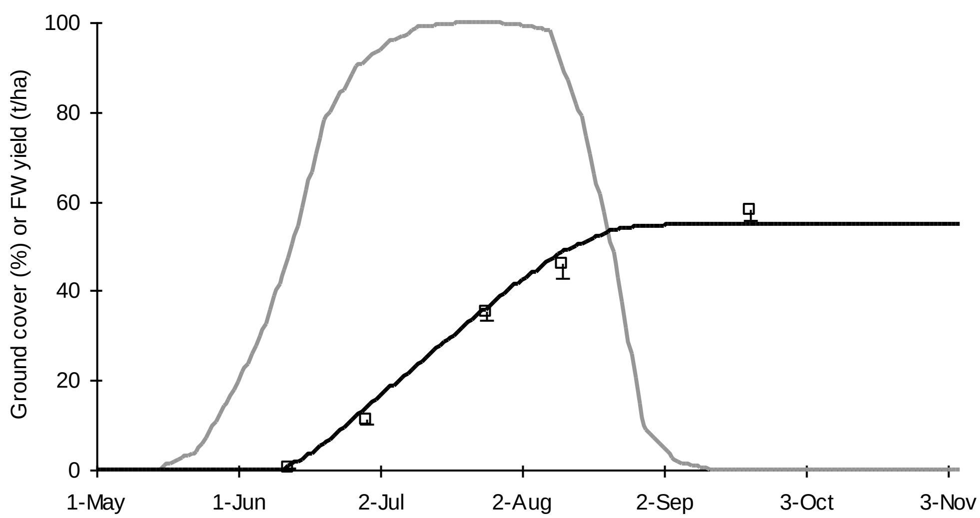


Figure 11. Comparison of modelled yield (black line) and measured yield (□ and 1 S.E.) for Russet Burbank given *(a)* 250 kg N/ha *(b)* 375 kg N/ha. Grey line is ground cover.

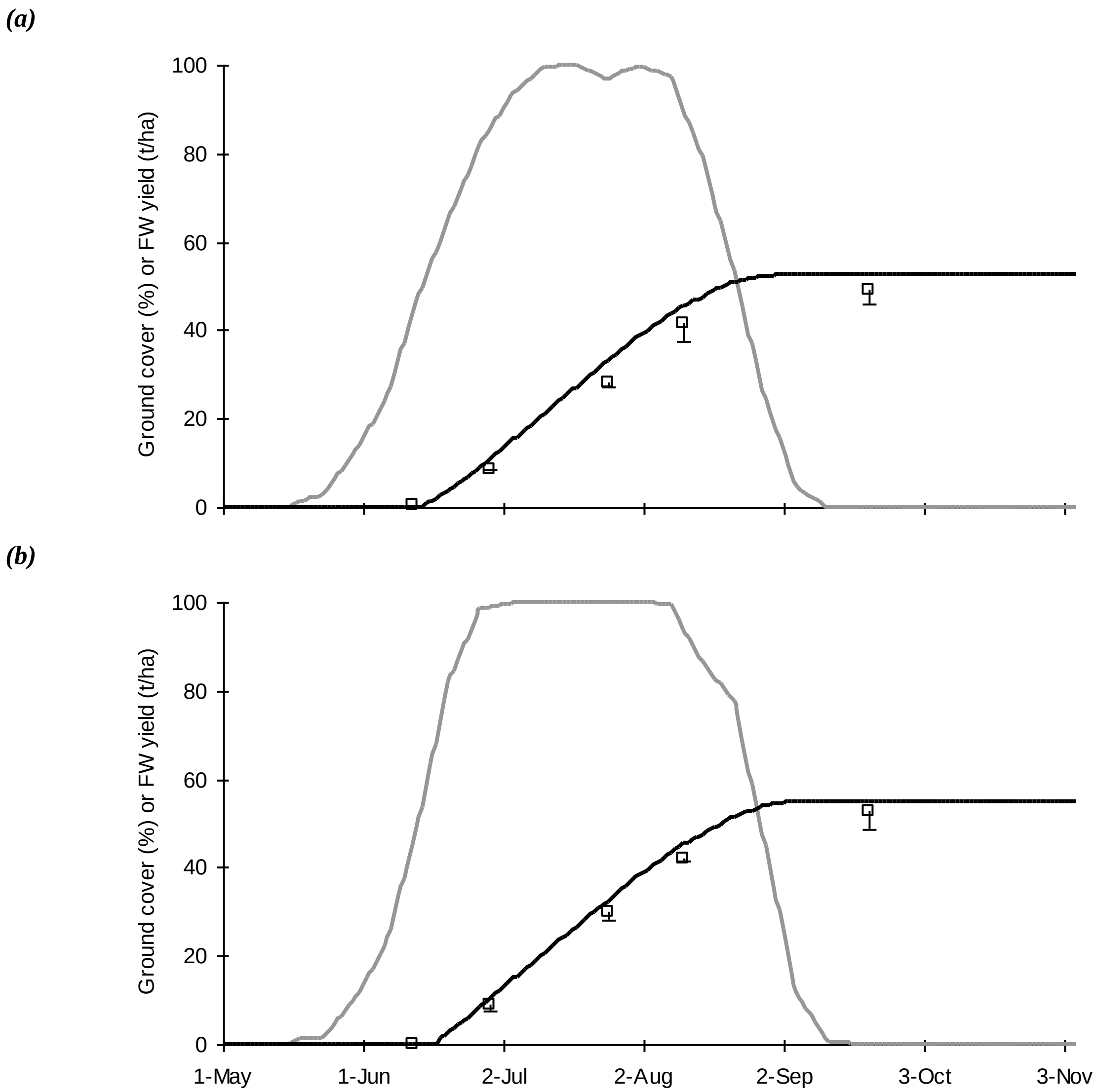


Table 31. Effect of early blight on ground cover and on tuber yield, Colorado 2006

Field	Variety	Ground cover (%) on 8 August	Ground cover (%) on 22 August	Prediction of yield made on 8 August (t FW/ha)	Achieved yield at final harvest (t FW/ha)
Circle 5	Norkotah	100	57	59	48
Circle 14	Yukon Gold	100	3	67	47
Circle 21	Centennial	99	15	66	52
Circle 37	Norkotah	100	7	65	51
Circle 43	Vokal	100	2	64	41

Effect of N application rate on yield and N uptake of Estima and Russet Burbank in 2007

Introduction

This experiment was similar in design and scope to those done in 2004-2006. The main objective of the experiment was to provide data with which to validate modules within the CUF N management and yield prediction model. A further objective was to investigate factors that may be limiting crop yield potential.

Materials and Methods

The experiment was done at Cageside Field at CUF. The experiment tested all combination of three varieties (Estima, Russet Burbank and a new PepsiCo variety) and four N applications rates (0, 125, 250 and 375 kg N/ha). Results for the new PepsiCo variety are not given in this report and standard errors (S.E.s) are for Estima and Russet Burbank only. Each treatment combination was replicated four times and allocated at random to blocks. Plots were four rows (3.05 m) wide and 10 m long. The experiment was planted by hand at 25 cm spacing into pre-formed ridges with 76.2 cm centres on 16 April. All seed was 30-35 mm and had an average weight of 23.5 g for Estima (E1) and 25.7 g for Russet Burbank (SE3). The N fertilizer was manually applied as ammonium nitrate in one application immediately after planting and was shallowly incorporated by raking. Plant emergence was recorded every 2-3 days until complete and ground covers were recorded each week using a grid. The crop received a total of 123 mm of irrigation. During the season, five harvests (5 June, 13 June, 13 July, 13 August and 18 September) were taken to measure yields and N uptakes. At each harvest, the number of plants and above-ground stems was recorded and all tubers > 10 mm were collected. The total fresh weight of the haulm was recorded and a representative sub-sample (*c.* 1 kg) was taken. The tubers were graded in 10 mm increments and the number and weight of tubers in each size grade was recorded. A sub-sample of tubers (*c.* 1 kg) was taken from the 50-60 mm grade, washed, chipped and then dried (together with the haulm) to a constant weight at 90 °C. The dried tubers and haulm were sent to a commercial laboratory for total N concentration to be measured.

Results and Discussion

Emergence, ground covers and radiation absorption

The average date of 50 % plant emergence for Estima and Russet Burbank was 17 May (31 DAP) and 19 May (33 DAP), respectively. Increasing the N application rate from 0 to 375 kg N/ha delayed the date of 50 % plant emergence from 17 to 19 May. All treatments achieved complete or near-complete emergence. With the exception of those crops that received no fertilizer, all crops achieved ground covers in excess of 95 % (Figure 12). The effect of variety and N application rate on season-long integrated ground cover and radiation absorption are shown in Table 32 and Table 33. Canopy persistence (integrated ground cover) was significantly reduced where no N had been applied. For both Estima and Russet Burbank, integrated ground cover was significantly increased by N applications up to *c.* 250 kg N/ha. On average, Russet Burbank absorbed *c.* 2.5 TJ/ha more energy than Estima and, for both varieties, the amount of radiation absorbed was maximised by N applications of *c.* 250 kg N/ha.

Table 32. Effects of variety and N application rate on season-long integrated ground cover (% days)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	3430	5391	5549	6000	5092
Russet Burbank	5019	6734	7509	7782	6761
Mean	4225	6062	6529	6891	5927

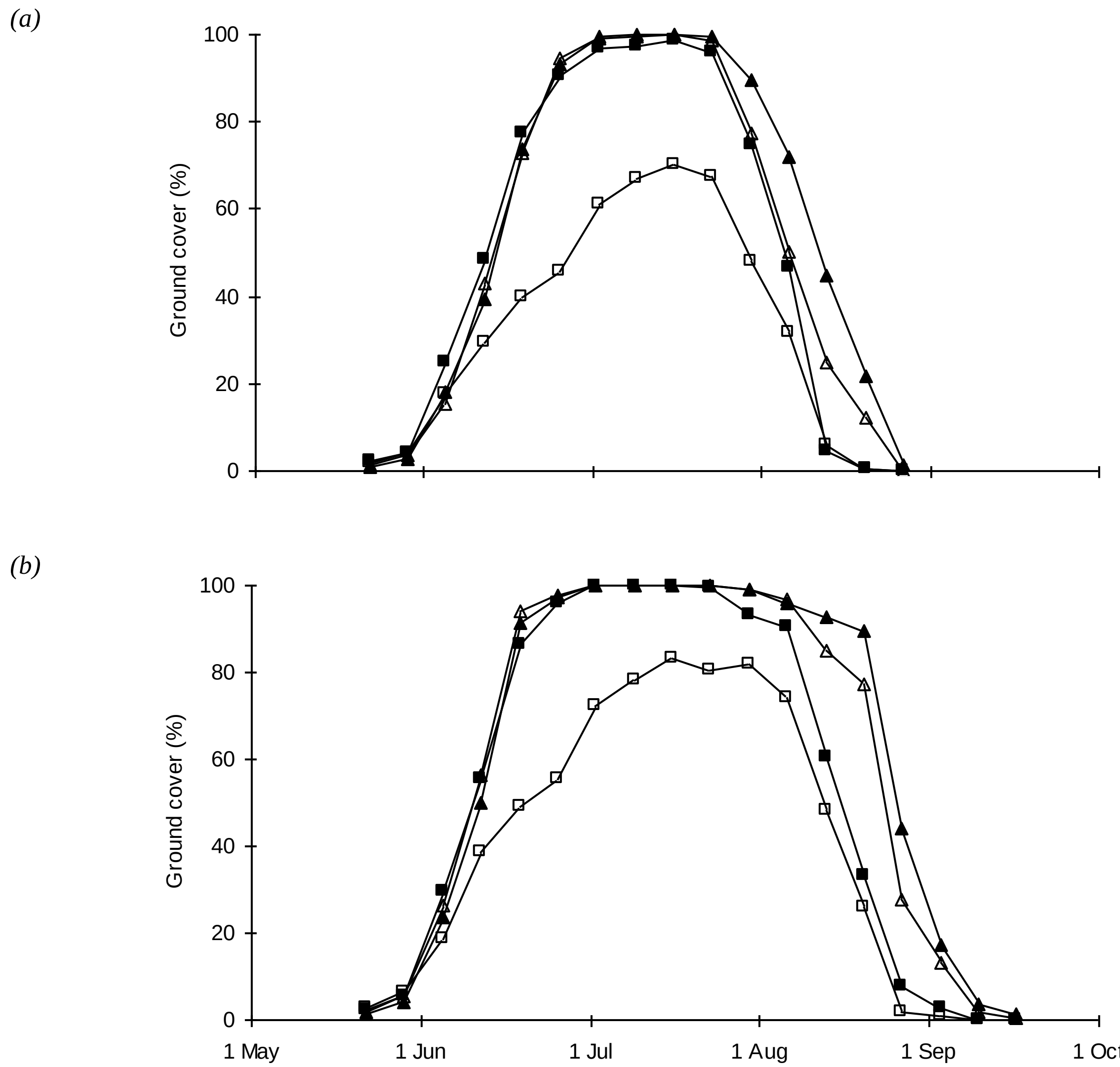
S.E. (21 D.F.) Variety, 105.1; N rate, 148.6; Variety and N rate 210.2

Table 33. Effect of variety and N application rate on season-long radiation absorption (TJ/ha)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	5.77	9.11	9.25	9.99	8.53
Russet Burbank	8.33	11.14	12.11	12.39	10.99
Mean	7.05	10.12	10.68	11.19	9.76

S.E. (21 D.F.) Variety, 0.170; N rate, 0.241; Variety and N rate 0.341

Figure 12. Ground cover development in (*a*) Estima and (*b*) Russet Burbank given 0, □; 125, ■; 250, △ or 375, ▲ kg N/ha.



Yield at final harvest 18 September

A final yield assessment was made on the 18 September (*c.* 124 DAE) when the canopies of all treatments had completely senesced. The main effect of variety on the number of stems, tubers > 10 mm per stem and the number of tubers > 10 mm is shown in Table 34. Estima had a slightly larger tuber population than Russet Burbank as a consequence of setting and retaining more tubers per stem. Increasing the N application rate from 0 to 375 kg N/ha had no significant effect on any of these variates.

Table 34. Main effect of variety on number of stems and tubers > 10 mm and tubers per stem

	Number of above-ground stems (000/ha)	Number of tubers > 10 mm per stem	Number of tubers > 10 mm (000/ha)
Estima	107	3.51	371
Russet Burbank	111	3.02	333
S.E. (21 D.F.)	3.3	0.126	11.1

The average tuber FW yield > 10 mm for both varieties was 47.9 t/ha (Table 35) compared with 51.8 t/ha in 2006. When no N had been applied, the average yield for both varieties was only 28.5 t FW/ha compared with 44.0 t/ha in 2006 and 45.3 t/ha in 2005. When averaged over all N application rates, both Estima and Russet Burbank produced similar yields. The yield increase in response to the first increment (125 kg/ha) of N was 18.9 t FW/ha. For the second and third increments of N, the yield increases were 6.2 and 8.6 t/ha, respectively. Owing to the limited number of N application rates tested, the optimum N application rate cannot be defined with certainty but for both varieties it was *c.* 250 kg N/ha. In 2006, the optimum N application in the Variety and N experiment was *c.* 125 kg N/ha. Thus the response to fertilizer was larger but yields were smaller in 2007 compared with 2006.

Table 35. Effect of variety and N application rate on tuber FW yield > 10 mm (t/ha)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	24.1	44.3	51.4	63.9	45.9
Russet Burbank	32.8	50.5	55.8	60.5	49.9
Mean	28.5	47.4	53.6	62.2	47.9

S.E. (21 D.F.) Variety, 1.69; N rate, 2.39; Variety and N rate 3.38

Efficiency of total and tuber dry matter production

The efficiency with which a crop converts absorbed radiation into dry matter is a key step in yield production. Using data from the first four harvests, values of total (i.e. tuber and haulm) DM yield were linearly regressed against radiation absorption on a plot-by-plot basis. The final harvest was omitted from the analysis due to difficulties in recovering haulm from senesced plants. The fitted line was constrained to pass through the origin and the fitted parameters were subject to analysis of variance. The slope of this relationship is an estimate of season-long radiation use efficiency (RUE). The average RUE for all treatments was 1.30 t DM/TJ (Table 36) and this value is typical for crops grown at CUF. Differences between Estima and Russet Burbank were small and non-significant, however in the absence of any N fertilizer the RUE was smaller than where N had been applied.

Table 36. Effect of variety and N application rate on season-long radiation use efficiency (t DM/TJ)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	1.06	1.20	1.42	1.48	1.29
Russet Burbank	1.20	1.36	1.34	1.33	1.31
Mean	1.13	1.28	1.38	1.40	1.30

S.E. (21 D.F.) Variety, 0.026; N rate, 0.036; Variety and N rate 0.051

A similar analysis was used to investigate the efficiency of tuber DM production except in this case the linear regression used data from all five harvests and the regression line was not constrained to pass through the origin. The average efficiency of tuber DM production was 1.15 t DM/ha and whilst there were some statistically significant differences between varieties and N application rates, these were generally small. The intersect of the fitted line with the x-axis (the apparent start of tuber bulking) was significantly affected by both variety and N application rate. Thus, on average, Estima started the linear phase of bulking once it had had absorbed *c.* 0.27 TJ/ha of energy compared with 0.56 TJ/ha for Russet Burbank. Similarly, increasing the N application rate from 0 to 375 kg N/ha delayed the start date of tuber bulking from 0.18 to 0.60 TJ/ha. These values for energy absorption were converted to DAE and are shown in Table 37. For both Estima and Russet Burbank, the apparent start of the linear phase of tuber bulking was earliest when no N had been applied. Applying N fertilizer delayed the start of tuber bulking by 1 to 2 weeks when 250 kg N/ha had been applied. In 2006, the effects of N fertilizer on the interval between crop emergence and the onset of tuber bulking were similar. As noted in 2006, a delay in bulking of one week represents a significant proportion of the growing season, particularly for short-season salad and seed potato crops. In conjunction with Farming Technologies, where the delay in tuber bulking is often much longer and is a large part of the potential growing season, an investigation is currently underway to determine the factors that influence the onset of bulking.

Table 37. Effect of variety and N application rate on estimated start date (DAE) of tuber bulking

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	15.0	19.8	22.0	21.8	19.6
Russet Burbank	10.3	21.3	26.0	26.3	23.4
Mean	17.6	20.5	24.0	24.0	21.5

S.E. (21 D.F.) Variety, 0.70; N rate, 0.98; Variety and N rate 1.39

Nitrogen uptake and redistribution in relation to radiation absorption

Ongoing work at CUF has shown that N uptake from the soil and redistribution within the crop is driven by the absorption of solar energy. 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 haulm are depleted and this is the major 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). When averaged over all N treatments, Estima had a faster rate of tuber N uptake than Russet Burbank (Table 38). Varietal differences in tuber N uptake rate explain many of the differences in canopy persistence between determinate and indeterminate varieties. Increasing the N application rate from 0 to 375 kg N/ha increased the rate of tuber N uptake in both varieties. The increase in the rate of tuber N uptake in response to fertilizer N is the reason why adding large amount of N fertilizer sometimes results in only modest increases in canopy persistence.

Table 38. Effect of variety and N application rate on rate of tuber N uptake in relation to radiation absorption (kg N/TJ)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	8.6	11.8	16.6	18.2	13.8
Russet Burbank	9.6	11.5	13.1	15.4	12.4
Mean	9.1	11.6	14.8	16.8	13.1

S.E. (21 D.F.) Variety, 0.29; N rate, 0.40; Variety and N rate 0.57

The second component of the CUF N model is an estimate of the maximum amount of N taken up by the crop. This was estimated by fitting an exponential curve to total N uptake in relation to radiation absorbed. The curve was constrained to pass through the origin. The final harvest was omitted from the analysis since total matter yield and N uptake is often underestimated due to incomplete recovery of all the haulm. The fitted asymptotic value is assumed to be equivalent to the maximum total N uptake. The average total N uptake was 165 kg N/ha (Table 39) and increasing the N application rate from 0 to 375 kg N/ha increased total N uptake from 95 to 232 kg N/ha. The maximum total N uptake of Estima receiving no N fertilizer was only 63 kg N/ha compared with 127 kg N/ha for Russet Burbank.

Table 39. Effect of variety and N application rate on estimated maximum total N uptake (kg N/ha)

	0 kg N/ha	125 kg N/ha	250 kg N/ha	375 kg N/ha	Mean
Estima	63	130	189	233	154
Russet Burbank	127	156	195	230	177
Mean	95	143	192	232	165

S.E. (21 D.F.) Variety, 7.0; N rate, 10.0; Variety and N rate 14.1

Using information on the rate of tuber N uptake (Table 38) and maximum total N uptake (Table 39) it is possible to predict canopy duration and, in turn, potential radiation absorption and yield. Table 40 compares values of predicted potential radiation absorption (based on measurements of tuber and total N uptake) and observed radiation absorption. For Estima, the predicted values were similar to those observed and were generally within *c.* 0.5 TJ/ha. For Russet Burbank, the predicted values were also close to those observed except when no N was applied where the predicted values were too large. This error was due to an overestimate of total N uptake in one plot of Russet Burbank.

Table 40. Comparison of predicted and observed radiation absorption for Estima and Russet Burbank

N applied (kg N/ha)	Estima		Russet Burbank	
	Predicted	Observed	Predicted	Observed
0	6.03	5.77	10.92	8.33
125	9.01	9.11	11.27	11.14
250	9.45	9.25	12.52	12.11
375	10.74	9.99	12.64	12.39
Mean	8.81	8.53	11.84	10.99

S.E. (21 D.F.) for predicted radiation absorption: Variety, 0.395; Variety and N rate, 0.789

S.E. (21 D.F.) for observed radiation absorption: Variety, 0.170; Variety and N rate, 0.341

Season and site variation in N nutrition

In a similar experiment in 2006, the optimum N application rate for both Estima and Russet Burbank was *c.* 125 kg N/ha, whilst in 2007 the optimum was much closer to 250 kg N/ha. Similarly, in 2006 the optimum N application rate for irrigated Estima in the CUF Reference Crop was 75 kg N/ha and this gave a tuber yield of 67.7 t/ha compared with an optimum N application rate and tuber FW yield in 2007 of 180 kg N/ha and 52.7 t/ha, respectively. Thus crops grown with similar agronomy on similar soils show large ranges in their fertilizer requirement and their tuber yield when given the optimum amount of N. It is probable that seasonal variation in yield and response to N fertilizer is due, in part, to variation in crop N uptake and N partitioning between canopy and tubers. The effects of variety and season on the quantity of N taken up by the tubers after the crop had absorbed 6 TJ/ha of radiation (i.e. at *c.* 60 DAE) are shown in Table 41. For Russet Burbank, tuber N uptake was reasonably consistent over all four seasons and averaged 56 kg N/ha, however, tuber N uptake in Estima averaged 75 kg N/ha in 2004-2006 but only 51 kg N/ha in 2007. Similarly, Table 42 compares maximum total N uptake of unfertilized crops and these data give an indication of the effective soil N supply of the fields in which these crops were grown and it is noticeable that the maximum total N uptake in 2007 was much smaller than in previous seasons especially in Estima. The variation in total N uptake is significant since it will affect the yield potential of the crop and also affect the optimum N application rate. Understanding the causes of this variation is important if we want to improve the precision of N fertilizer recommendations.

Table 41. Effect of variety and season on estimated tuber N uptake (kg N/ha) after the crop has absorbed an arbitrary 6 TJ/ha of radiation. Crops received no N fertilizer

	2004	2005	2006	2007
Estima	70	74	81	51
Russet Burbank	57	53	60	54
Mean	64	64	71	53
S.E.	3.1	3.6	4.4	3.0

Table 42. Effect of variety and season on estimated maximum total N uptake (kg N/ha) for crops that received no N fertilizer

	2004	2005	2006	2007
Estima	147	190	168	63
Russet Burbank	152	114	162	127
Mean	150	152	165	95
S.E.	15.3	9.5	14.0	14.1

A factor that could be important in determining maximum N uptake and response to N fertilizer is the quantity of soil mineral N available to the crop. Unfortunately we do not have many reliable data to test this hypothesis, however previous work (CUPGRA Annual Report for 2003, pp. 109-115) showed that measurements of soil mineral nitrogen at planting or crop emergence were poor predictors of fertilizer N requirement. Thus, variation in the quantity of soil mineral N at CUF is probably not a major cause of variation in crop N uptake. It is probable that the seasonal variation in total N uptake was due to difference in root activity as a result of difference in soil conditions. An experiment in 2006 on soil conditions (p. 66) showed that total N uptake and, in consequence, yield potential was reduced when the crop was grown in unirrigated or soil cultivated whilst wet (Table 53 and Table 55).

Table 43. Main effects of cultivation and irrigation treatments on maximum total N uptake and yield at final harvest of Maris Piper. CUF 2006

	Crop rainfed		Crop irrigated		Mean	
	kg N/ha	t FW/ha	kg N/ha	t FW/ha	kg N/ha	t FW/ha
Soil cultivated when wet	204	41.8	228	51.9	216	46.9
Soil cultivated when dry	215	50.0	268	64.4	243	57.2
Mean	210	45.9	249	58.1	229	52.0

S.E. (6 D.F.) for N uptake: Cultivation 11.7; Irrigation 11.7; Cultivation and Irrigation 16.6

S.E. (6 D.F.) for tuber yield: Cultivation 2.94; Irrigation 2.94; Cultivation and Irrigation 4.15

Soil conditions in 2007 were generally good but due to the dry April and early May, crop growth before and just after emergence may have been hampered by dry and cloddy seed bed conditions. Incident radiation in May 2007 was less than the long term average (4.36 compared with 5.10 TJ/ha) and this may have reduced the rate of crop growth and N uptake. In consequence, although there may have sufficient soil mineral N to produce crops with an adequate potential the crop was unable to take up this N efficiently.

Conclusions

Work will continue in 2008 to investigate soil factors that impair crop N uptake, limit crop potential and increase N fertilizer requirement. A component of this work will be to quantify what constitutes “good” or “poor” soil conditions. Once this is done it may be possible to modify fertilizer application in response to soil and environmental conditions.

Effects of timing and rate of N application on yield of Estima in 2007

Introduction

The CUF N management model has shown itself to be useful in understanding how the yield potential of a crop is created. At its simplest, the yield potential of a crop is related to the size of its N reserves created early in the season (i.e. total N uptake) and the rate at which these reserves are depleted by the growing tubers later in the season (i.e. the rate of tuber N uptake). The principal objective of this experiment was to investigate the effects of varying the time and rate of N applications on total N uptake and rate of tuber N uptake and thus the effects of the N treatments on potential yield. A practical outcome of this experiment would be to help define the latest date at which N applied to a potato crop could be expected to increase N uptake and yield.

Materials and Methods

The experiment was done in Cageside Field, CUF. Estima seed (E1; 30-35 mm; 23.5 g) was planted at 25 cm spacing into pre-formed ridges with 76.2 cm centres on 11 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 44. Each treatment combination was replicated four times and allocated at random to blocks. Each plot was eight rows (6.10 m) wide and 4 m long. Nitrogen applications at planting were made using ammonium nitrate broadcast by hand onto the ridges and then incorporated by raking. Within-season applications were made using a urea and ammonium nitrate solution applied with tractor-mounted sprayer. The sprayer was calibrated to apply 15 kg N/ha in 447 l/ha water per pass and two passes of the tractor and sprayer was used to apply 30 kg N/ha. Immediately after the N was applied a small quantity (*c.* 10 mm) of irrigation water was applied to minimise the risk of fertilizer scorch.

Table 44. Summary of N application timings and rates

Date (DAE)	Nitrogen applied (kg N/ha)							
11 April (-)	60	45	30	15	120	90	60	30
4 June (24)	0	15	15	15	0	30	30	30
21 June (41)	0	0	15	15	0	0	30	30
11 July (61)	0	0	0	15	0	0	0	30
Total applied	60	60	60	60	120	120	120	120
Treatment code	T1-60	T2-60	T3-60	T4-60	T1-120	T2-120	T3-120	T4-120

Plant emergence was measured in each plot every three to four days until complete and ground covers were measured weekly using a grid. The crop was sampled on four occasions (11 June, 3 July, 30 July and 17 August). At each harvest, ten plants (area = 1.91 m^2) were taken from guarded areas within each plot. The number of plants and total number of stems was recorded and all tubers > 10 mm were collected. The total haulm fresh weight was recorded and a representative sub-sample (*c.* 1 kg) was then removed. 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 removed and then dried, together with the haulm, to constant weight (usually 48 hours) 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 to 116 mm of irrigation during the growing season.

Results and Discussion

Emergence, ground cover and radiation absorption

The N treatments had no effect on the date of 50 % emergence which averaged 11 May (30 days after planting) and complete emergence was obtained in nearly all plots. The development of ground cover for selected treatments is shown in Figure 13 and summarised in Table 45. Increasing the total amount of N applied from 60 to 120 kg N/ha increased season-long integrated ground cover and radiation absorption. Applying 60 or 120 kg N/ha as four equal splits (i.e. T4) significantly decreased integrated ground cover and radiation absorption when compared with T1, T2 and T3. There was no disadvantage from applying all the N at planting (i.e. T1) compared with T2 or T3.

Figure 13. Effect of time and rate of N application on ground cover development. Key: T1-60, □; T4-60, ■; T1-120, △ and T4-120, ▲.

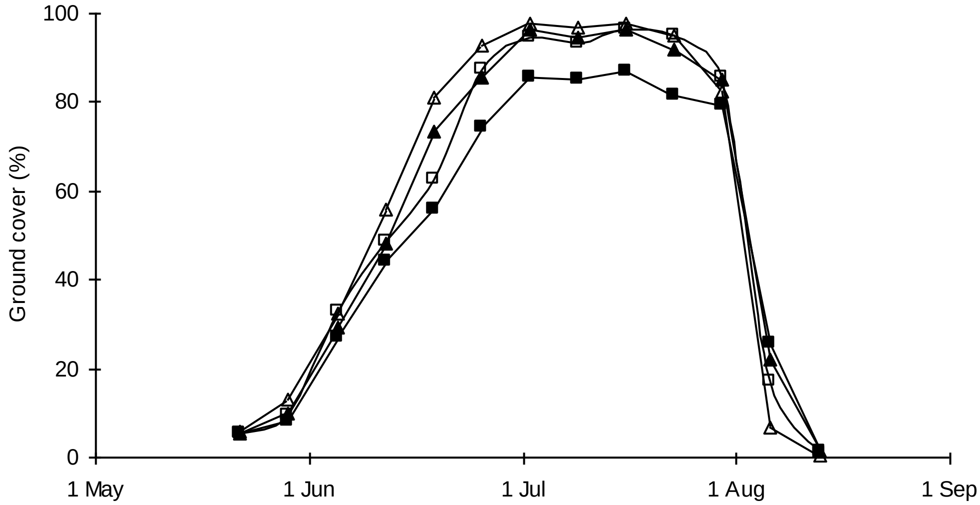


Table 45. Effect of time and rate of N application on season-long integrated ground cover and radiation absorption

	Integrated ground cover (% days)			Radiation absorbed (TJ/ha)		
Timing	60 kg N/ha	120 kg N/ha	Mean	60 kg N/ha	120 kg N/ha	Mean
T1	5122	5331	5226	8.59	8.91	8.75
T2	5147	5360	5253	8.61	8.98	8.80
T3	4953	5355	5154	8.34	8.98	8.66
T4	4645	5192	4918	7.82	8.73	8.27
Mean	4967	5309	5138	8.34	8.90	8.62
S.E. (21 D.F.)	53.7 (N); 75.9 (Timing); 107.4 (Timing and N)			0.092 (N); 0.130 (Timing); 0.184 (Timing and N)		

Tuber fresh weight yields

The number of above-ground stems and number of tuber > 10 mm remained stable throughout the course of the season (Table 46) and were not affected by timing or rate of N application.

Table 46. Mean number of stems and tubers at each harvest

	Harvest 1 (11 June)	Harvest 2 (3 July)	Harvest 3 (30 July)	Harvest 4 (17 August)
Total number of stems (000/ha)	106 ± 12.7	108 ± 10.8	107 ± 12.0	106 ± 11.6
Number of tubers > 10 mm (000/ha)	418 ± 48.4	426 ± 46.8	391 ± 56.7	431 ± 36.4

At the first harvest (11 June, 31 DAE), the mean tuber FW yield was 3.8 t/ha and was not affected by either timing or rate of N application (Table 47). At the second harvest (3 July, 53 DAE), the average yield had increased to 27.3 t/ha. Overall, yields were significantly larger with 120 kg N/ha than with 60 kg. At the third harvest (30 July, 80 DAE), the average total tuber FW yield had increased to 40 t/ha (Table 48). Yields were significantly larger when 120 kg N/ha had been applied compared with 60 kg and there was a small but statistically significant yield benefit from the T2 treatment i.e. splitting the N applications 75 % at planting and the remainder at *c.* 24 DAE. More complex splits (i.e. T3 and T4) were no better than applying the entire N requirement at planting (T1). The final harvest was taken on 17 August (98 DAE) when the crops had completely senesced. The average yield at this harvest was 45 t/ha. Increasing the total N application rate from 60 to 120 kg N/ha increased tuber FW yield by *c.* 6 t/ha. There was no significant benefit from any of the splitting treatments.

Table 47. Effect of time and rate of N application on tuber FW yield > 10 mm (t/ha) at Harvest 1 and Harvest 2

	Harvest 1 (11 June)			Harvest 2 (3 July)		
Timing	60 kg N/ha	120 kg N/ha	Mean	60 kg N/ha	120 kg N/ha	Mean
T1	4.1	4.2	4.1	25.4	30.5	28.0
T2	3.1	3.8	3.4	23.9	29.8	26.9
T3	3.8	3.3	3.5	28.3	28.0	28.1
T4	4.1	3.7	3.9	25.8	26.5	26.1
Mean	3.8	3.7	3.8	25.9	28.7	27.3
S.E. (21 D.F.)	0.19 (N); 0.26 (Timing); 0.37 (Timing and N)			0.73 (N); 1.03 (Timing); 1.45 (Timing and N)		

Table 48. Effect of time and rate of N application on tuber FW yield > 10 mm (t/ha) at Harvest 3 and Harvest 4

	Harvest 3 (30 July)			Harvest 4 (17 August)		
Timing	60 kg N/ha	120 kg N/ha	Mean	60 kg N/ha	120 kg N/ha	Mean
T1	36.4	41.3	38.8	41.4	45.9	43.6
T2	42.3	47.1	44.7	41.7	48.4	45.0
T3	33.4	43.2	38.3	44.9	47.2	46.0
T4	33.4	43.0	38.2	40.8	50.4	45.6
Mean	36.4	43.6	40.0	42.2	48.0	45.1
S.E. (21 D.F.)	1.25 (N); 1.77 (Timing); 2.50 (Timing and N)			1.10 (N); 1.56 (Timing); 2.21 (Timing and N)		

Radiation use efficiency

Using data from all four harvests, values of total dry matter yield were regressed against radiation absorption on a plot-by-plot basis. The fitted parameters were subjected to analysis of variance. The slope of the regression line is a measure of radiation use efficiency (RUE). When averaged over all treatments, whole-season RUE was 1.30 (± 0.077) t/TJ. The timing of N application had no effect on RUE but increasing the amount of N applied from 60 to 120 kg N/ha resulted in a small but significant increase in RUE from 1.26 to 1.34 t/TJ.

Nitrogen Uptake

The CUF N management model shows that the yield potential of a crop is related to maximum total N uptake and the rate at which growing tubers use reserves of N. Regression analysis of individual plot data from all harvests showed that the average rate of tuber N uptake was 12.1 kg N/TJ (Table 49) and increasing the amount of N fertilizer applied from 60 to 120 kg N/ha increased the rate of tuber N uptake from 10.9 to 13.4 kg N/TJ. The timing of application of N fertilizer had no significant effect on the rate at which tubers took up N. Maximum total N uptake averaged 130 kg N/ha and was increased from 114 to 145 kg N/ha when the amount of N fertilizer was increased from 60 to 120 kg N/ha. These values are smaller than usually found at CUF and possible reasons for this are discussed later in this report. The timing of N application had no statistically significant effect on total N uptake, although there was some evidence that the maximum N uptake was largest for the T2 treatment (i.e. 75 % of the N applied at planting and the remainder at around tuber initiation).

Table 49. Effect of rate and timing of N application on the rate of tuber N uptake and maximum haulm N uptake

	Rate of tuber N uptake (kg N/TJ)			Maximum total N uptake (kg N/ha)		
Timing	60 kg N/ha	120 kg N/ha	Mean	60 kg N/ha	120 kg N/ha	Mean
T1	10.8	11.6	11.2	113	134	123
T2	11.0	13.2	12.1	125	157	141
T3	9.9	14.2	12.1	113	147	130
T4	11.8	14.5	13.1	106	142	124
Mean	10.9	13.4	12.1	114	145	130
S.E. (21 D.F.)	0.38 (N); 0.54 (Timing); 0.76 (Timing and N)			4.3 (N); 6.0 (Timing); 8.5 (Timing and N)		

Increasing the N application rate from 60 to 120 kg N/ha increased the maximum total N uptake by *c.* 27 %. However, the increase in N application rate increased tuber FW yield by only 13 % (42.2 to 48.0 t/ha). The apparent discrepancy is due to the increase in N application rate also causing an increase in the rate at which N is transferred from haulm to the tubers.

Conclusions

The yield increase resulting from applying an extra 60 kg N/ha was explicable in terms of increased total N uptake, canopy persistence and radiation absorption. There were no statistically significant yield benefits from applying N as multiple splits and thus applying all the N at planting would be a sensible strategy. However, there were some consistent indications that a 75 + 25 % split (T2) resulted in a larger total N uptake, a more persistent canopy, increased radiation absorption and yield. It is planned to repeat this experiment in 2008 to test whether N uptake can be increased by manipulating N supply early (< 25 DAE) in the season.

Effect of soil conditions, irrigation and N application rate on yield and N uptake of Maris Piper in 2006

Introduction

The effects of poor soil conditions on crop growth, yield, N fertilizer and water requirement have been previously studied in many experiments at CUF. Whilst these experiments have provided much useful information the interpretation of results was sometimes limited by experimental designs which precluded the study of interactions between soil conditions, water and N supply or had factors that were confounded within the experimental design. The purpose of this experiment, using a split-plot design, was to allow robust analysis of the effects of soil conditions, irrigation and N fertilizer on the growth and yield of Maris Piper. In addition, the experiment also provided material for use within the BPC Bruising Project (R263) and also allowed the effect of soil conditions on factors such as secondary growth, common scab and tuber mis-shapes to be quantified.

Materials and Methods

Experimental design

The experiment tested all combinations of two soil conditions (Cultivated-dry and Cultivated-wet); two irrigation regimes (Unirrigated and Irrigated so that soil moisture deficits did not exceed 30 mm) and four N application rates (0, 100, 200 & 300 kg N/ha). The experiment was a randomised split-plot design with three replicates containing cultivation and irrigation treatments allocated at random to mainplots and N fertilizer treatments allocated at random to sub-plots.

Cultivation and irrigation treatments

The cultivation treatments were imposed as follows. Ridges were initially drawn up using a Rumpstad Rotoridger bed-tiller working at *c.* 25 cm on 27 March. These were knocked down on 5 April using shallow spring-tining. The plots to be Cultivated-wet were irrigated with 18 mm on 6 April at 15:00 h and left to dry for 24 hours. The Rumpstad Rotoridger was then used to draw up ridges again on the whole experiment. Very uneven ridges were made in the Cultivated-wet plots so on 18 April, these were power-harrowed, avoiding the compacted layer created by the bed-tiller by cultivating only 15 cm deep. The Cultivated-wet plots were then re-ridged using a fixed-body Cousins ridger but the Cultivated-dry plots were also re-ridged at the same time to avoid any further confounding of treatments.

Overhead irrigation was applied through a boom (RST Irrigation) and hose reel (Perrot SA, SH63/280) combination. Mean irrigation amounts were estimated from 12 raingauges per irrigation treatment, situated at ground level and not shielded by foliage. Soil moisture deficits were estimated and irrigation treatments scheduled using the Cambridge University Farm Potato Irrigation Scheduling System model based on a modified Penman-Monteith evapotranspiration equation. Irrigation was applied on 10, 24 and 29 June, 5, 14, 18, 24 July and 7 August, totalling 182 mm.

Crop planting, sampling and analysis

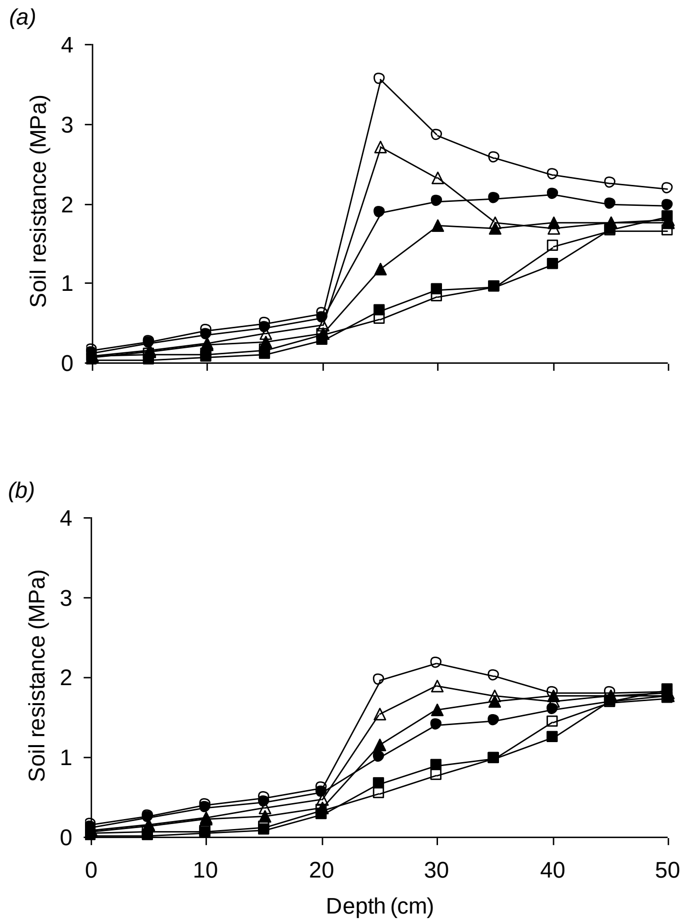
The experiment was planted by hand with Maris Piper (certification grade = AA; count = 1256/50 kg) on 20 April into pre-formed ridges with 76.2 cm centres. The within-row spacing was 25 cm, giving a plant population of 52 493/ha. Each plot was 7 m long and eight rows (6.10 m) wide. Ammonium nitrate was applied as one dressing immediately after planting and shallowly incorporated by raking. Emergence was measured every 3-4 days until complete and ground covers were measured weekly using a grid. Crop samples to measure yield and N uptake were taken on four occasions (15 June, 12 July, 14 August and 26 September). Each harvest was of 10 plants (area 1.91 m^2) and was taken from rows 2 and 3 of each plot. A two-plant discard was left between each harvest area. At each harvest, the number of plants and stems was recorded and all tubers > 10 mm collected. The haulm was weighed in the field and a representative sub-sample (*c*. 1 kg) was taken and then dried at 90 °C to constant weight (*c*. 48 hours). The tubers were graded in 10 mm increments and the number and weight of tubers within each grade was recorded. A sub-sample of tubers (*c*. 1 kg) was taken from the 50-60 mm grade, chipped and then dried at 90 °C to constant weight. The dried haulm and tubers were then sent for measurement of total N content at a commercial laboratory.

Results and Discussion

Soil Resistance

Soil resistance readings were taken using an Eijkelkamp Penetrograph penetrometer on four occasions: immediately after the primary ridge-forming cultivation treatments had taken place, at emergence and on 19 June and 17 July following dry spells (Figure 14). Immediately after rotary cultivation there was no difference in resistance between soils cultivated whilst dry or wet. There was still water draining through the profile from the pre-cultivation irrigation in the Cultivated-wet plots and this probably reduced the soil strength in the compacted zone. At emergence, significantly higher soil resistances were observed at the 20-25 cm depth where the rotary cultivator tines were working but all soils were at or above field capacity so the differences were small (data not shown). Once the soil started to dry out through root uptake of water, the differences in soil resistance between 25 and 40 cm became much more obvious, particularly in Unirrigated crops. On 19 June, at the depth of rotary cultivation (25 cm), there was an increase in resistance from 1.18 MPa in Unirrigated Cultivated-dry treatments to 2.72 MPa in Cultivated-wet plots and by 17 July, following a very hot period, this difference had increased from 1.89 MPa to 3.56 MPa (Figure 14a), a resistance well above the limit for root penetration by potatoes (Stalham *et al*. 2007). Increases in resistance from cultivating soil whilst wet extended below the depth of cultivation and down to 40 cm in Unirrigated crops. The increased resistance in compacted soil slows down rate of root penetration, thereby forcing the crop to access all of its water from shallow horizons. As the soil dries, its strength (i.e. resistance) increases and root progress is impeded further (completely stopped). The same effects on soil resistance between dry and wet soil cultivation were observed in Irrigated plots but the magnitude of the differences were smaller since the soil dried out less between irrigation events (Figure 14b).

Figure 14. Soil resistance on three occasions. *(a)* Unirrigated; *(b)* Irrigated. Cultivated-dry, 7 April, ■; Cultivated-dry, 19 June, ▲; Cultivated-dry, 17 July, ●; Cultivated-wet, 7 April, □; Cultivated-wet, 19 June, △; Cultivated-wet, 17 July, ○. Mean of four rates of N application.



Emergence and ground cover

The mean date for 50 % plant emergence was 22 May (32 days after planting). The date of 50 % plant emergence in the Cultivated-wet treatments was *c.* 2 days later than the Cultivated-dry treatments. Increasing the N application from 0 to 300 kg N/ha had no significant effect on emergence. The overall average, final plant stand was > 99 % of intended and was not affected by any treatment. The effects of soil cultivations, irrigation and selected N application rate on ground cover are shown in Figure 15. In the Cultivated-dry treatments initial canopy expansion was rapid and not markedly affected by either irrigation or N application rate. In the Cultivated-wet treatments, the poor soil condition slowed canopy expansion and this effect was only partially alleviated by irrigation and applying 200 kg N/ha. Table 50 summarises the main effect of cultivation and irrigation on the time taken to achieve 50 % ground cover.

Figure 15. Effect of soil cultivations, irrigation and N application rate on development of ground cover. *(a)* Cultivated-dry; *(b)* Cultivated-wet. Unirrigated-0 kg N/ha, □; Unirrigated-200 kg N/ha, ■; Irrigated-0 kg N/ha, △ and Irrigated-200 kg N/ha, ▲.

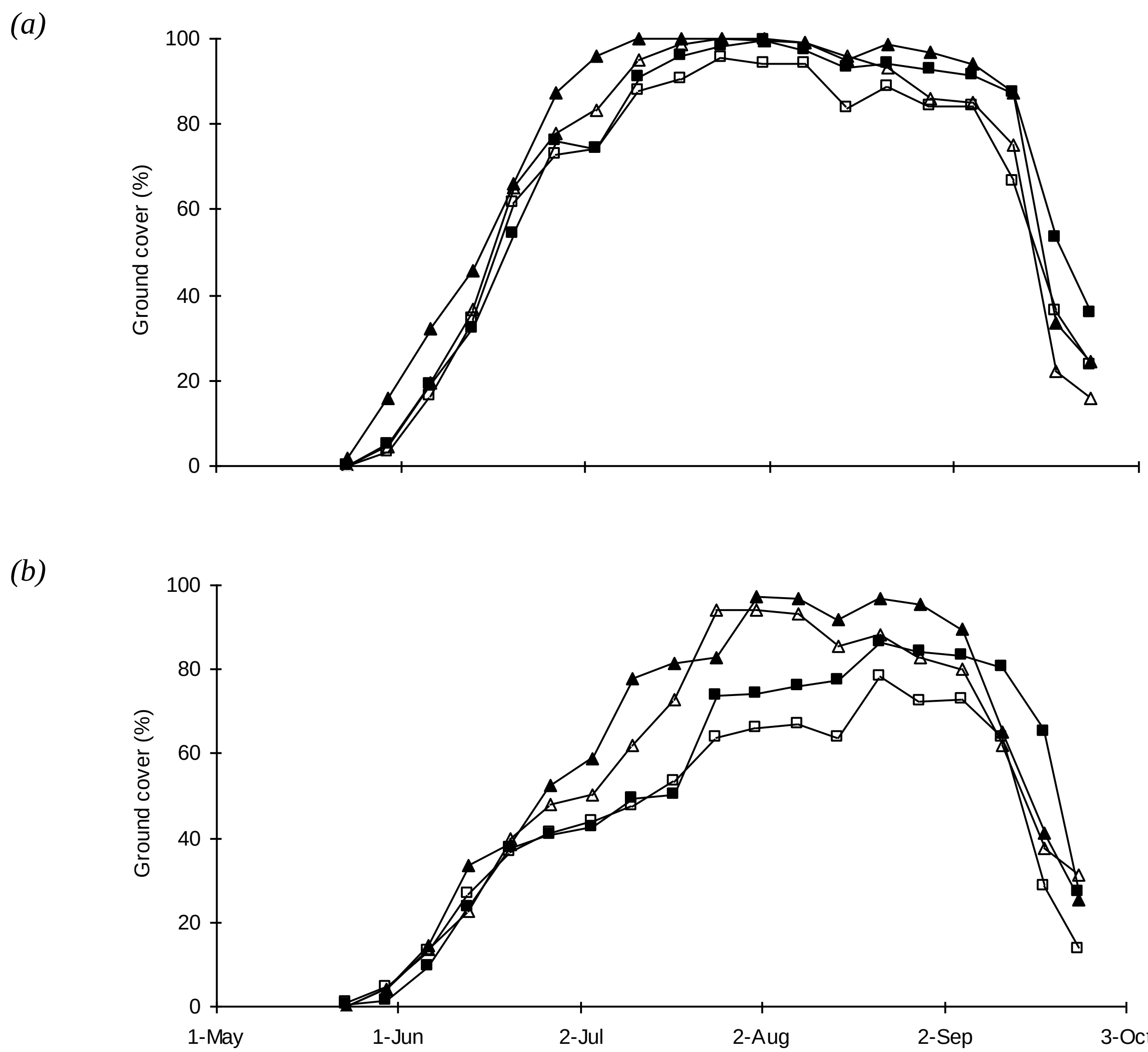


Table 50. Main effects of soil conditions and irrigation on time taken to achieve 50 % ground cover (days after emergence). Mean of four rates of N application

	Irrigated	Unirrigated	Mean
Cultivated-dry	25.2	25.9	25.6
Cultivated-wet	34.8	47.7	41.2
Mean	30.0	36.8	33.4

S.E. (6 D.F.) Cult, 1.56; Irrig, 1.56; Cult and Irrig, 2.20

The effects of soil conditions, irrigation and N application rate on season-long integrated ground cover are shown in Table 51. The crops were soil was cultivated dry had the most persistent ground covers. Crops that received irrigation had more persistent ground covers than the Unirrigated and this effect was most noticeable in the Cultivated-wet treatments. Increasing the N application rate tended to increase canopy persistence but, again, the increase was larger in Cultivated-wet treatments. In summary, the most persistent canopies were associated with Cultivated-dry and Irrigated crops and applying water and N could not remove the detrimental effects of poor soil conditions caused by cultivating wet soils.

Table 51. Effect of soil conditions, irrigation and N application rate on season-long integrated ground cover (% days)

N applied	Cultivated-dry		Cultivated-wet		
(kg N/ha)	Irrigated	Unirrigated	Irrigated	Unirrigated	Mean
0	8507	7938	6981	5722	7287
100	8886	8155	8028	6248	7829
200	9218	8448	7569	6294	7882
300	9067	8594	8240	7193	8273
Mean	8920	8284	7705	6364	7818

S.E. (24 D.F.) N rate, 125; Cult and Irrig 388; Cult, Irrig and N rate, 445

Soil moisture deficits

In Unirrigated plots, soil moisture deficits (SMD) were lower in the Cultivated-wet treatments than the Cultivated-dry as a consequence of the smaller canopies and the reduced uptake potential based on a smaller rooting system. The SMD exceeded the Limiting SMD for the whole of July. There were only small differences in SMD between

Irrigated treatments but soils were kept wet throughout the season (< 30 mm SMD) and therefore below the Limiting SMD.

Number of stems, tubers and tuber fresh weight yields

The average number of stems measured at the four harvests was 146 000/ha and this was not affected by soil conditions, irrigation or N application rate. The effect of cultivation and irrigation on the number of tubers >10 mm is shown in Table 52. Once errors are taken into consideration there was little change in the number of tubers after 12 July (*c.* 51 DAE). At the first sampling, the number of tubers was significantly smaller in the Cultivated-wet and the Unirrigated treatments than were soils were cultivated dry or irrigation was applied. The smaller number of tubers may be a consequence of a slower growth rate in the Cultivated-wet and Unirrigated treatments caused by the slow expansion of ground cover. The effects of cultivation and irrigation were no longer significant at the third and fourth samplings and this may have been due to secondary growth in the Cultivated-wet and Unirrigated treatments causing an increase in the number of tubers > 10 mm.

Table 52. Main effect of cultivation and irrigation on number of tubers > 10 mm on four occasions. Mean of four rates of N application

	15 June (*c.* 24 DAE)	12 July (*c.* 51 DAE)	14 August (*c.* 84 DAE)	26 September (*c.* 127 DAE)
Cultivated-wet	263	343	421	436
Cultivated-dry	382	464	463	518
Irrigated	374	432	460	500
Unirrigated	271	375	424	453
Mean	322	404	444	477
S.E. (6 D.F.)	19.5	13.5	25.0	23.9

Over the course of the four samplings, the average tuber fresh weight (FW) yield increased from 1.3 to 52 t/ha (Table 53). Yields of the Irrigated treatments were always significantly larger than yields of Unirrigated treatments. The benefit of eight irrigations (totalling 182 mm) averaged over all the other factors was *c.* 12 t FW/ha. The Cultivated-dry treatments always had a numerically larger yield than the Cultivated-wet treatments but on one occasion (14 August) this difference was not statistically significant. On average, the yield penalty at final harvest for cultivating the soil whilst wet was *c.* 10 t FW/ha. There was no evidence of any interaction between the cultivation and irrigation treatments and thus the yield response to irrigation was similar in Cultivated-wet and dry soils. The effect of N fertilizer was small and non-significant at each harvest and therefore, irrespective of soil conditions or irrigation, the optimum N application rate was zero. This experiment has shown that when soil conditions are good and the crop is irrigated, substantial yields (64 t/ha) may be achieved without use of N. There was also no evidence that increasing the N application rate improved yields when soil conditions were poor. Thus the effects of poor soil conditions cannot be alleviated by applying more N.

Table 53. Main effects of cultivation and irrigation on tuber fresh weight yield > 10 mm on four occasions. Mean of four rates of N application

	15 June (*c.* 24 DAE)	12 July (*c.* 51 DAE)	14 August (*c.* 84 DAE)	26 September (*c.* 127 DAE)
Cultivated-wet	0.9	12.9	30.7	46.9
Cultivated-dry	1.6	18.6	36.9	57.2
Irrigated	1.6	18.6	42.1	58.1
Unirrigated	0.9	13.0	25.5	45.9
Cultivated-wet-Irrigated	1.1	16.2	39.3	51.9
Cultivated-wet-Unirrigated	0.7	9.6	22.2	41.8
Cultivated-dry-Irrigated	2.2	21.0	44.9	64.4
Cultivated-dry-Unirrigated	1.0	16.3	28.9	50.0
Mean	1.3	15.8	33.8	52.0
S.E. for Cult or Irrig. (6 D.F.)	0.15	0.99	2.59	2.94
S.E. for Cult and Irrig (6 D.F.)	0.21	1.40	3.66	4.15

Onset of tuber bulking

Work in the USA and in the Variety and Nitrogen experiment at CUF (p. 37) has demonstrated that the onset of the linear phase of tuber bulking is sometimes delayed from the date of tuber initiation. The size of this delay appears to be larger in indeterminate varieties than determinate and also where N has been applied. In this experiment, the linear phase of tuber bulking started at *c.* 24 DAE. Neither irrigation treatment nor N application rate had any significant effect on the onset of tuber bulking. However, cultivating the soil whilst dry resulted in a small (*c.* 4 days) but statistically significant delay in the onset of bulking. At present we do not know if this effect is repeatable or the mechanism by which it occurs. However, the Cultivated-dry treatments also had the largest total N uptake (see Table 55) and this large N uptake (as opposed to N application rate) may have suppressed tuber bulking.

Total dry matter yield, nitrogen uptake and radiation absorption

The average total (tuber and haulm) dry matter (DM) yield was 14.2 t/ha (Table 54). The total DM yield was significantly smaller in the Cultivated-wet and Unirrigated treatments. Compared with the effects of cultivation and irrigation, the effect of N was relatively small and erratic (data not shown). The N treatments had no effect on total DM yield in the Cultivated-dry treatments but applying 100-200 kg N/ha increased DM yield relative to 0 kg N/ha in the Cultivated-wet treatments. Over the entire season, the average radiation absorption was 13.14 TJ/ha and radiation absorption was reduced in the Cultivated-wet and in the Unirrigated treatments. The variation in radiation absorption explained *c.* 60 % of the variation in total DM yield and, therefore, most of the effects of compaction and irrigation may be explained via their effects on canopy expansion and persistence. Radiation use efficiency was calculated by using values of total DM production and radiation absorption from each harvest. These data 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. radiation use efficiency as t DM/TJ) were then subjected to analysis of variance. The overall, radiation use efficiency was 1.13 t DM/TJ and whilst this was not significantly affected by the cultivation treatments, the Unirrigated treatments were less efficient than the Irrigated treatments due to a failure to meet potential evapotranspiration.

Table 54. Main effects of cultivation and irrigation on total dry matter (DM) yield at final harvest, season-long integrated ground cover and radiation absorption and radiation use efficiency. Mean of four rates of N application

	Total DM on 26 September (t/ha)	Season-long integrated GC (% days)	Total radiation absorption (TJ/ha)	Radiation use efficiency (t DM/TJ)
Cultivated-wet	12.89	7034	11.70	1.16
Cultivated-dry	15.51	8602	14.57	1.11
Irrigated	16.05	8312	13.98	1.23
Unirrigated	12.36	7324	12.29	1.04
Cultivated-wet-Irrigated	14.33	7705	12.85	1.22
Cultivated-wet-Unirrigated	11.46	6364	10.55	1.11
Cultivated-dry-Irrigated	17.77	8920	15.11	1.23
Cultivated-dry-Unirrigated	13.26	8284	14.04	0.98
Mean	14.20	7818	13.14	1.13
S.E. for Cult or Irrig (6 D.F.)	0.674	275	0.530	0.022
S.E. for Cult and Irrig (6 D.F.)	0.953	388	0.750	0.031

Earlier work has shown that canopy persistence and thereby radiation absorption and yield production is related to total N uptake by the crop and the rate at which tubers take up nitrogen in relation to radiation absorption. The rate of tuber N uptake was estimated by linear regression using tuber N uptake and radiation absorption data from each harvest. The overall mean rate of tuber N uptake was 13.8 kg N/TJ (Table 55) and there was some evidence that the rate of N uptake was smaller in the Dry-cultivated and Unirrigated plots than in other plots. Increasing the amount of N applied from 0 to 300 kg N/ha had no statistically significant effect on the rate of tuber N uptake (data not shown). After absorption of 10 TJ/ha of energy (*c.* 20 August), the average tuber N uptake was 124 kg N/ha and, for comparison, experiments in 2004 and 2005 gave average tuber N uptake values of 110 and 117 kg N/ha, respectively. The pattern of total N uptake was described by fitting an exponential curve to values of total N uptake measured at each harvest. When averaged over all treatments the maximal total N uptake was 229 kg N/ha. Numerically, total N uptake was smaller in the Cultivated-wet and in the Unirrigated treatments but due to the relatively large standard errors these differences were not significant. Increasing the amount of N applied from 0 to 300 kg N/ha resulted in a relatively small increase in total N uptake from 208 to 248 kg N/ha. For comparison, average total N uptake by Maris Piper in experiments in 2004 and 2005 was 199 and 208 kg N/ha, respectively.

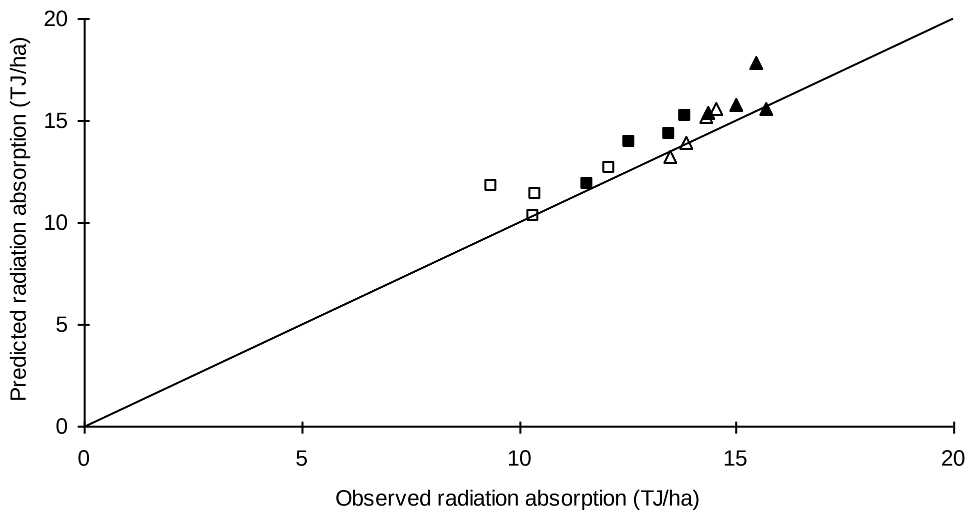
Table 55. Main effects of cultivation and irrigation on tuber and total N uptake. Mean of four rates of N application

	Estimate of rate of tuber N uptake (kg N/TJ)	Tuber N uptake after absorption of 10 TJ/ha (kg N/ha)	Estimate of maximal total N uptake (kg N/ha)	Rates of tuber and total N uptake equivalent (DAE)
Cultivated-wet	14.1	129	216	61
Cultivated-dry	13.5	120	243	53
Irrigated	14.1	126	249	55
Unirrigated	13.4	122	210	59
Cultivated-wet-Irrigated	13.6	124	228	58
Cultivated-wet-Unirrigated	14.5	133	204	65
Cultivated-dry-Irrigated	14.7	128	269	53
Cultivated-dry-Unirrigated	12.3	110	216	53
Mean	13.8	124	229	57
S.E. for Cult or Irrig (6 D.F.)	0.25	1.5	11.7	1.4
S.E. for Cult and Irrig (6 D.F.)	0.35	2.0	16.6	2.0

Within the CUF N management model, a key time in a crop's development is the point at which the rate of tuber N uptake becomes equivalent to the rate of total N uptake. At this point, haulm N reaches a maximum and then decreases as N from the haulm is withdrawn to supply the tubers. On average, this occurred at 57 DAE and was not significantly affected by either irrigation or N application rate (N data not shown). However, in the Cultivated-wet soils, this point was delayed by nine days when compared with the Cultivated-dry soils. On the basis of a single experiment it is not possible to judge the significance of this finding but this extra nine days may be linked to the prolonged (albeit slow) increase in ground covers of the Cultivated-wet plots (Figure 15). Other work at CUF has indicated a link between the time at which the haulm becomes a net exporter of N and the slowing or cessation of leaf appearance and rate of root extension. These data suggest that in compacted soils the period of root extension may be extended and this results in an extended period of canopy N uptake. Work in 2007 studied this in more detail (p. 79).

Using information on the pattern of total (i.e. tuber and haulm) and tuber N uptake in relation to radiation absorption it is possible to predict the pattern of haulm N uptake in relation to radiation absorption and thus predict the effects of soil condition and irrigation on canopy persistence and potential radiation absorption. Figure 16 compares predictions of potential radiation absorption based on measurements of haulm and tuber N with observed radiation absorption measured at the final harvest. Generally, the model overestimated radiation absorption by *c.* 1 TJ/ha (approximately equivalent to a tuber FW yield of 4–5 t/ha). However, the model was sufficiently accurate to predict the effects of soil conditions, irrigation and N application rate on the crop's potential to absorb radiation.

Figure 16. Comparison of predicted and observed radiation absorption for Wet-cultivated-Unirrigated, □; Wet-cultivated-Irrigated, ■; Dry-cultivated-Unirrigated, △; Dry-cultivated-Irrigated, ▲. Line is 1 : 1 relationship.



Conclusions

This experiment has generated much useful data and has shown that poor soil conditions, as a consequence of cultivating wet soils, result in large yield penalties. Importantly, this experiment has also shown that this yield penalty is only partially alleviated by use of irrigation whilst applying N had no effect on yield irrespective of soil conditions. This experiment was repeated in 2007 to gather more detailed information on the effects of soil cultivations, water and N supply on crop performance and yield production.

Effects of soil conditions, irrigation and N application rate on yield and N uptake of Maris Piper in 2007

Introduction

An experiment at in 2006 tested the effects of soil cultivation, irrigation and N application rate on yields and N nutrition of Maris Piper. In this experiment, soils that were cultivated whilst too wet suffered a large yield penalty and this yield penalty was only partially removed by applying irrigation. Nitrogen fertilizer had no effect on yield irrespective of soil conditions or use of irrigation. 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 2007 experiment was to further investigate the effects of soil conditions, water and nitrogen supply on crop growth and yield. In addition, the experiment also provided material for use within the BPC Bruising Project (R263) and also allowed the effect of soil conditions on factors such as secondary growth and tuber mis-shapes to be quantified.

Materials and Methods

Experimental design

The experiment tested all combinations of two soil conditions (Cultivated-dry and Cultivated-wet); two irrigation regimes (Unirrigated and Irrigated so that soil moisture deficits did not exceed 30 mm) and three N application rates (0, 150 and 300 kg N/ha). The experiment was a randomized plot design with four replicates containing cultivation and irrigation treatments allocated at random to mainplots and N fertilizer treatments allocated at random to sub-plots.

Cultivation and irrigation treatments

Details of the sequence of cultivations, irrigation and planting operations are given in Table 56. Soil moisture deficits were estimated and irrigation treatments scheduled using the Cambridge University Farm Potato Irrigation Scheduling System model based on a modified Penman-Monteith evapotranspiration equation. Irrigation was applied on 25 April, 3 May (both pre-emergence), 11 June, 10 & 17 July; 3 & 9 August, 5 & 13 September and totalled 191 mm.

Table 56. Details of cultivation and irrigation operations around planting

Operation	Date
Plough @ 25–30 cm	16 March 2007
Spring tine (two passes) @ 10–15 cm	26 March 2007
Irrigation (19.8 mm) on Cultivated-wet plots with boom (RST Irrigation and reel (Perrot SA, SH63/280) combination	19 April 2007 (evening)
Rumpstad Rotoridger (ridging bodies removed) @ 25 cm	20 April 2007 (afternoon)
Ridged with fixed-body Cousins ridger	20 April 2007 (afternoon)
Planted and fertilizer applied	23 April 2007
Re-ridged with fixed-body Cousins ridger	23 April 2007
Irrigation (19.0 mm)	25 April 2007

Crop planting, sampling and analysis

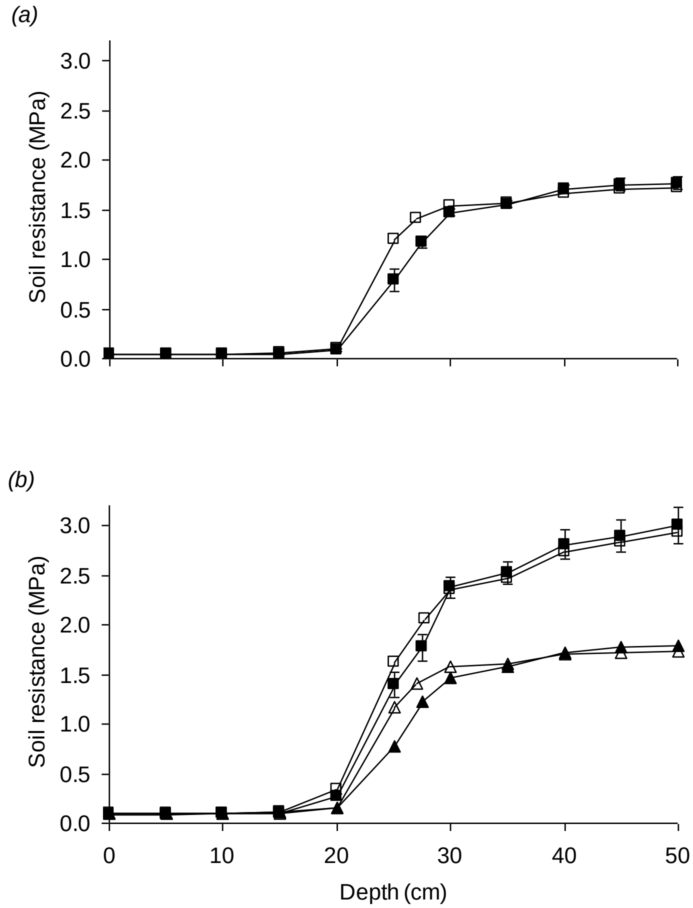
The experiment was planted by hand using Maris Piper (certification grade E1; 30-35 mm; 21.6 g) into pre-formed ridges on 23 April. The ridges had 76.2 cm centres and the within-row spacing was 25 cm giving an intended plant population of 52 493/ha. Each plot was eight rows (6.10 m) wide and 10 m long. 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 by a re-ridging operation. Soil resistance readings were taken using an Eijkelkamp Penetrograph penetrometer in the centre of the ridge to a depth of 50 cm on three occasions: 3 May, 25 May (50 % emergence) and on 10 August following a dry spell. Soil bulk density was measured at emergence and after final harvest on 8 October. Duplicate soil cores (100 cm^3) were taken from the centre of the ridge at 5 cm increments to a depth of 30 cm from all 150 N plots and dried for 24 h at 105 °C. Plant emergence was measured every 3-4 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 (20 June, 19 July, 24 August and 24 September). At each harvest, 10 plants (1.91 m^2) were taken from rows two and three of each eight-row plot. An unharvested discard area of at least two plants was left between adjacent harvest areas or plot ends. At each harvest, the number of plants and stems was recorded and all tubers > 10 mm were collected. The haulm FW was recorded and a representative sub-sample (*c.* 1 kg) was removed. The tubers were graded in 10 mm increments and the number and weight of tubers within each grade was recorded. A sub-sample of tubers (*c.* 1 kg) was taken from the 50-60 mm size grade and was then washed, chipped and dried (together with the haulm sub-samples) to constant weight at 90 °C. The dried haulm and tuber samples were then sent to a commercial laboratory for measurement of total N concentration.

Results and Discussion

Soil resistance and bulk density

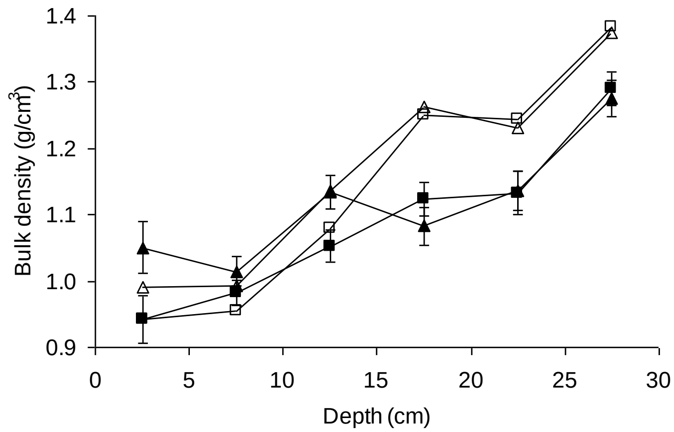
Soon after planting, all plots were irrigated to close to field capacity and although significantly higher soil resistances were observed at the 20-25 cm depth where the rotary cultivator tines were working, the differences were small between the two cultivation regimes (Figure 14*a*). Even when the soil had dried appreciably through uptake of water by roots, the differences in soil resistance at 20 and 30 cm between cultivation regimes did not become more obvious (Figure 14*b*). As the soil dries, its strength (i.e. resistance) increases and root progress is impeded further. Unlike 2006 however, soil resistances during the period when root extension was taking place were below the ultimate limit for root penetration by potatoes (3 MPa, Stalham *et al*. 2007). It is clear that the soil was not above its plastic limit in the Cultivated-wet plots at the time of cultivation and this failed to create significant compaction. A similar amount of time elapsed between pre-irrigation and cultivation in 2007 (20 hours) and 2006 (18 hours) but the cultivation in 2006 started at 09:00 h on a dull, cool morning whereas in 2007 it started at 15:00 h on a sunny, warm day. In 2007, the seedbed was cloddier and it was also hot and dry in the seven days prior to the pre-cultivation irrigation which may have resulted in insufficient wetting.

Figure 17. Soil resistance on two occasions (3 May data not shown). ***(a)*** **25 May;** ***(b)*** **10 August. Unirrigated, ■; Irrigated ▲. Closed symbols, Cultivated-dry; open symbols, Cultivated-wet.**



Soil bulk density was increased between 15 and 30 cm by cultivating soils whilst wet (Figure 18). These measurements did not reflect soil resistance reading closely, since the penetrometer only showed significant differences between the two cultivation regimes at 20 to 30 cm below the ridge apex. Part of the reason for this difference is the compression that the penetrometer base plate creates on the ridge apex before the ridge has reached its final density. This can make the apparent depth appear shallower than actual by 2-3 cm, which does not explain the differences. The probable answer is that the soil can easily move aside as the penetrometer tip is inserted in the ridge owing to the low packing density of peds, whereas the structure deeper in the profile is more tightly packed creating greater restraining lateral forces.

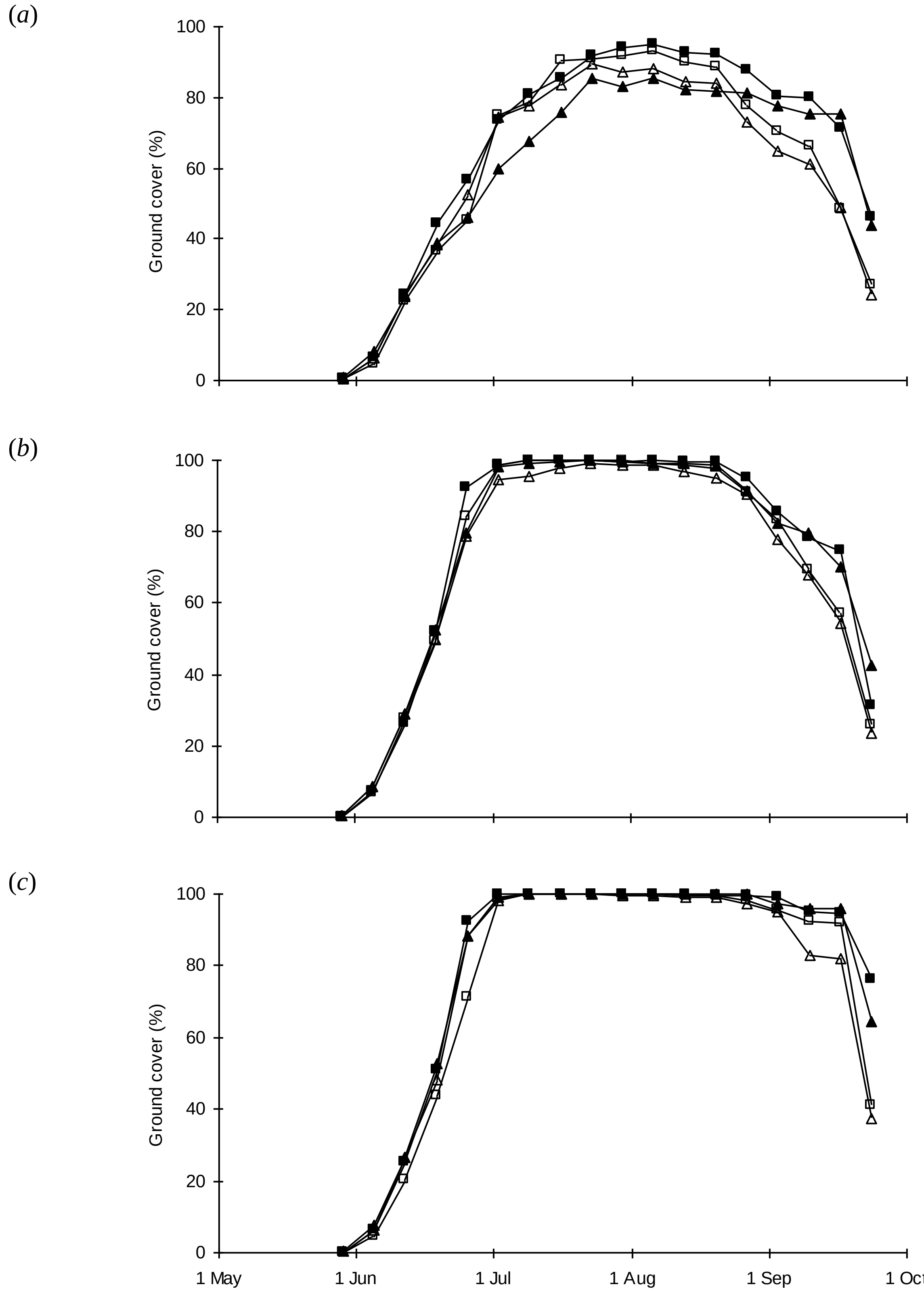
Figure 18. Soil bulk density on two dates. 25 May, ■; 8 October, ▲; Cultivated-dry, closed symbols; Cultivated-wet, open symbols.



Emergence, ground covers and radiation absorption

The mean date for 50 % plant emergence was 26 May (33 DAP). The Cultivated-wet plots achieved 50 % plant emergence *c.* 2 days before the Cultivated-dry plots and this was opposite to the effects seen in 2006. Increasing the N application rate delayed the date of 50 % plant emergence from 32 (0 kg N/ha) to 35 DAP (300 kg N/ha). Final plant establishment averaged 94 % and was significantly reduced when 300 kg N/ha had been applied. The slower emergence in soils cultivated whilst dry was probably a consequence of a cloddy seedbed that reduced the efficiency of water uptake by the developing crop and this problem may have been compounded by high rates of N application. The effect of soil cultivations, irrigation and N application rate on ground cover are shown in Figure 19. In the absence of N fertilizer, initial canopy expansion was slow and crops failed to achieve complete ground cover. When 150 or 300 kg N/ha was applied, canopy expansion was rapid, and all crops attained 100 % ground cover. When 300 kg N/ha had been applied, canopy senescence was delayed by 2-3 weeks when compared with the intermediate N rate. In all cases irrigation increased canopy persistence but in the Cultivated-wet and unfertilized crop irrigation early in the season reduced ground cover. The effects of cultivating the soils whilst wet or dry on ground cover development and persistence were smaller than the effects of either irrigation or N application rate.

Figure 19. Effect of soil cultivations, irrigation and N application rate on development of ground cover. *(a)* 0 kg N/ha; *(b)* 150 kg N/ha; *(c)* 300 kg N/ha. Cultivated-dry Unirrigated, □; Cultivated-dry Irrigated, ■; Cultivated-wet Unirrigated, △; Cultivated-wet Irrigated, ▲.



When averaged over all factors, the season-long integrated ground cover was 8804 % days (Table 57). In a similar experiment in 2006, the average integrated ground cover was 7818 % days. The first increment of 150 kg N/ha increased integrated ground cover by *c.* 1300 % days whilst the second increment of N increased ground cover by a further 600 % days. Cultivating the soil whilst dry and applying irrigation increased integrated ground cover relative to crops in wet cultivated soils and unirrigated, however these effects were small and not statistically significant. The overall average radiation absorption was 13.22 TJ/ha. Neither the cultivation nor the irrigation treatments had any significant affect on the amount of radiation absorbed by the crop. Increasing the amount of N applied from 0 to 300 kg N/ha increased radiation absorption from 11.60 to 14.36 TJ/ha.

Table 57. Effects of cultivation, irrigation and N application rate on season-long integrated ground cover (% days)

N applied	Cultivated Wet		Cultivated Dry		
(kg N/ha)	Unirrigated	Irrigated	Unirrigated	Irrigated	Mean
0	7411	7527	7667	8839	7736
150	8772	9204	8989	9309	9069
300	9411	9806	9371	9844	9608
Mean	8532	8846	8676	9164	
Mean	8920		8689		8804

S.E. (9 D.F.) Cultivation, 146.8; Cultivation and Irrigation, 207.6;
S.E. (24 D.F.) N rate, 124.7; N rate, Cultivation and Irrigation 290.8

Soil moisture deficits

Low evaporation rates and adequate rainfall meant that the requirement for irrigation in 2007 was considerably lower than in 2006. Soil moisture deficits in the Unirrigated crops only exceeded the Limiting SMD for a two-week period starting at the beginning of August and for the final two weeks of growth but there was sufficient shortage of soil water during these periods for irrigation to affect productivity more than in 2006 (see next section). Soil moisture deficits in Irrigated crops were maintained below 27 mm throughout the season.

Number of stems, tuber and tuber fresh weight (FW) yields

The average number of stems measured at the four harvests was 138 000/ha (Table 58) and this variate was not affected by cultivations, irrigation or N application rate. The average number of tubers > 10 mm per stem increased between the first and second sampling but was relatively stable thereafter. The effects of cultivation and irrigation on the number of tubers per stem were small and non-significant. At the first harvest, increasing the N application rate from 0 to 300 kg N/ha reduced the number of tubers per stem and this was probably a consequence of a delay in tuber initiation as a consequence of the delay in emergence. However, at subsequent harvests, increasing the N application rate to 150 kg N/ha increased the number of tubers per stem and this may have been due to better tuber retention as a result of faster growth rates. After *c.* 50 DAE the average tuber population > 10 mm stabilised at 446 000/ha. The tuber population was not affected by cultivations or irrigation. At the final harvest the tuber population for the 0, 150 and 300 kg N/ha treatments was 408, 466 and 470 000/ha, respectively.

Table 58. Average number of stems, tubers > 10 mm per stem and number of tubers > 10 mm on four sampling occasions

	Harvest 1 20 June *c.* 25 DAE	Harvest 2 19 July *c.* 54 DAE	Harvest 3 24 August *c.* 90 DAE	Harvest 4 24 September *c.* 121 DAE
Stems (000/ha)	139 ± 19.3	142 ± 19.0	135 ± 19.7	134 ± 15.0
Tubers per stem	1.65 ± 0.775	3.09 ± 0.543	3.42 ± 0.446	3.39 ± 0.377
Tubers > 10 mm (000/ha)	221 ± 106.5	434 ± 73.2	455 ± 59.7	448 ± 46.7

Between 25 and 121 DAE, the average tuber FW yield > 10 mm increased from 1.1 to 58.1 t/ha (Table 59). At all samplings, the effects of cultivations on tuber yield were small and non-significant. Tuber yields were increased significantly by irrigation at the third and fourth sampling and the overall response to irrigation at final harvest was *c.* 14 t FW/ha. At the first sampling (*c.* 25 DAE) yields were smaller when 300 kg N/ha had been applied. This reduction in yield was probably due to high rates of N application delaying emergence. At the second and third harvests, yields were significantly larger when 150 kg N/ha had been applied when compared with no N fertilizer, however yields were not increased by applying more N. At the final harvest, the largest tuber FW yield resulted from applying 300 kg N/ha. Since the experiment tested only three N rates the optimum N application rate cannot be defined with any certainty, however it is probably between 150 and 300 kg N/ha. For comparison, in a similar experiment in 2006, there was no response to N fertilizer.

Table 59. Main effects of cultivation, irrigation and N application rate on tuber > 10 mm FW yield (t/ha) on four sampling occasions

	Harvest 1 20 June *c.* 25 DAE	Harvest 2 19 July *c.* 54 DAE	Harvest 3 24 August *c.* 90 DAE	Harvest 4 24 September *c.* 121 DAE
Cultivated-wet	1.3	22.3	47.4	58.0
Cultivated-dry	1.0	22.0	47.2	58.1
Unirrigated	1.0	21.2	42.8	51.0
Irrigated	1.2	23.1	51.7	65.1
0 kg N/ha	1.4	18.0	38.6	46.8
150 kg N/ha	1.4	25.5	51.2	59.8
300 kg N/ha	0.6	22.9	52.0	67.6
Mean	1.1	22.1	47.3	58.1
S.E. (6 D.F.) Cult. or Irrig.	0.10	0.54	1.07	1.23
S.E. (24 D.F.) N rate	0.17	0.73	1.31	1.26

The effect of cultivating wet or dry soil, irrigation and N supply on tuber DM concentration are shown in Table 60. At the first harvest, tuber DM concentration was not affected by any treatment or combination of treatments. At subsequent harvests, tuber DM concentration was smaller in dry cultivated plots and those plots that had been irrigated. Increasing the amount of N applied to the crop resulted in a systematic decrease in tuber DM concentration.

Table 60. Main effects of cultivation, irrigation and N application rate on tuber DM concentration (%) on four sampling occasions

	Harvest 1 20 June *c.* 25 DAE	Harvest 2 19 July *c.* 54 DAE	Harvest 3 24 August *c.* 90 DAE	Harvest 4 24 September *c.* 121 DAE
Cultivated-wet	12.5	18.7	24.1	25.3
Cultivated-dry	11.5	18.2	23.1	24.8
Unirrigated	12.2	19.1	24.3	25.5
Irrigated	11.8	17.8	23.0	24.5
0 kg N/ha	12.5	19.5	25.5	26.4
150 kg N/ha	12.2	18.8	23.6	24.8
300 kg N/ha	11.2	17.1	22.8	23.9
Mean	12.0	18.5	23.6	25.0
S.E. (6 D.F.) Cult. or Irrig.	0.41	0.16	0.25	0.38
S.E. (24 D.F.) N rate	0.60	0.18	0.28	0.20

Total DM yield, RUE and the onset of tuber bulking

The mean total dry matter yield for all treatments was 17.3 t/ha (Table 61) compared with 14.2 t/ha in 2006. Soil conditions had no effect on total DM but DM yields were increased by use of irrigation and increasing amounts of N. Radiation use efficiency (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 dry matter production was 1.36 t DM/TJ and this value was typical for crops grown at CUF in 2007. Radiation use efficiency was increased in irrigated crops and where N had been applied but was not affected by soil conditions. The increase in RUE caused by irrigation was responsible for the significant increase in total DM and tuber FW yield in the absence of an increase in ground cover persistence and radiation absorption. On average, absorption of each TJ of energy was associated with the production of 1.19 t of tuber DM. The efficiency of tuber DM production was increased by applying irrigation and by applying N fertilizer.

Studies in the USA and UK have shown that there is often a significant lag between tuber initiation (which typically occurred at 19-25 DAE) and the onset of the linear phase of tuber bulking. In a similar experiment in 2006, the average start data of tuber bulking was estimated to be *c.* 24 DAE. Nitrogen application rate had no effect on the onset of bulking but it was delayed by 4 days in soils that were cultivated whilst dry. In 2007, the linear phase of tuber bulking started at *c.* 26 DAE (Table 61) and was delayed by both irrigation and when 300 kg N/ha had been applied. However, the delay in the onset of tuber bulking was relatively small and was unlikely to have had much effect on yield.

Table 61. Main effects of cultivation, irrigation and N application rate on total DM yield, radiation use efficiency and the onset of tuber bulking

	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)
Cultivated-wet	17.37	1.39	1.21	25.4
Cultivated-dry	17.15	1.33	1.16	25.6
Unirrigated	15.50	1.27	1.09	23.8
Irrigated	19.02	1.46	1.28	27.1
0 kg N/ha	14.30	1.29	1.15	24.7
150 kg N/ha	17.48	1.36	1.17	24.2
300 kg N/ha	19.99	1.44	1.24	27.6
Mean	17.26	1.36	1.19	25.5
S.E. (6 D.F.) Cult. or Irrig.	0.395	0.019	0.028	1.00
S.E. (24 D.F.) N rate	0.395	0.027	0.025	1.08

Table 62 summarises the main effects of the cultivation, irrigation and N treatments on tuber FW yields in 2006 and 2007. In 2006, N had no effect on yield whilst cultivating dry soils and applying irrigation increased tuber yields by *c.* 11 t/ha when compared with soils cultivated whilst wet and not irrigated. In 2007, the effects of the treatments were markedly different: soil cultivation had no effect on tuber yield, irrigation increased yield by 14 t/ha and N increased yield by 20 t/ha. These differences between seasons may be due to two reasons: first, in 2007, the irrigation treatment on the 19 April was applied to a drier soil than in 2006 and second, the soil in 2007 was also allowed to drain for slightly longer before cultivation. Therefore in 2006, the cultivations were imposed on soils that were much wetter than those in 2007 resulting in more severe damage to the soil structure. Other experiments at CUF in 2007 also demonstrated a large response to N fertilizer, although it is not known whether this was due to smaller than average quantities of soil mineral N or due to other factors that may have impeded N uptake.

Table 62. Main effects of cultivations, irrigation and N application on tuber FW yield (t/ha) in 2006 and 2007

Treatments		2006	2007
Soil cultivation	Wet	46.9	58.0
	Dry	57.1	58.1
Irrigation	Unirrigated	45.9	51.0
	Irrigated	58.1	65.1
N application rate	0 kg N/ha	50.4	46.8
	300 kg N/ha	52.8	67.6

Effect of soil conditions, irrigation and N application rate on N uptake

The rate of tuber N uptake for each plot was estimated by linear regression using values of tuber N uptake and radiation absorption from each harvest. The overall mean rate of tuber N uptake was 13.6 kg N/TJ (Table 63). Cultivation had no effect on the rate of tuber N uptake but the rate of tuber N uptake was increased by irrigation and N application. After the crop had absorbed 10 TJ/ha of energy (*c*. 101 and 82 DAE for unfertilized or fertilized crops, respectively), the average tuber N uptake was 121 kg N/ha. In 2006, the average tuber N uptake was 124 kg N/ha. The pattern of total N uptake for each plot was described by fitting an exponential curve to total N uptake and radiation absorption data. The average, asymptotic value for N uptake was 237 kg N/ha. Cultivating the soils whilst they were wet increased the value for total N uptake but the effect was small and not statistically significant. The effects of irrigating the crop and applying N fertilizer were statistically significant and explain the effects of the irrigation and N treatments on canopy persistence and yield. A key date within a crop's development is the point at which the rate of tuber N uptake (which is relatively constant for the whole season) exceeds the rate of total N uptake (which decreases as the season progresses). At this point the canopy becomes a net exporter of N and the process of canopy senescence has begun. The model calculates this point in terms of radiation absorption but since the pattern of radiation absorption is known, this can be converted to a calendar date. For all treatments this point was reached at 61 DAE (compared with 57 DAE in 2006). Neither cultivation nor irrigation had any significant effect on the date at which the haulm became a net exporter of N, however increasing the amount of N fertilizer from 0 to 300 kg N/ha advanced the date at which the canopy became a net exporter of N from 69 to 57 DAE. This seems counter-intuitive, however increasing the N application rate resulted in an increase in the rate of tuber N uptake and, furthermore, since the canopies of the 0 kg N/ha were smaller they took longer to absorb the radiation needed.

In 2006 and 2007 the relative effects of soil cultivation, irrigation and N application rate on growth and yield were very different. However, the effects of the treatment in both seasons could be interpreted in terms of effects on N uptake, N redistribution and crop potential yields. These two experiments suggest that CUF N management model is sufficiently robust to cope with many of the variables encountered in commercial crop production.

Table 63. Main effect of cultivations, irrigation and N application rate on tuber and total N uptake

	Estimated rate of tuber N uptake (kg N/TJ)	Tuber N uptake after absorption of 10 TJ/ha (kg N/ha)	Estimate of maximal total N uptake (kg N/ha)	DAE when rate of tuber and total N uptake were equivalent
Cultivated-wet	13.7	123	243	63
Cultivated-dry	13.4	119	231	59
Unirrigated	12.9	117	217	59
Irrigated	14.2	125	258	63
0 kg N/ha	10.8	99	188	69
150 kg N/ha	13.3	121	233	58
300 kg N/ha	16.5	143	291	57
Mean	13.6	121	237	61
S.E. (6 D.F.) Cult. or Irrig.	0.28	1.8	10.5	1.3
S.E. (24 D.F.) N rate	0.38	3.1	14.0	1.8

Conclusions

This experiment will be repeated in 2008 when it is intended to create combinations of ridge conditions (fine and cloddy) and sub-soil condition (uncompacted and smeared) together with contrasting irrigation regimes and to test the effects of these treatments on yield, N uptake and tuber quality. An objective in the future work is develop methods to quantify soil conditions so that in future it may be possible to relate soil conditions to N requirement and yield potential.

Effect of Maris Piper stock, N application rate and uniformity of irrigation on yield and N uptake in 2006

Introduction

This experiment was part of the Size and Uniformity Project (R257). The frequent, detailed harvests provided an opportunity to test aspects of the CUF Yield and N Management model in the variety Maris Piper.

Materials and Methods

The experiment was done on Huntingdon Road Pasture, CUF. The experiment tested all combinations of two stocks of Maris Piper (early and late produced), two N application rates (165 and 330 kg N/ha) and two irrigation regimes (variable and scheduled). Each treatment combination was replicated four times. The early-produced seed stock of Maris Piper was planted on 11 May 2005 and emerged (50 % plants) on 1 June whilst the late-produced stock was planted on 24 June and emerged on 8 July. The experiment was planted by hand (35 cm within-row spacing) on 5 April. No fertilizer P or K was used and fertilizer N was applied at a rate of 165 kg N/ha as liquid on 15 April. An additional 165 kg N/ha was applied as solid ammonium nitrate to the high nitrogen treatment plots in a single dose immediately after planting and incorporated by raking. Pre-emergence herbicide was applied following planting. Irrigation was applied with a boom irrigator and requirements were determined by the CUF Scheduling model. Scheduling was based on ground cover data for the normal N and early stock. For the variable water treatment SMDs were alternatively allowed to reach high levels and were then over-irrigated. The date of plant emergence was recorded at least every 4 days for each individual plant in the harvest rows of all plots. This was facilitated by the use of a string marked with the expected position of all plants. Ground cover was recorded weekly from the start of emergence until final harvest. Tuber and haulm dry matter yield and N uptake was measured on five occasions (5 June, 19 June, 3 July 31 July and 20 September). Samples of six plants were taken for the first three harvest and 12 and 16 plants were taken on 31 July and 20 September. Two guard plants were left at the end of each plot on each sampling occasion and any missing plants were noted, although the area sampled was not adjusted for missing plants. Plants were dug carefully to avoid tuber detachment and placed in nets and boxes and returned to the laboratory. Dry weights were determined on sub-sample of whole stems (*c*. 1-2 kg) and undamaged washed and chipped tubers (*c*. 0.5-1 kg) from each plot, dried at 90 °C for 48 hours and samples retained for nitrogen analysis.

Results and discussion

Emergence

When averaged over all treatments, 50 % plant emergence occurred on 14 May (39 days after planting). The date of attaining 50 % emergence was slightly delayed in the late produced stock and in the treatments receiving 330 kg N/ha. Most plants emerged within a week of each other but some plants continued to emerge over the following week and even later where the late stock received high N. By mid June emergence was largely complete (≥ 97 %) for most treatments but lower for late-produced seed with high N (92 %).

The SMDs in the variable irrigation plots was allowed to reach levels slightly above the limiting deficit in June and approached the Limiting SMD in early August whilst the scheduled irrigation plots received more frequent irrigation throughout the season. The variable irrigation plots were over-watered on 26 June, 10 July and 19 July and rain from mid-August onwards was sufficient to keep the SMD below the Limiting SMD. A total of 130 mm water was applied to the variable irrigation plots *cf*. 215 mm applied to the scheduled plots.

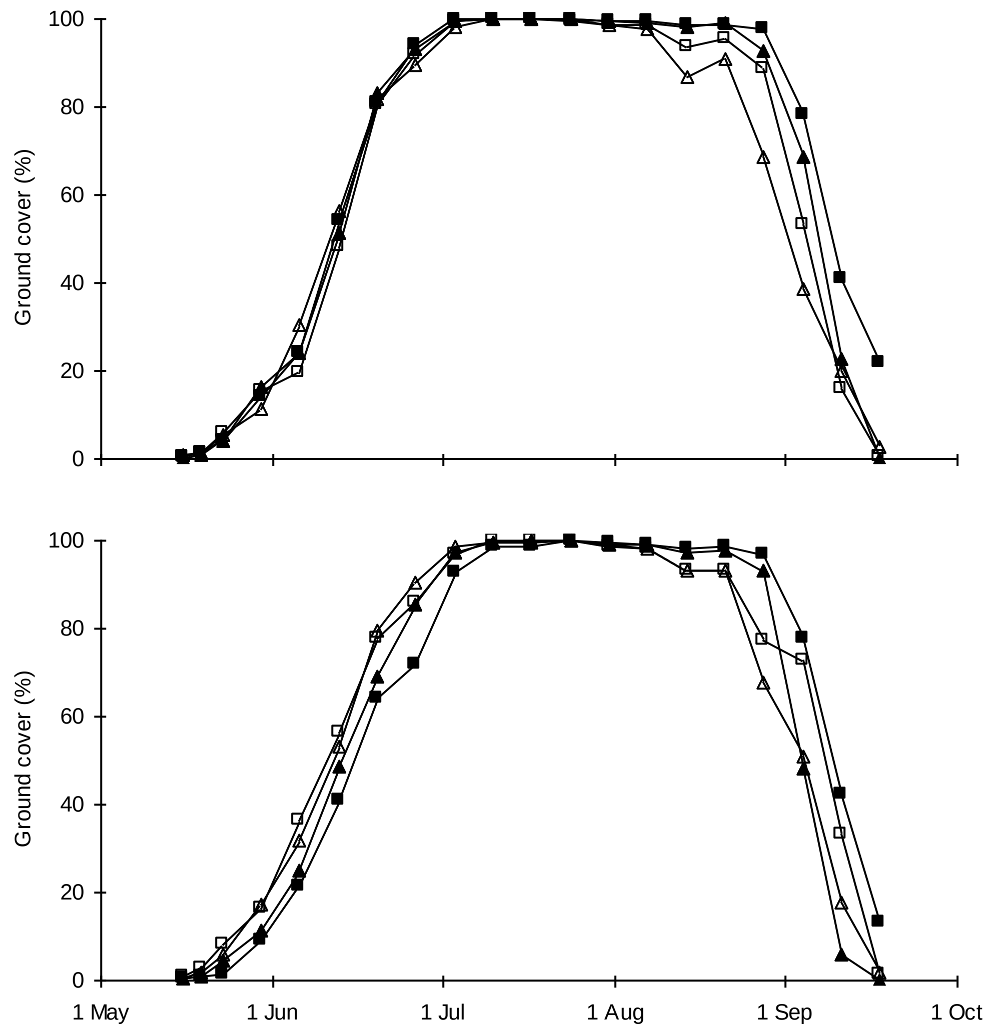
Development of ground cover and radiation absorption

The effect of the treatments on the pattern of ground cover development is shown in Figure 20. Ground cover expanded at a similar rate with variable and scheduled irrigation although with scheduled irrigation full canopy cover was achieved at the beginning of July slightly earlier than with variable irrigation in most cases. Senescence began at the end of August, and whilst decrease in ground cover was slightly delayed with high N, little ground cover remained in any treatment by mid-September.

Figure 20. The effect of stock and rate of nitrogen on ground cover for *(a)* scheduled irrigation and *(b)* variable irrigation plots in Maris Piper. Late seed and 165 kg N/ha, □; Late seed and 330 kg N/ha, ■; Early seed and 165 kg N/ha, △; Early seed and 330 kg N/ha, ▲.

(a)

(b)



The effects of the treatments on season long integrated ground cover and radiation absorption are shown in Table 64 and Table 65, respectively. The overall mean integrated ground cover was 8551 % days (i.e. equivalent to maintaining complete ground cover for 86 days). This value was similar to the values found for Maris Piper in the Soil Conditions and N experiment and was substantially larger than values found for Russet Burbank and Estima in the Variety and N experiment and the Shade and N experiment. However, in 2005 the overall, average integrated ground cover in a similar experiment was 10280 % days showing that the canopy was less persistent in 2006. Increasing the N application rate from 165 to 330 kg N/ha resulted in a numerical increase in integrated ground cover but this was not statistically significant. Similarly, the effects of seed stock and irrigation regime were also non significant. On average the Maris Piper crop absorbed 14.55 TJ/ha of energy and this was not significant affected by either stock, irrigation or N application rate.

Table 64. Effects of irrigation regime, seed stock and N application rate on season long integrated ground cover (% days)

	Variable irrigation		Scheduled irrigation		
N applied (kg N/ha)	Early	Late	Early	Late	Mean
165	8379	8713	8230	8429	8438
330	8270	8534	8764	9087	8664
	8474		8627		8551

S.E. (21 D.F.) Irrigation, 176.0; N rate, 176.0; Irrigation, stock and N rate, 351.9

Table 65. Effects of irrigation regime, seed stock and N application rate on season long radiation absorption (TJ/ha)

	Variable irrigation		Scheduled irrigation		
N applied (kg N/ha)	Early	Late	Early	Late	Mean
165	14.43	14.88	14.24	14.38	14.48
330	14.10	14.20	14.88	15.27	14.61
	14.40		14.69		14.55

S.E. (21 D.F.) Irrigation, 0.250; N rate, 0.250; Irrigation, stock and N rate, 0.500

Development of total DM yield, tuber FW yield and N uptake

The effect of the treatments on total (haulm and tuber) DW yield and on tuber FW yield is shown in Table 66 and Table 67. Total DW yield increased steadily with time from Harvest 1 to the penultimate harvest (Harvest 7). However, the rate of increase slowed between the penultimate and final harvest so that the final, total DM was relatively modest. The relationship between total DM yield and radiation absorption for selected treatments is shown in Figure 21. For two thirds of the season (up to the absorption of *c.* 10 TJ/ha of energy) there was an approximately linear relation between DM production and radiation absorption and the slope of this relationship (RUE) was *c.* 1.25 t DM/TJ. However, for the latter third of the season, the RUE was much smaller and averaged only 0.31 t DM/TJ, indicating that for a significant proportion of the season yield potential was being lost. The hypothesis is supported by the pattern of development of tuber FW yield

(Table 67) which shows that up to the penultimate harvest the rate of tuber bulking was relatively constant. However, between the penultimate and final harvests (51 days), tuber FW yield increased by an average of only 12 t/ha. In comparison, in a similar experiment in 2005, average yields increased from 21 to 72 t/ha over a period of 77 days.

Table 66. Main effects of irrigation regime, seed stock and N application rate on total DW yield (t/ha)

	Harvest 1 5 June	Harvest 3 19 June	Harvest 5 3 July	Harvest 7 31 July	Harvest 8 20 September
Mean	0.58	2.99	5.97	12.54	14.19
Scheduled	0.56	3.21	6.70	13.39	14.97
Variable	0.61	2.78	5.25	11.69	13.41
Early stock	0.61	2.89	6.16	12.75	13.74
Late Stock	0.55	3.09	5.79	12.33	14.64
165 kg N/ha	0.63	3.22	6.32	12.89	13.83
330 kg N/ha	0.54	2.77	5.62	12.19	14.55
S.E. (21 D.F.)	0.042	0.185	0.265	0.384	0.739

At present the reasons for the poor performance of these crops during the latter part of the season is not known but may due to the effects of early blight as noted in other experiments in 2006.

Figure 21. Relationship between total DM yield and radiation absorption for early-produced seed. Scheduled irrigation-N165, □; scheduled irrigation-N330,■; variable irrigation-N165, △ and variable irrigation N330, ▲.

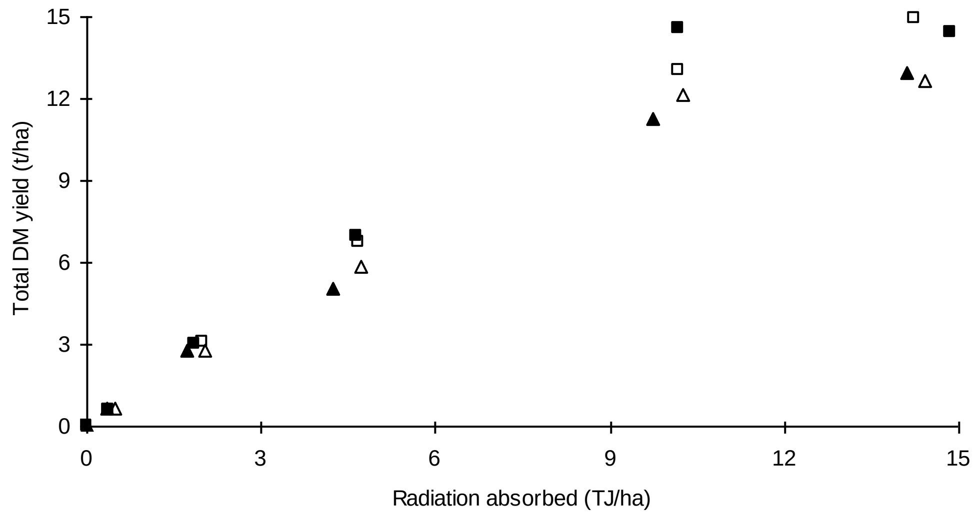


Table 67. Main effects of irrigation regime, seed stock and N application rate on tuber FW yield (t/ha)

	Harvest 1 5 June	Harvest 3 19 June	Harvest 5 3 July	Harvest 7 31 July	Harvest 8 20 September
Mean	0.12	7.2	16.1	34.7	46.8
Scheduled	0.11	7.3	18.4	37.4	49.4
Variable	0.13	7.0	13.8	32.1	44.2
Early stock	0.12	7.0	16.7	35.1	46.1
Late Stock	0.12	7.3	15.6	34.4	47.6
165 kg N/ha	0.15	8.1	17.9	36.7	46.5
330 kg N/ha	0.09	6.3	14.4	32.7	47.1
S.E. (21 D.F.)	0.017	0.44	0.89	1.28	1.94

The effects of timing of seed production, N application rate and irrigation scheduling on total N uptake are shown in Table 68. On average, total N uptake reached a maximum of 268 kg N/ha at the penultimate harvest and then decreased by *c.* 40 kg at the final harvest. This decrease was probably due to a failure to fully recover senescing/senesced haulm at the final harvest. Total N uptake was numerically larger when irrigation had been scheduled and, for the latter part of the season, when 330 kg N/ha had been applied.

Table 68. Main effects of irrigation regime, seed stock and N application rate on total N uptake (kg N/ha)

	Harvest 1 5 June	Harvest 3 19 June	Harvest 5 3 July	Harvest 7 31 July	Harvest 8 20 September
Mean	0.6	118	200	268	226
Scheduled	0.6	128	225	279	240
Variable	0.6	107	174	257	211
Early stock	0.6	122	205	274	217
Late Stock	0.6	113	194	262	234
165 kg N/ha	0.7	120	187	247	200
330 kg N/ha	0.5	115	212	289	251
S.E. (21 D.F.)	0.08	7.8	8.4	9.7	12.2

The rate of tuber N uptake and asymptotic value of total N uptake was estimated from the parameters of straight lines or exponential curves fitted to value of tuber and total N uptake in relation to radiation absorption, respectively. From these data estimates were made of maximum haulm N uptake and potential canopy persistence. The rate of tuber N uptake was significantly increased when the N application rate was increased from 165 to 330 kg N/ha but the onset of the linear phase of N uptake was delayed by the larger N application rate (Table 69). Increasing the N application rate from 165 to 330 kg N/ha increased the asymptotic value for total N uptake from 229 to 284 kg N/ha. This represents an efficiency of N uptake of *c.* 33 %. Haulm N uptake was significantly increased when the N application rate was increased and also when irrigation was scheduled. When averaged over all treatments, the CUF N model estimated the potential radiation absorption to be *c.* 17.8 TJ/ha. The model estimated that potential radiation absorption would be increased by applying more N, but would not be affected by either irrigation regime or seed stock. When compared with what the crop actually absorbed during the season (Table 65), the model overestimated yield by about 3 TJ/ha which is equivalent to 15-18 t tuber FW/ha. The CUF N model would therefore have predicted that, on average, the potential yield for this crop should have been 62-65 t/ha rather than the 47 t/ha that was actually achieved. The CUF N model assumes that senescence is the inevitable consequence of the transfer of N from haulm to tuber and it is probable that the factor that reduced RUE between the penultimate and final harvest was also responsible for the premature senescence of the crop which disrupted the N translocation resulting in a failure to achieve yield potential.

Table 69. Main effects of irrigation regime, seed stock and N application rate on parameters of N uptake and potential radiation absorption

	Rate of tuber N uptake (kg N/TJ)	Start of tuber N uptake (TJ/ha)	Asymptotic total N uptake (kg N/ha)	Maximum haulm N uptake (kg N/ha)	Potential radiation absorption (TJ/ha)
Mean	11.75	0.47	256	157	17.83
Scheduled	12.26	0.42	273	170	18.04
Variable	11.23	0.52	240	143	17.61
Early stock	11.89	0.51	251	156	17.30
Late Stock	11.60	0.43	262	158	18.36
165 kg N/ha	10.95	0.24	229	142	16.93
330 kg N/ha	12.54	0.70	284	171	18.72
S.E. (21 D.F.)	0.417	0.088	13.2	4.6	0.426

Precision irrigation and non-water based suppression of potato common scab in 2007

Introduction

This experiment formed part of the LINK Collaborative Research grant (SA-LINK LK0989) and was primarily designed to improve the efficiency of common scab control. In June 2007, it was noticed that one of the irrigation application methods (sprinkler) had resulted in a much paler canopy suggesting that this crop had taken up less N. This opportunity was used to test the effect of the irrigation treatments on N uptake, canopy persistence and yield.

Materials and Methods

The experiment was a fully-randomized factorial design involving four irrigation treatments (unirrigated; late irrigation from the end of the scab control period (8 weeks post tuber initiation); bi-daily drip irrigation for 8 weeks post-initiation; twice-daily micro-sprinkler irrigation for 8 weeks post-initiation) and four levels of sulphur amendment (0, 50, 125, 250 kg S/ha). There were three replicate blocks. The experiment was planted on 4 April using 35-40 mm Maris Piper seed at 30 cm spacing into pre-formed ridges. Sulphur amendments (micronised elemental sulphur (695 g S/l) suspension fertilizer, Omex) were sprayed onto ridges just prior to planting and incorporated into the ridge by raking following dibbing. Irrigation was scheduled using the CUF Potato Irrigation Scheduling Scheme. Drip irrigation was via Nelson Pathfinder ultra-low flow (1.25 l/m/min, 20 cm emitter spacing) tape (Wroot Water Ltd) installed in the ridge after planting at a depth of 50-60 mm and 20 mm to the right of the centre of the ridge to avoid the seed tuber. Drip-irrigated plots were calibrated to receive the same total dose of irrigation each morning (05:00) and evening (19:00) as the sprinklers but the application took 3.1 times longer. The sprinklers (Dan Modular Small Swivel Yellow Anti-mist nozzles) were on 1 m risers and installed in every alternate furrow at 1 m spacing. They were adjusted to run at very low pressure (*c*. 0.5-0.6 bar) to reduce the risk of misting and drift into adjacent plots. Application amounts at each irrigation ranged from 1-2 mm (i.e. 2-4 mm/day) to account for an expanding crop canopy and variable atmospheric demand. A total of 143 mm was applied during the 8 weeks of scab control (*c*. 3.0 mm/day).

Plant emergence was measured every 3-4 days until complete and ground covers were measured weekly from 50 % plant emergence to final harvest using a grid. Two harvests of 12 plants (2.743 m^2) were taken on 16 July (*c.* 70 DAE) and 13 September (*c*. 129 DAE). Measurements of N uptake were restricted to drip and sprinkler irrigated plots that received no sulphur (a total of six plots). At each harvest, the number of plants and stems was recorded and all tubers > 10 mm were collected. The haulm FW was recorded and a representative sub-sample (*c.* 1 kg) was removed. The tubers were graded in 10 mm increments and the number and weight of tubers within each grade was recorded. A sub-sample of tubers (*c.* 1 kg) was taken from the 50-60 mm size grade and was then washed, chipped and dried (together with the haulm sub-samples) to constant weight at 90 °C. The dried haulm and tuber samples were then sent to a commercial laboratory for measurement of total N concentration.

Results and Discussion

Emergence and ground cover

On average, 50 % plant emergence was attained on 7 May (33 DAP) and the final plant population was only 91 % of that intended. The pattern of ground cover development for the drip and sprinkler irrigated crops is shown in Figure 22 whilst Table 70 shows the effects of the treatments on season-long integrated ground cover and radiation absorption. There was some evidence that expansion of the canopy was slower when drip irrigation had been used. The season-long integrated ground cover average 7403 % days and the average total radiation absorbed was 11.89 TJ/ha. Irrigation treatment had no significant effect on either integrated ground cover or radiation absorption.

Figure 22. Effect of drip irrigation (□) and sprinkler irrigation (■) on the development of ground cover in Maris Piper, CUF 2007.

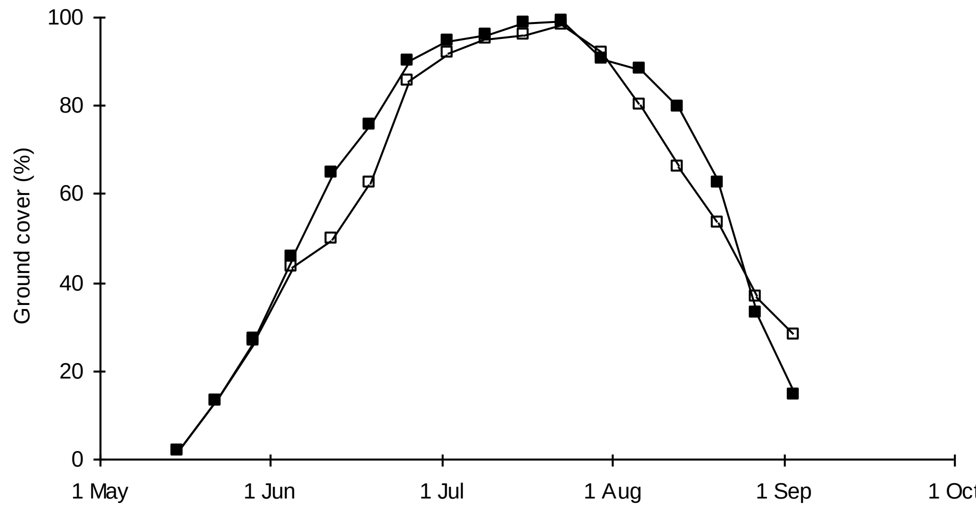


Table 70. Effect of drip or sprinkler irrigation on season-long integrated ground cover and radiation absorption

	Integrated ground cover (% days)	Radiation absorption (TJ/ha)
Drip irrigation	7254	11.64
Sprinkler irrigation	7552	12.14
Mean	7403	11.89
S.E. (2 D.F.)	445.8	0.609

Yields and N uptakes on 16 July and 13 September

The method of irrigation had no effect on stem population and this was *c.* 105 000/ha at both harvests (Table 71). Between the two harvests, there was a small increase in the number of tubers per stem and, in consequence, tuber population but these increases were not statistically significant. At the first harvest, there was an indication that sprinkler irrigation increased the number of tubers set per stem but this effect was temporary and was not evident at the second harvest.

Table 71. Stem and tuber population at the first and second harvests

	Harvest 1 16 July	Harvest 2 13 September
Number of stems (000/ha)	104 ± 8.9	105 ± 9.3
Tubers > 10 mm per stem	3.80 ± 0.248	4.08 ± 0.337
Number of tubers > 10 mm (000/ha)	396 ± 13.2	424 ± 21.5

The first sampling was taken on 16 July (70 DAE) when tuber FW yield averaged 33.2 t/ha (Table 72). Tuber FW and total DW yield were numerically larger when irrigation had been applied using sprinklers but these effects were not statistically significant. Haulm and total N uptake was larger when the crops had been drip irrigated but the difference was only 12-14 kg N/ha and was not significant. Thus large differences in canopy appearance were apparently generated by relatively small differences in haulm and total N uptake. At the second harvest on 13 September, the average yield had increased to 51.6 T/ha and the total DM yield had increased to 15.2 t/ha (Table 73). Tuber, haulm and total N uptake were numerically larger when irrigation water had been applied by a drip system but these effects were non-significant.

Table 72. Effect of drip or sprinkler irrigation on tuber FW yield, total DW yield and N uptake on 16 July

	Tuber FW yield (t/ha)	Total DW yield (t/ha)	Tuber N uptake (kg N/ha)	Haulm N uptake (kg N/ha)	Total N uptake (kg N/ha)
Drip	30.3	9.42	61	52	113
Sprinkler	36.0	9.67	62	38	101
Mean	33.2	9.54	62	45	107
S.E. (2 D.F.)	1.57	0.429	5.4	6.7	12.0

Table 73. Effect of drip or sprinkler irrigation on tuber FW yield, total DW yield and N uptake on 13 September

	Tuber FW yield (t/ha)	Total DW yield (t/ha)	Tuber N uptake (kg N/ha)	Haulm N uptake (kg N/ha)	Total N uptake (kg N/ha)
Drip	48.7	15.20	135	21	156
Sprinkler	54.4	15.20	121	16	137
Mean	51.6	15.20	128	19	147
S.E. (2 D.F.)	5.90	1.65	14.5	1.8	16.2

Efficiency of total and tuber DM production and parameters of N uptake and redistribution

The efficiency with which absorbed radiation was converted to total or tuber DM yield was estimated from the parameters of linear regressions of total or tuber DM yield against radiation absorption. Similarly, the rate of tuber N uptake and asymptotic value of total N uptake was estimated from the parameters of straight lines or exponential curves fitted to tuber and total N uptake in relation to radiation absorption respectively. The efficiency of total DM production averaged 1.33 t/TJ and differences between drip and sprinkler irrigation were small and non-significant (Table 74). The mean value was similar to that found in other experiments at CUF in 2007 (i.e. Variety and Nitrogen p. 49 and Rate and Timing of N p. 59). The efficiency with which absorbed radiation was converted to tuber DM averaged 1.09 t DM/TJ and this value was again similar to those found in other experiments. The rate of tuber N uptake was numerically larger when drip irrigation was used but this difference was not statistically significant and the average rate of tuber N uptake was 10.7 kg N/ha/TJ. Between the first harvest (70 DAE) and the second (129 DAE), average total N uptake increased by 40 kg N/ha (from 107 to 147 kg N/ha). This increase in total N uptake is a little larger than would be expected but it is still consistent with the bulk of N uptake occurring early in the growing season. Furthermore, between the first and second harvests the crops absorbed an average of 5.73 TJ/ha and this corresponds to an average rate of total N uptake of *c.* 7 kg N/TJ. This is slower than the rate of tuber N uptake and resulted in removal of N from the canopy leading to senescence. Since N uptake was only measured on two occasions, the asymptotic value for total N uptake could not be estimated with certainty and differences between treatments were non-significant.

Table 74. Effect of drip or sprinkler irrigation on efficiency of total and tuber DM production, rate of tuber N uptake and the asymptotic value of total N uptake

	Radiation use efficiency for total yield (t DM/TJ)	Radiation use efficiency for tuber yield (t DM/ha)	Rate of tuber N uptake (kg N/TJ)	Asymptotic value for total N uptake (kg N/ha)
Drip	1.36	1.08	11.6	205
Sprinkler	1.30	1.09	9.9	172
Mean	1.33	1.09	10.7	188
S.E. (2 D.F.)	0.075	0.182	0.80	46.0

Conclusions

Despite generating visual difference in canopy colour or "vigour", the effects of irrigation method on total N uptake and the rate of tuber N uptake were small and non-significant. In consequence, sprinkler irrigation had no significant effect on canopy persistence, total DM yield or tuber FW yield. Thus, the main conclusion from this experiment is that large differences in canopy appearance (i.e. as colour or "vigour") early in the season may be due to relatively small, and statistically insignificant, changes (*c.* 12-14 kg N/ha) in haulm or total N uptake and these visual differences do not always translate into yield differences.

SECTION 3

Timing of crop sampling

The CUF N management model relies on a crop sample taken at *c.* 50 DAE to measure N uptake by the haulm and tubers. There would economies if this sample could also be used to accurately measure tuber FW yield, mean tuber size and tuber size distribution. The purpose of this section is to investigate whether the optimal timing for the accurate measurement of yield and tuber size distribution is similar to the optimal time of sampling for measurement of crop N status. This analysis is based on several data sets collected in commercial crops within the USA, however conclusions will be relevant to UK grown crops.

Travis (1987) showed that the mean tuber size (μ) was related to tuber yield and the number of tubers by the equation:

$$\mu = k\left(\frac{Y}{N}\right)^{\frac{1}{3}} \quad \text{Equation 1}$$

where Y is the total fresh weight yield, N is the number of tubers and k is a dimensional factor that is related to tuber shape. For the varieties grown by Farming Technologies Corporation in California and Colorado, k at final harvest had values ranging from 117-119 (Asterix, Innovator and Norkotah) to 130-134 (Bildstar and Island Sunshine) to 139 (Red Lasoda). Travis (1987) also showed that if yield and μ were measured at an early harvest (Y_1 and μ_1, respectively) then mean tuber size at a subsequent harvest with a yield of Y_2 could be estimated by:

$$\mu_2 = \mu_1\left(\frac{Y_2}{Y_1}\right)^{\frac{1}{3}} \quad \text{Equation 2}$$

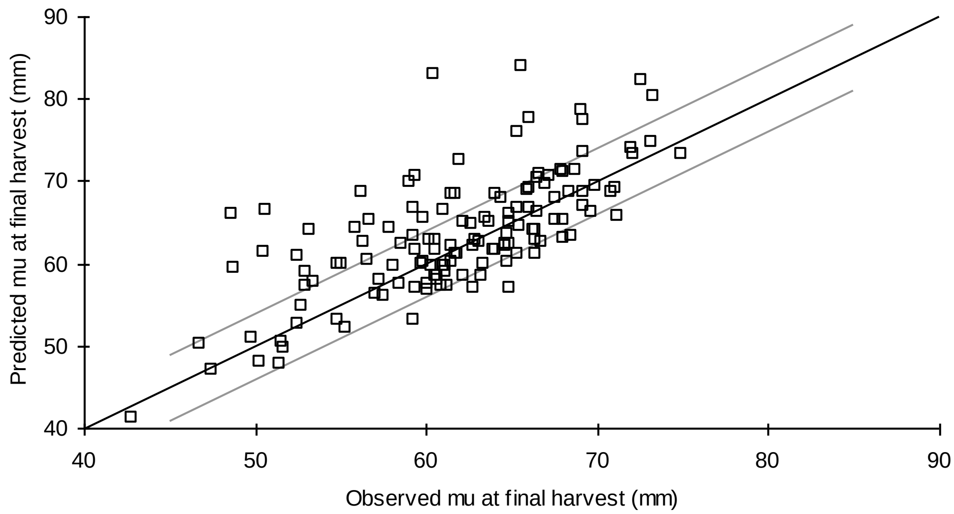
This relationship assumes that the number of tubers and tuber shape remain relatively constant between harvests. O'Brien *et al.* (1998) showed that there was little change in tuber populations > 10 mm from *c.* 45-50 DAE. Thus, for initial yield samples in

California and Colorado taken from 45 DAE onwards, the tuber population > ½ inch (12.7 mm) should be sufficiently stable for predictive purposes.

The purpose of the following section was to assess the accuracy of the CUF model (based on Equation 2) in predicting the mean tuber size at defoliation. The predictions use measured values of yield and mean tuber size at an early sampling (i.e. Y_1 and μ_1) and the measured yield at the defoliation sample (Y_2) to predict the mean tuber size at defoliation (μ_2). These predicted values were then compared with observed values of mean tuber size that were estimated directly from the graded harvest data. Data were used from Colorado 2005 (33 Crops), Colorado 2006 (25 Crops), Colorado 2007 (52 Crops), California 2006 (17 Crops) and California 2007 (9 Crops). Thus, in total, predictions of μ at final harvest were made for 136 crops.

For all 136 crops, the average observed value for mu was 61.8 mm whilst the average predicted value was 63.4 mm showing that using Equation 2 resulted in a slight overestimate of μ. The relationship between the predicted and observed mean tuber size is shown in Figure 23. Ideally all the points should lie upon the red 1 : 1 line but most values lie within ± 4 mm of the 1 : 1 line. The limit of ± 4 mm is arbitrary but is similar to typical standard errors associated with the measurement of μ in commercial crops. However, for some crops the predicted μ are substantially greater than those observed and using these predicted values to guide defoliation could result in large financial losses. It is important that the causes for these errors are understood.

Figure 23. Comparison of observed μ at final harvest with those predicted using tuber yield and mean tuber size measured at the initial harvest. The black line is the 1 : 1 relationship and the grey lines are the 1 : 1 relationship ± 4 mm.

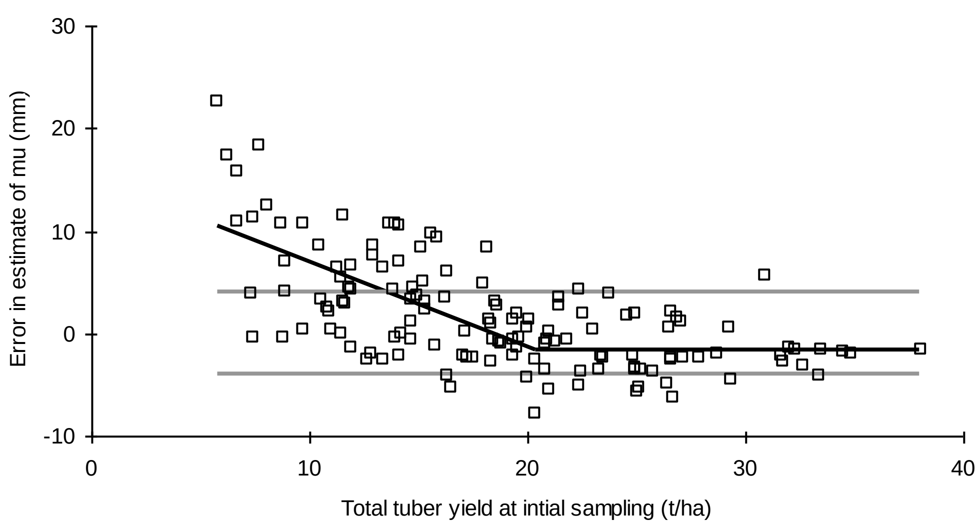


Further examination of the data showed that the largest errors in the estimate of μ were associated with estimates that were based on small yields at the initial sampling (Y_1). The relationship between the error in the estimate of μ at the final harvest and yield at the initial harvest is illustrated in Figure 24. The error (as mm) is calculated as predicted–observed and thus positive values for error were caused by the predicted being larger than the observed mean tuber size. These data were analysed by fitting a "bent stick" model to the data. This regression explained 45 % of the variation in the error in mu and also showed that once the yield at the first sampling (Y_1) exceeded 20.3 ± 0.28 t/ha the error was then independent of the yield and the errors in estimate of μ were generally within 4 mm of the observed μ. Of the 136 crops analyses, 82 had yields less than the 20.3 t/ha threshold and these would have compromised the accuracy of predictions. Therefore to minimise the risk of overestimating final mean tuber size, the yield at the first sampling should be at least 20 t/ha. For crops in California and Colorado this occurs, on average, at 42 DAE and 57 DAE, respectively (Table 75). However, factor such as slow initial bulking (as sometime seen in Asterix and Island Sunshine) or damage to the crop canopy may delay this. The initial sampling, therefore, needs to be scheduled according to crop development rather than any rigidly fixed date. This is important and needs to be considered when planning crop sampling strategies.

Table 75. Estimates (from CUF Yield model) of time from emergence to achieve 20 t/ha

Colorado 2007	Number of fields	Days	S.E.
Agria	1	47	-
Asterix	2	70	5.1
Bildstar	7	49	3.0
Canela	1	61	-
Centennial	2	57	5.0
Fabula	1	41	-
Innovator	3	57	1.7
Island Sunshine	5	63	3.6
Norkotah	16	62	1.7
Rio Grande	1	56	-
Satina	5	66	2.4
Yukon Gold	8	46	1.8
Mean for Colorado 2007		57	1.3
California 2007	Number of fields	Days	S.E.
Asterix	3	45	4.2
Innovator	4	43	1.0
Norkotah	3	46	0.7
Red Lasoda	8	38	1.6
Satina	7	43	1.5
Yukon Gold	1	46	-
Mean for California 2007		42	1.0

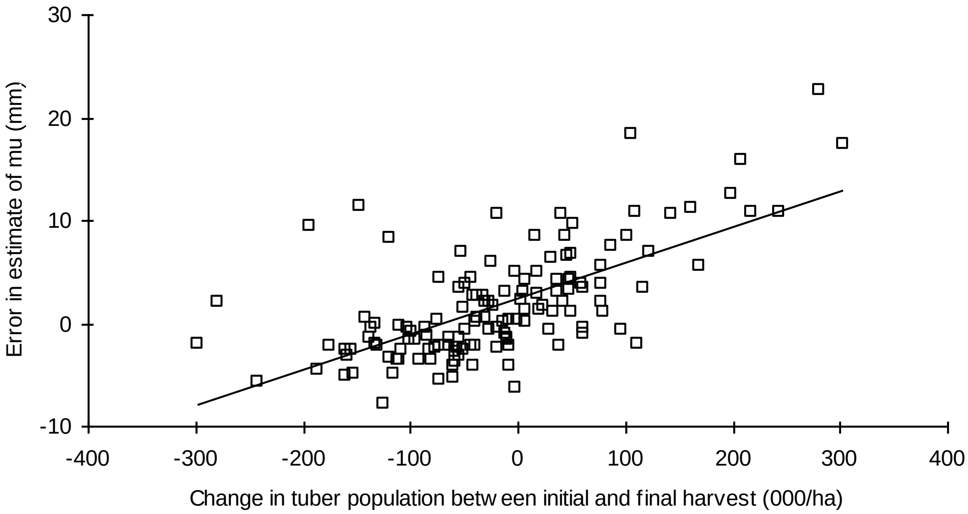
Figure 24. Relationship between errors in the estimate of μ at final harvest and tuber yields at the initial sampling. The black line is fitted (see text) and the grey lines are ± 4 mm.



There may be several reasons why predictions of μe prone to error when they are based on small yields. The equation developed by Travis (1987, Equation 2 above) assumes that the number of tubers and tuber shape remains relatively constant between harvests, thus changes in tuber population and tuber shape may explain why predicted values of μ differ from observed values. Figure 25 shows that if there is an increase in the number of tubers between the first and final harvest then the predictions of mean tuber size based on the first harvest will be too large (i.e. a positive error). Predictions of μ will also be too large if the value for k decreases between the initial and final harvest (i.e. the tubers become longer). Simple linear regression shows that changes in tuber population and shape between the initial and final harvest account for 43 and 25 % of the error in the estimate of mean tuber size, respectively. If these two factors are combined in multiple linear regressions then the regression equation explains 92 % of the variation (Table 76). Thus, if tuber shape and tuber population remained constant between the initial and final harvests (or any changes were predictable) then μ at final harvest could be predicted with much more certainty. A key step in achieving much more reliable predictions of μ would be to have reliable data forming the basis of the predictions and this is related to the timing of sampling.

Figure 25. Relationship between error in the estimate of mu and (a) changes in tuber population between initial and final Sampling; (b) changes in tuber shape between initial and final sampling. The black line is regression line (see text).

(a)



(b)

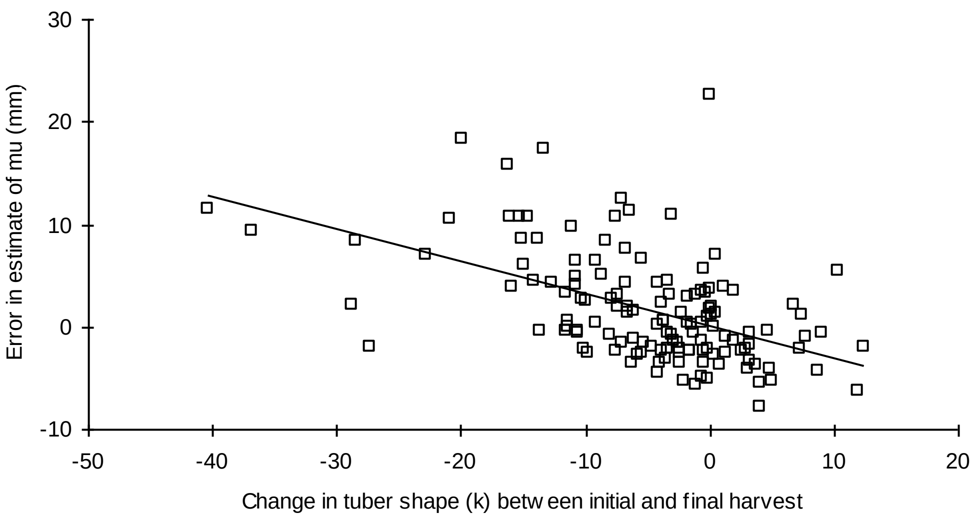


Table 76. Regression parameters relating errors in the estimate of mu to changes in tuber population and change in tuber shape between the initial and final harvests

Independent variable	Constant	Slope	R^2	F ratio
Change in tuber population (000/ha)	2.35 (± 0.352)	0.035 (± 0.0034)	43.1	< 0.001
Changes in tuber shape (k)	0.12 (± 0.46)	-0.316 (± 0.0462)	25.4	< 0.001
Change in tuber population (000/ha) Changes in tuber shape (k)	0.32 (± 0.146)	0.044 (± 0.0012) -0.045 (± 0.0015)	92.4	< 0.001

Maximum crop value is attained at a precisely defined mean tuber size and decision support systems need to be able to accurately predict changes in mean tuber size with changes in yield. The CUF model can achieve this precision but needs high quality input data and this quality cannot be achieved from harvests taken too early in the season. For crops in the USA, reliable estimates of yield and mean tuber size are obtained once total tuber yield is *c.* 20 t/ha, and depending on the variety/location this is typically achieved 45-55 DAE. For crops in the UK, tuber yields of 20 t/ha are also dependent on variety and location but are typically achieved *c.* 50 DAE and are therefore also suitable for measurement of N uptake in order to predict canopy persistence.

Varietal differences in N uptake and fertilizer requirements

Current N recommendations for potatoes in England and Wales (RB 209, MAFF 2000) are based, in part, upon the intended season length (i.e. from emergence to defoliation/senescence) and the determinacy of the variety. At present, a variety's determinacy can be inferred from N response experiments or observations of the effects of N supply on canopy architecture. However, these methods tend to be slow, ambiguous and can delay the optimising of the agronomy of a new variety. The CUF N management model shows that yield potential is related to total N uptake and the rate at which N is then transferred to the tubers. Long-lived varieties are associated with large total N uptakes and relatively slow rates of transfer of N to the tubers. Conversely, varieties that have limited canopy persistence tend to be associated with limited total N uptakes and rapid rates of transfer to the tubers. Using measurements of haulm and tuber N uptake taken *c*. 50 DAE, the CUF N management model can be used to estimate the maximum amount of N taken up by the crop haulm (as kg N/ha) and the rate at which N is transferred from the haulm to the tubers in relation to the amount of solar radiation absorbed by the crop (as kg N/TJ). Dividing the value for haulm N by the rate at which it is transferred from the haulm to the tuber gives a crude estimate (as TJ/ha) of how much energy the crop would need to absorb before the canopy was totally depleted of N and therefore completely senesced. This value is a measure of canopy persistence and can be used to rank varieties according to their determinacy so that fertilizer N requirements can be calculated. Values for tuber N uptake rate, maximum haulm N uptake and the ratio of these variates for several crops grown at CUF and elsewhere in the UK are shown in Table 77. Within each experiment the ranking of the ratio corresponds with the variety's determinacy group. For example for CUF 2004, Cara (determinacy group 4) had the largest ratio, Estima (determinacy group 1) had the smallest and Maris Piper and Russet Burbank (determinacy group 3) had similar but intermediate ratios. Similarly, for CUF 2005, Estima had the smallest ratio; Maris Piper and Burbank had large but similar ratios, whilst Hermes was intermediate. A further experiment at CUF in 2005 with Courlan and Estima suggested that Courlan was much more determinate than Estima. Other experiments and observations have shown that planting Courlan into cold soils inhibits leaf appearance and branching (i.e. making an already determinate variety become even more determinate). These results suggest that Estima may be at the upper end of determinacy Group 1 whilst Courlan may be at the lower end. Experiments at CUF in 2007 and measurements of commercially-planted crops in Shropshire show that Hermes is probably as indeterminate as Saturna. This is in contrast to current recommendations where Hermes is determinacy group 2 compared with group 3 for Saturna. However as noted in the BPC document *How to implement new 'RB209' nitrogen fertiliser recommendations on your farm – and save money* (BPC 2001), the current determinacy ranking for Hermes (determinacy group 2) was not certain and some agronomists would have placed Hermes in a more indeterminate group (determinacy group 3). The results from the studies in 2007 support this view. This example shows how the CUF N management model could be used to rapidly characterise new varieties as to their probable N requirement. This system has already been used to help refine PepsiCo's best practice guidelines for existing and new varieties. It is anticipated that work in 2008 will further develop this system.

In principle, the CUF N management model could also be used during the early stages of a varietal selection and development program to help identify traits for total and tuber N uptake that are associated with efficient N use and a canopy persistence that fills the intended growing season. Short season crops will tend to have a small value for 'r' (the shape of the exponential curve relating total N uptake to radiation absorption) and therefore the period over which they take up the bulk of their N is relatively short. Likewise, for similar N application rates, the asymptotic value for N uptake ('b') tends to be smaller in short season varieties compared with longer season varieties. Furthermore, in short season crops the linear phase of tuber N uptake tends to occur immediately after tuber initiation and the rate of tuber N uptake is also faster. In longer-season varieties (i.e. Russet Burbank) there is sometimes an appreciable delay between tuber initiation and the onset of the linear phase of N uptake and tuber bulking in relation to radiation absorption.

Table 77. Varietal differences in rates of tuber N uptake, maximum haulm N uptake and the ratio of haulm N to rate of tuber N uptake

Experiment, year (and N application rate)	Rate of tuber N uptake (kg N/TJ)	Maximum haulm N uptake (kg N/ha)	Ratio of haulm N uptake to rate of tuber N uptake (TJ/ha)
CUF 1997 (N160)			
Dovekie	17.3	124	7.2
Hermes	13.4	166	12.4
S.E.	0.68	5.0	0.44
CUF 1997 (N250)			
Cara	6.7	210	31.5
Estima	20.6	155	7.5
Hermes	17.5	185	10.5
Dovekie	14.1	118	8.4
Saxon	19.8	140	7.1
S.E.	1.05	15.5	0.66
CUF 2004 (N200)			
Cara	9.9	189	19.3
Estima	15.9	113	7.2
Maris Piper	13.5	152	11.3
Russet Burbank	14.9	149	10.1
S.E.	0.94	4.8	0.91
CUF 2005 (N200)			
Estima	15.0	82	5.5
Hermes	15.9	107	6.9
Maris Piper	14.5	119	8.3
Russet Burbank	12.5	104	8.3
S.E.	0.70	54.3	0.52
CUF 2005 (N100)			
Courlan	16.9	52	3.1
Estima	13.2	83	6.5
S.E.	0.63	3.4	0.19
CUF 2007 (N200)			
Hermes	13.8	110	8.2
Lady Rosetta	18.1	88	4.8
Saturna	16.4	119	7.8
Smiths Comet	19.8	89	4.5
S.E.	1.15	10.5	0.84
Shropshire 2007 (N351)			
Hermes	14.2 (± 0.96)	319 (± 14.5)	22.7 (± 2.32)
Saturna	13.4 (± 1.10)	220 (± 13.9)	16.8 (± 2.26)

Collation and preliminary analysis of N uptake data collected since 1997 show that when calculated on a plot-by-plot basis, the rate of tuber of N uptake is significantly correlated with the asymptotic value for total N uptake (Figure 26). Thus, for Estima increasing the total N uptake from 100 to 300 kg N/ha increases the rate of tuber N uptake from 11.7 to 21.2 kg N/TJ. This increase in the rate of tuber N uptake explains why canopy persistence is not directly correlated with total N uptake. Similarly, at a total N uptake of 200 kg N/ha there is more than a two-fold difference in the rate of tuber N uptake between contrasting varieties (Table 78). For a total N uptake of 200 kg N/ha the canopy persistence of Courlan might be only half that of Maris Piper and this illustrates why it sometime difficult to obtain canopies of Courlan than persist for a long as intended.

Figure 26. Relationship between rate of tuber N uptake and the asymptotic value for total N uptake in Estima (1997-2007). m = 0.048 (± 0.0017)b + 6.90 (± 0.327); n = 426; R^2 = 66.5; F <0.001

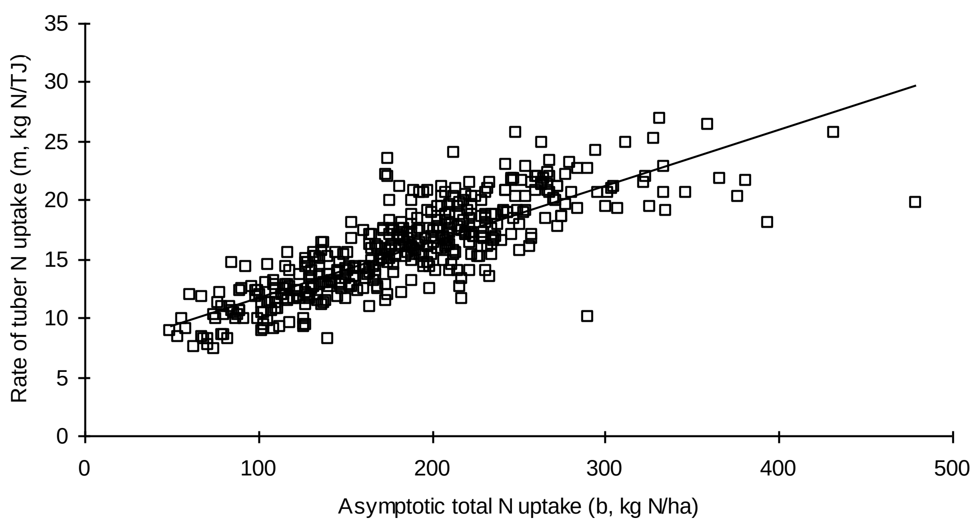


Table 78. Regression parameters for rate of tuber N uptake against total N uptake for four contrasting varieties and an estimate of the rate of tuber N uptake when total N uptake was 200 kg N/ha

Variety	Number of plots	R2	F	Rate of tuber N uptake (kg N/TJ)
Courlan	16	64.1	<0.001	27.7 ± 2.08
Estima	426	66.5	<0.001	16.5 ± 0.11
Maris Piper	198	57.1	<0.001	11.9 ± 0.13
Russet Burbank	85	59.1	<0.001	13.3 ± 0.26

Table 79 summarises the parameters of N uptake redistribution that are associated with short- or long-season crops. The preliminary analysis shows that some parameters are correlated, for example large total N uptakes (associated with varieties that use N efficiently) are often associated with longer delays between T.I. and the onset of tuber N uptake. However, an "ideal" crop would have the capacity to take large quantities of N but would start transferring N to the tuber (i.e. start to bulk) at T.I. It is not known at present how much plasticity there is within these relationships for different genotypes but analysis of historic data sets will continue in 2008 and will further investigate the relationships between N applied, N uptake and redistribution in relation to canopy persistence and yield formation.

Table 79. Varietal characteristics associated with short or long-season varieties

	Short season	Long season
Shape parameter of total N uptake curve (r)	Small	Large
Asymptotic value for total N uptake (a, kg N/ha)	Small	Large
Rate of tuber N uptake (m, kg N/TJ)	Large	Small
Onset of tuber N uptake (c, TJ/ha)	Small	Large

Use of the CUF N management model in commercial crops in 2006 and 2007

Introduction

The earlier parts of this report have described the detailed testing and refinement of various components of the CUF N management model under experimental conditions at CUF. The following part of the report is concerned with the testing of the model on commercially grown crops. The objectives of this work were:

1. To examine the practicalities of obtaining good quality information on crop growth and development and of sourcing good quality meteorological data.
2. To examine the accuracy of the N prediction model when used in a commercial context.

Material and Methods

In 2006 and 2007, the N prediction model was tested on twenty five crops shown in Table 80. Eighteen of these crops were destined for processing, six crops were for the table sector and one (Maris Peer MI) was grown for seed. For three of these crops the growers were unable to supply details of planting and emergence dates and weekly measurement of ground cover. One of the crops (Lady Rosetta BU-2) was a reduced N area (24 m wide strip that received 200 kg N/ha) within a normally fertilized (260 kg N/ha) crop of Lady Rosetta (BU-1).

For all crops, measurements of yield and N uptake were made on two occasions. The first sampling was typically 65 DAE and the second sampling was at the time of defoliation or commercial harvest (*c*. 110 DAE). At each sampling, between three and five replicate samples (each of *c.* 2.75 m^2) were hand dug from representative areas within each crop. The number of plants and above ground stems was recorded and all tubers > 10 mm were collected. The haulm was weighed in the field using either an electronic or spring balance and a representative sub-sample of the haulm (1-2 kg) was collected. The tubers and haulm sub-samples were then returned to CUF for processing. The tubers were graded in 10 mm increments and the number and weight of tubers in each size grade was recorded. A sub-sample of 50-60 mm tubers (*c*. 1 kg) was taken and the tubers washed and chipped. The tuber and haulm sub-samples were then dried at 90°C in a fan assisted oven until constant weight (typically 48 hours). The dried material was then sent to a commercial, accredited laboratory for measurement of total N content using a Dumas combustion method. The Marfona (LH and BW) and Maris Piper (GE) crops were sampled by commercial field personnel and the remainder of the crops were sampled by CUF staff.

The CUF N model relies upon the provision of daily values of total incident radiation. No suitable meteorological sites were found for Marfona (LH and BW) and Maris Piper (GE) in Suffolk in 2006. The meteorological site in Somerset experienced technical problems which prevented the collection of any useful data. The crops of Russet Burbank (MC, VF, BR, MQ) and Maris Peer (MI) used data from Morley Research Centre (near Wymondham, Norfolk) and the Lady Rosetta (EU, BU-1, US, JW) used data from Broom's Barn (Higham, Suffolk). In 2007, no suitable meteorological sites could be found for the crops grown in Yorkshire, Shropshire or Staffordshire. The two Russet Burbank (UT-1 and UT-2) crops in Staffordshire and the two Estima crops in Somerset (GC and NA) were also sampled as part of the BPC/CUF grower collaboration project (R295) that started in spring 2007.

Problems with sourcing good quality meteorological data were also encountered in the BPC/CUF Grower Collaboration Project. Hopefully, the problem will be resolved in the 2008 growing season by the purchase of pyramometers and data loggers which, after calibration against the CUF meteorological station, will be loaned to growers and placed close to crops being studied. The growers will periodically download the loggers and e-mail the data back to CUF. In addition, CUF has made an informal arrangement with British Sugar plc to use their meteorological data which is collected at each sugar factory for running yield prediction models.

Table 80. Details of commercial crops used in 2006 and 2007 for testing of N prediction model

Variety and field code	County	Emergence and ground cover data	Yield and N uptake data	Proximity of met. station to crop (km)	Date of planting	Date of 50 % plant emergence	Total amount of N applied (kg N/ha)	Date of first sampling	Date of second sampling
Marfona (LH)	Suffolk	No	Yes	n.a.	n.a.	n.a.	n.a.	22 Jun 06	26 Jul 06
Russet Burbank (MC)	Norfolk	Yes	Yes	24	4 Apr 06	8 May 06	220	3 Jul 06	24 Aug 06
Russet Burbank (VF)	Norfolk	Yes	Yes	24	2 Apr 06	8 May 06	240	3 Jul 06	24 Aug 06
Sante (LE)	Somerset	Yes	Yes	n.a	2 May	27 May	135	26 Jul 06	15 Aug 06
Lady Rosetta (EU)	Suffolk	Yes	Yes	18	15 Mar 06	7 May	280	4 Jul 06	22 Aug 06
Lady Rosetta (BU-1)	Suffolk	No	Yes	26	19 Mar 06	7 May	260	4 Jul 06	22 Aug 06
Lady Rosetta (BU-2)	Suffolk	Yes	Yes	26	19 Mar 06	7 May	200	4 Jul 06	22 Aug 06
Marfona (BW)	Suffolk	No	Yes	n.a	n.a.	n.a.	n.a.	3 Jul 06	26 Jul 06
Maris Piper (GE)	Suffolk	No	Yes	n.a.	n.a.	n.a.	n.a.	4 Jul 06	17 Jul 06
Russet Burbank (BR)	Norfolk	Yes	Yes	66	2 Apr 07	3 May 07	240	23 Jul 07	28 Aug 07
Russet Burbank (MQ)	Norfolk	Yes	Yes	70	17 Mar 07	30 Apr 07	220	23 Jul 07	28 Aug 07
Maris Peer (MI)	Norfolk	Yes	Yes	76	21 Apr 07	19 May 07	100	23 Jul 07	28 Aug 07
Lady Rosetta (US)	Norfolk	Yes	Yes	30	10 Apr 07	10 May 07	246	20 Jul 07	29 Aug 07
Lady Rosetta (JW)	Norfolk	Yes	Yes	41	30 Mar	3 May 07	252	20 Jul 07	29 Aug 07
Estima (GC)	Somerset	Yes	Yes	n.a.	26 Apr 07	26 May 07	160	25 Jul 07	23 Aug 07
Estima (NA)	Somerset	Yes	Yes	n.a.	18 Apr 07	19 May 07	172	25 Jul 07	23 Aug 07
Hermes (CO)	Yorkshire	Yes	Yes	n.a.	3 Apr 07	1 May 07	135	12 Jul 07	5 Sep 07
Hermes (RG)	Shropshire	Yes	Yes	n.a.	13 Apr 07	6 May 07	351	11 Jul 07	4 Sep 07
Saturna (RG)	Shropshire	Yes	Yes	n.a.	13 Apr 07	5 May 07	351	11 Jul 07	4 Sep 07
Hermes (CF)	Cambridgeshire	Yes	Yes	1	28 Mar 07	11 May 07	200	2 Jul 07	21 Aug 07
Lady Rosetta (CF)	Cambridgeshire	Yes	Yes	1	28 Mar 07	1 May 07	200	2 Jul 07	21 Aug 07
Smiths Comet (CF)	Cambridgeshire	Yes	Yes	1	28 Mar 07	6 May 07	200	2 Jul 07	21 Aug 07
Saturna (CF)	Cambridgeshire	Yes	Yes	1	28 Mar 07	29 Apr 07	200	2 Jul 07	21 Aug 07
Russet Burbank (UT-1)	Staffordshire	Yes	Yes	n.a.	18 Apr 07	13 May 07	220	31 Jul 07	12 Sep 07
Russet Burbank (UT-2)	Staffordshire	Yes	Yes	n.a.	18 Apr 07	13 May 07	165	31 Jul 07	12 Sep 07

Results and Discussion

Ground covers and radiation absorption

Ground cover development was measured in 19 commercial crops in 2006 and 2007. For some of these crops it was not possible to calculate the standard error for ground cover since only one measurement was reported (although more replicate measurements may have been taken in the field). The pattern of ground cover development in 2006 and 2007 is shown in Figures 27 to 30. With the exception of the Lady Rosetta (EU) grown in 2006, all crops achieved complete ground cover. The crop with the most persistent ground cover was Russet Burbank (MC) grown in Norfolk in 2006 (Table 81) which had an integrated ground cover of 7691 % days. Several other crops achieved integrated ground covers in excess of 7000 % days including the Russet Burbank crops at VF, BR and MQ, the Hermes crops at CO and RG and the Saturna crop at RG.

Owing to the problems in sourcing good quality meteorological data in 2006 and 2007, radiation absorption was estimated for only thirteen crops (Table 81). Radiation absorption was calculated by summing the products of the daily value for ground cover (calculated by linear interpolation) and the daily value for incident radiation. The smallest value for radiation absorption was 9.36 TJ/ha (a Maris Peer seed crop grown in Norfolk) and the largest was 14.35 TJ/ha for Russet Burbank (VF). As might be expected there was a highly significant correlation between season-long canopy persistence and radiation absorption (Figure 31). The regression explained *c.* 75 % of the variation in radiation absorption and the slope of the relationship (0.0018 TJ/ha/% day) was similar to values calculated for other UK crops.

Figure 27. Pattern of ground cover development for *(a)* Russet Burbank-BU, □; Russet Burbank-VF, ■; *(b)* Lady Rosetta-BU1, □; Lady Rosetta-EU, ■; (*c*) Sante-LE in 2006.

(a) *(b)* *(c)*

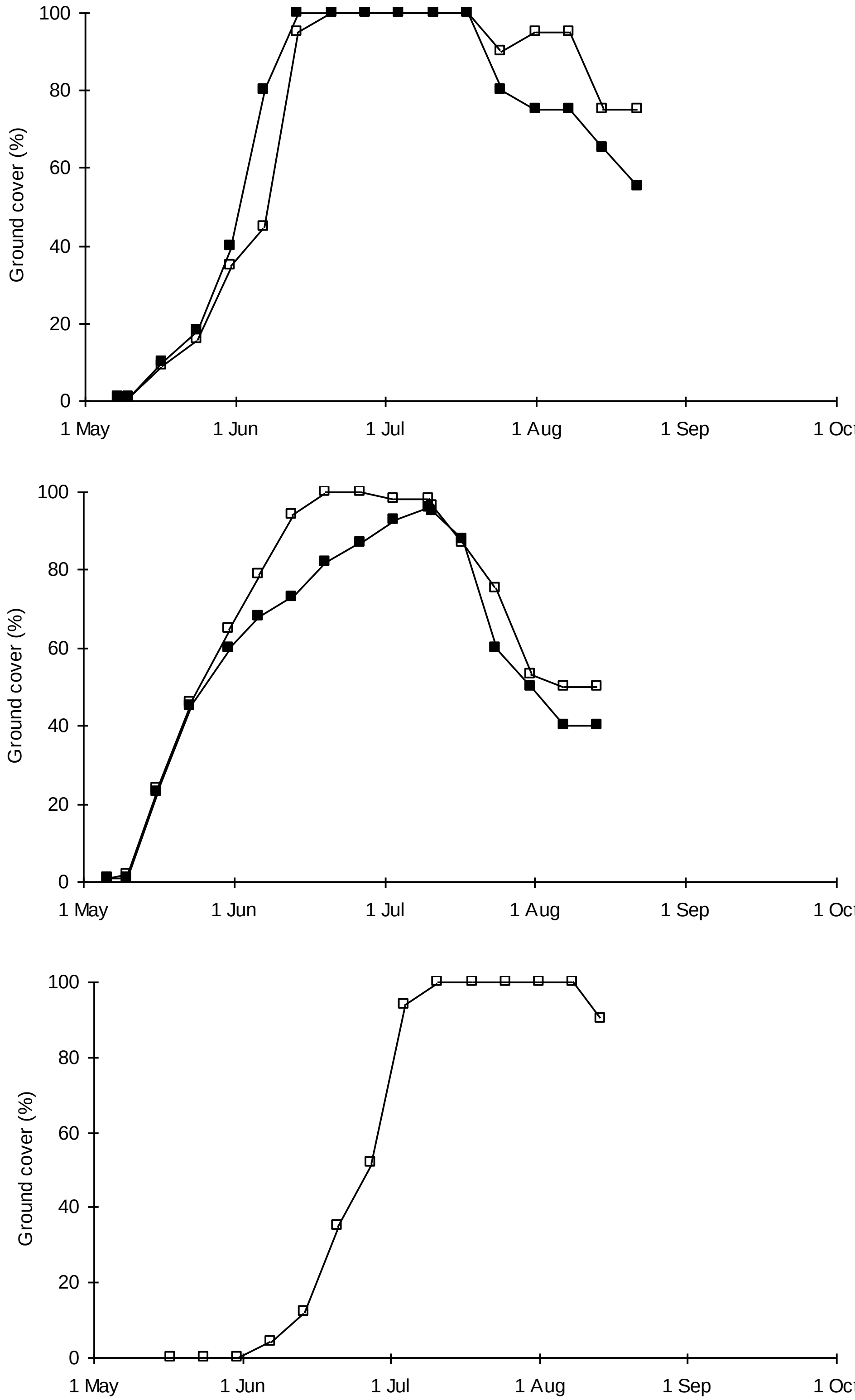
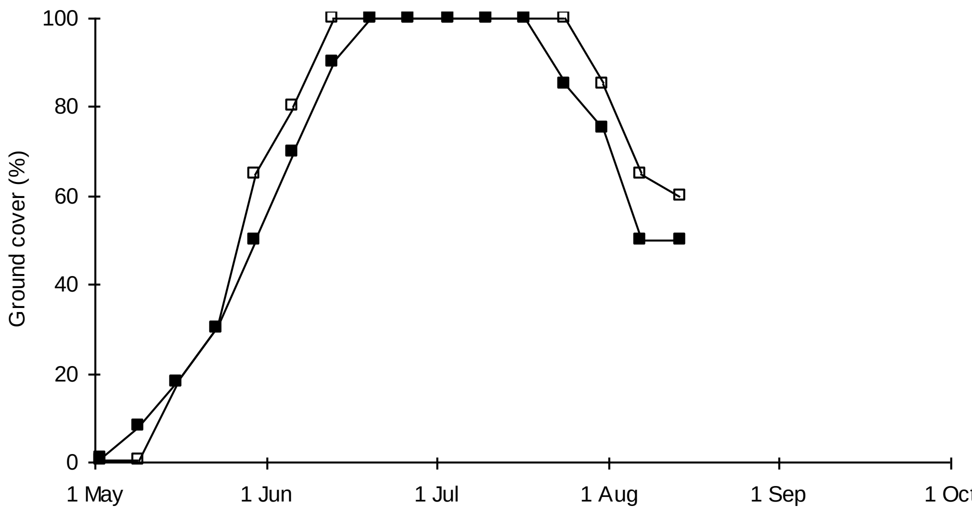


Figure 28. Pattern of ground cover development for *(a)* Russet Burbank-BR, □; Russet Burbank-MQ, ■; *(b)* Lady Rosetta-US, □; Lady Rosetta-JW, ■; (*c)* Maris Peer-MI in 2007.

(a)



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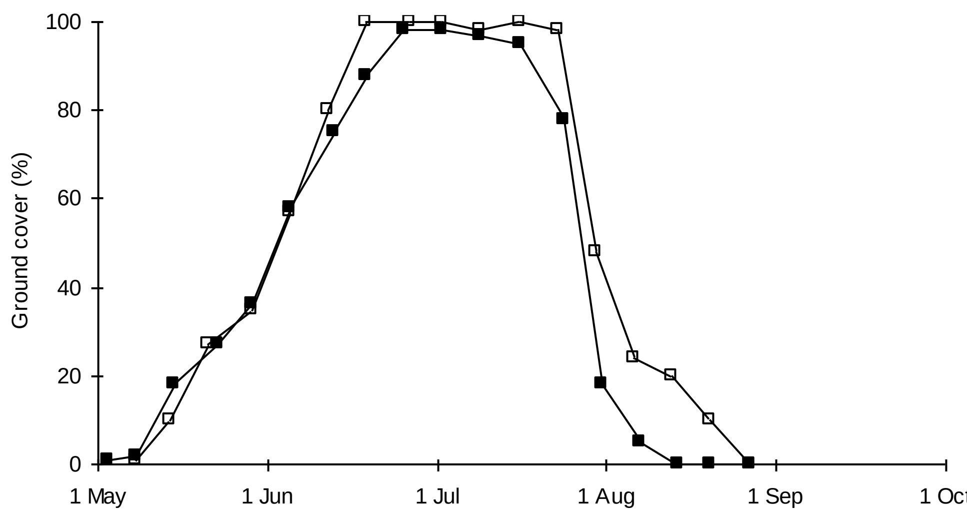


(c)

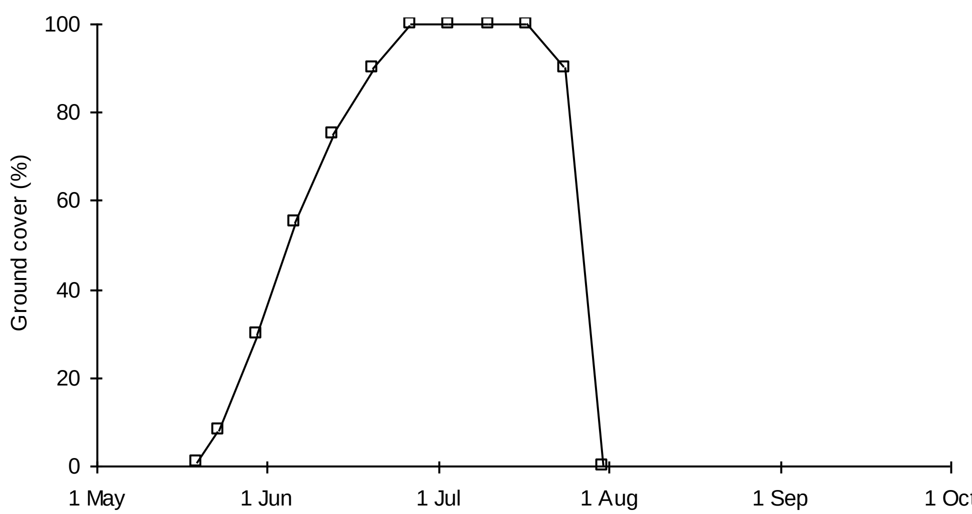
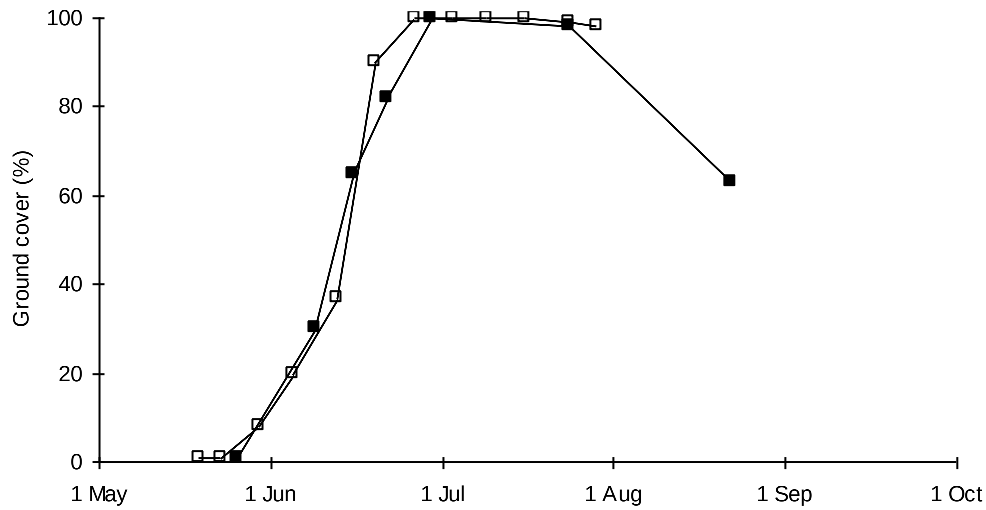


Figure 29. Pattern of ground cover development for *(a)* Estima-NA, □; Estima-GC, ■; *(b)* Hermes-C0; (*c)* Hermes-RG, □; Saturna-RG, ■ in 2007.

(a)



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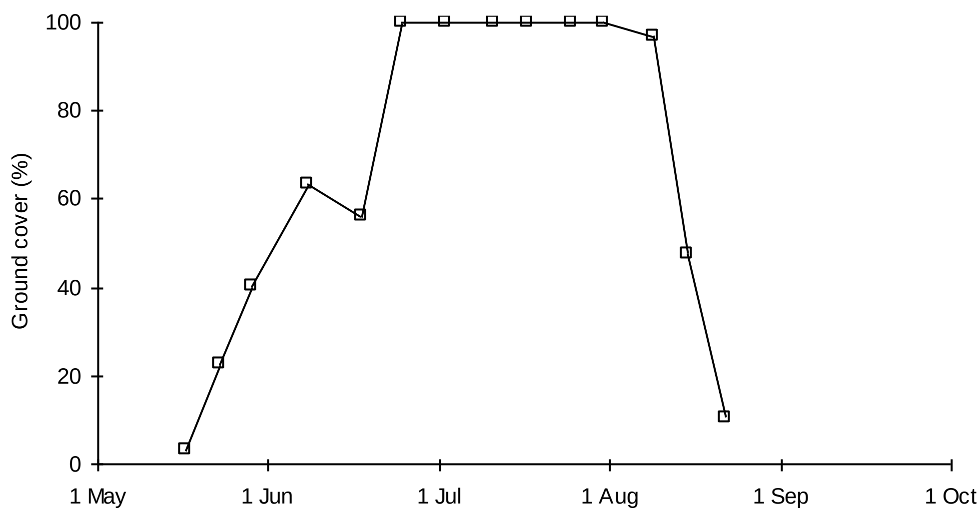

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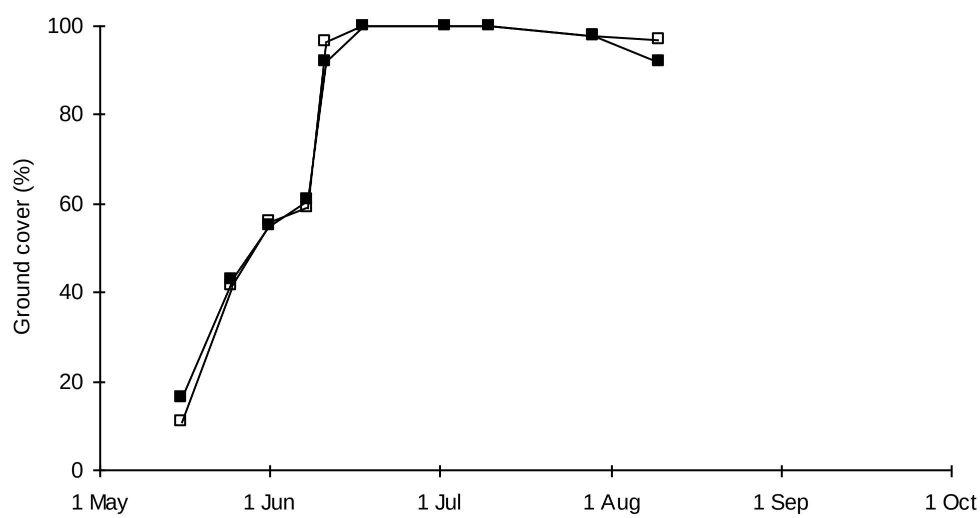


Figure 30. Pattern of ground cover development for *(a)* Hermes-CF, □, Lady Rosetta-CF, □; Saturna-CF, ▲; and Smith's Comet-CF, △.

(*a*)

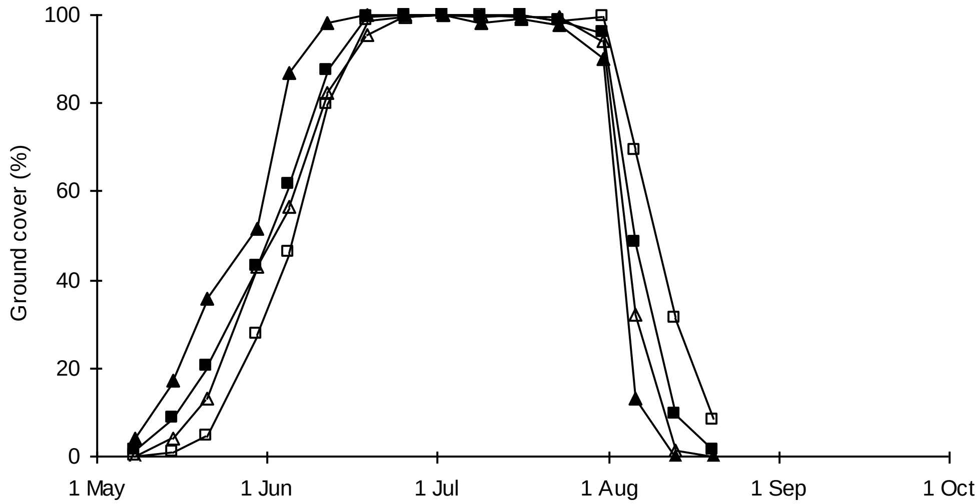


Table 81. Integrated ground cover and radiation absorption for 19 crops studied in 2006 and 2007

Variety and field code	County	N applied (kg N/ha)	Integrated ground cover (% days)	S.E.	Radiation absorbed (TJ/ha)	S.E.
Russet Burbank (MC)	Norfolk	220	7691	-	14.29	-
Russet Burbank (VF)	Norfolk	240	7527	-	14.35	-
Sante (LE)	Somerset	135	5151	-	-	-
Lady Rosetta (EU)	Suffolk	280	6200	-	12.53	-
Lady Rosetta (BU-1)	Suffolk	260	6967	-	14.07	-
Russet Burbank (BR)	Norfolk	240	7547	-	13.76	-
Russet Burbank (MQ)	Norfolk	220	7036	-	12.79	-
Maris Peer (MI)	Norfolk	100	5227	-	9.36	-
Lady Rosetta (US)	Norfolk	246	6346	-	11.38	-
Lady Rosetta (JW)	Norfolk	252	5616	-	10.07	-
Estima (GC)	Somerset	160	6560	-	-	-
Estima (NA)	Somerset	172	4894	-	-	-
Hermes (CO)	Yorkshire	135	7229	155.6	-	-
Hermes (RG)	Shropshire	351	7333	27.8	-	-
Saturna (RG)	Shropshire	351	7350	38.3	-	-
Hermes (CF)	Cambridgeshire	200	6730	67.6	11.32	0.117
Lady Rosetta (CF)	Cambridgeshire	200	6842	177.8	11.47	0.310
Smith's Comet (CF)	Cambridgeshire	200	6484	61.7	10.87	0.095
Saturna (CF)	Cambridgeshire	200	6963	104.1	11.57	0.178

Figure 31. Relationship between radiation absorption and integrated ground cover for 13 crops in 2006 and 2007. RA = 0.0018 (± 0.00003)GC; n = 13; R^2 = 75.2; F < 0.001.

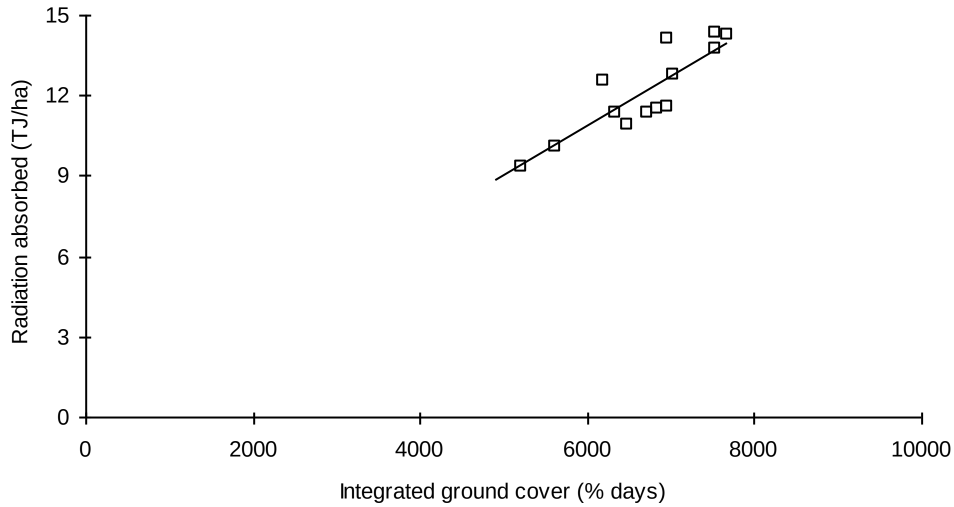
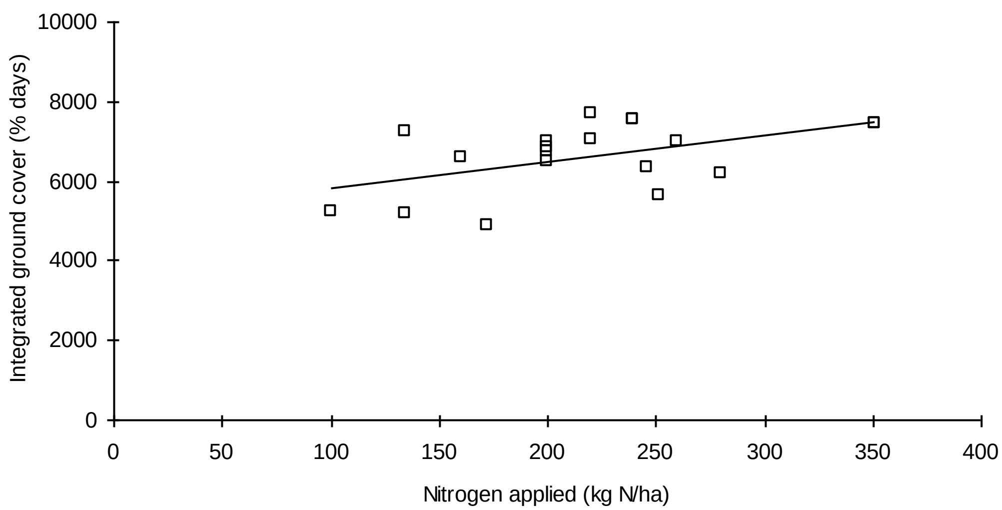


Figure 32. Relationship between integrated ground cover and N application rate for 19 crops in 2006 and 2007. GC = 6.27 (± 2.74)N + 5243 (± 625); n = 19; R^2 = 19.0; F = 0.035.



The relationship between integrated ground cover and N application rate was statistically significant but was weak (Figure 32). Therefore, applying large amounts of N fertilizer was no guarantee of persistent canopies, large values for radiation absorption or large tuber yields.

Measured yields and N uptake

Dry and fresh weight yields and N uptakes were measured on two occasions for all 25 crops. For some crops it was not possible to measure haulm yield and N uptake at the second harvest since they had already been defoliated. Generally, for each crop the number of plants, stems and tubers were similar at the first and second harvests (See Appendix Tables *1a* to *1f*) and this suggests that the crops were reasonably uniform and the first and second samples were taken from the same seed sizes/stocks within each field. For all 25 crops the average tuber FW yield at the first sampling was 34.1 t/ha and this had increased to 58.0 t/ha at the second sampling. The largest tuber FW yield at the second sampling was 70.2 t/ha (Lady Rosetta BO-2, 2006) and the smallest was 46.3 t/ha (Lady Rosetta JW, 2007).

Total (haulm and tuber) N uptake was measured at both harvests for 16 crops. For these crops, total N averaged 166 kg N/ha at the first harvest and 182 kg N/ha at the second. The small increase in total N uptake between the first and second harvests is consistent with the hypothesis that most N is taken up early in the season (within *c.* 55 DAE).

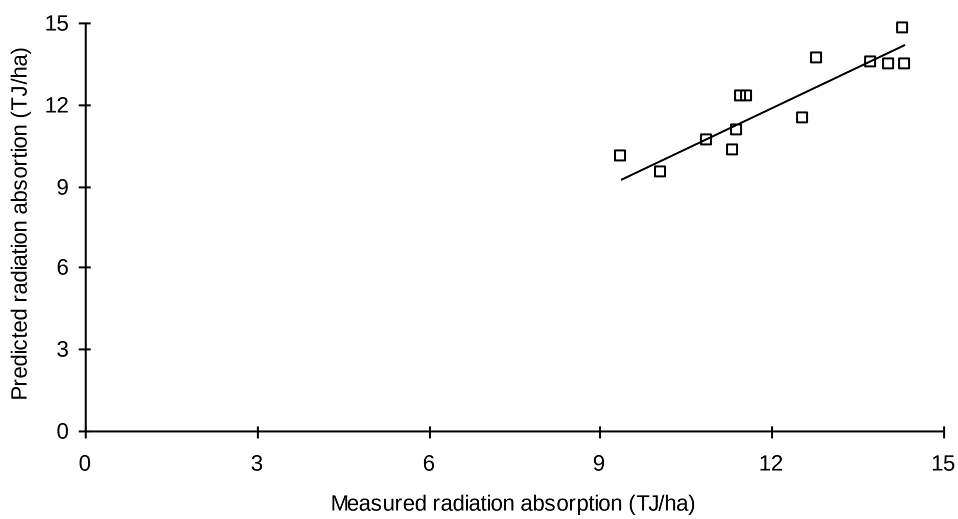
Prediction of potential radiation absorption based on N sampling

In total, predictions of potential radiation absorption were made for 13 crops. The predictions were based upon measured values for haulm and tuber N uptake at the first harvest in relation to an estimate the amount of radiation absorbed by the crop at the first harvest. For these 13 crops the amount of radiation absorbed by the crop at final harvest was estimated to be 12.03 TJ/ha (Table 82). In comparison, the CUF N model predicted that these crops had the potential to absorb 12.05 TJ/ha. These results suggest that, on average, the CUF model does not over or under-estimate potential radiation absorption and this is also illustrated in Figure 33. With the exception of one crop (Lady Rosetta (EU) all prediction or potential radiation absorption were within 1 TJ/ha of that actually achieved. Since, on average, the absorption of 1 TJ/ha of energy will generate *c.* 5 t tuber FW/ha it is possible from sample taken relatively early in the growing season to predict the final potential yield of the crop.

Table 82. Comparison of measured and predicted radiation absorption for 13 commercial crops studied in 2006 and 2007

Variety and grower/field code	County	N applied (kg N/ha)	Measured radiation absorption (TJ/ha)	S.E.	Predicted radiation absorption (TJ/ha)	S.E.
Russet Burbank (MC)	Norfolk	220	14.29	-	14.77	-
Russet Burbank (VF)	Norfolk	240	14.35	-	13.47	-
Lady Rosetta (EU)	Suffolk	280	12.54	-	11.45	-
Lady Rosetta (BU-1)	Suffolk	260	14.07	-	13.49	-
Russet Burbank (BR)	Norfolk	240	13.76	-	13.56	-
Russet Burbank (MQ)	Norfolk	220	12.79	-	13.67	-
Maris Peer (MI)	Norfolk	100	9.36	-	10.07	-
Lady Rosetta (US)	Norfolk	246	11.38	-	11.03	-
Lady Rosetta (JW)	Norfolk	252	10.07	-	9.52	-
Hermes (CF)	Cambridgeshire	200	11.32	0.117	10.31	0.700
Lady Rosetta (CF)	Cambridgeshire	200	11.47	0.310	12.29	1.055
Smith's Comet (CF)	Cambridgeshire	200	10.87	0.095	10.69	0.568
Saturna (CF)	Cambridgeshire	200	11.57	0.178	12.28	0.693
Mean			12.03		12.05	

Figure 33. Comparison of measured and predicted radiation absorption for 13 commercial crops studied in 2006 and 2007. Predicted = 1.00 (± 0.0176) Measured; R^2 = 78.7; F < 0.001.



Ongoing work at CUF on split N applications (p. 59) suggests that late applications of N have little material affect on N uptake, canopy longevity and yield potential. Thus, whilst the CUF N management system can identify crops which may yield less than intended this information may come too late to permit any remedial action (i.e. applying more N as a top-dressing). However, experiments in the UK and USA will test the reliability of the CUF N management system when making predictions at 30-40 DAE. If these are sufficiently accurate then this would permit top-dressings to be modified on the basis of crop N status.

A feature of the CUF N model is to provide advance warning of potential shortfalls in yield. Once provided with this information growers and their agronomists can better plan the marketing of their crops. The CUF N management system makes predictions of potential radiation absorption. If these predictions are used in conjunction with values for long-term average incident radiation then it is possible to estimate the date of canopy senescence. This information is of use to growers and agronomist for planning defoliation and harvesting schedules.

In summary, the CUF N management model has shown itself to be sufficiently robust for use in commercial crop as opposed to experimental crops where inputs are carefully controlled and within-crop variation is minimised. The predictions produced by the model are robust and of practical utility for the pro-active management of potato crops. The key limitation to more wide-spread use of the model is the provision of reliable meteorological data and supply of accurate information of crop emergence and ground cover development.

Analysis and modelling of the relationship between total N uptake, canopy persistence and yield can be used to understand limitations crop productivity. The Lady Rosetta crop (JW, 2007) received a total of 252 kg N/ha but this relatively large N application resulted in a total N uptake of only 137 kg N/ha (Table 83). This total N uptake was only sufficient for a canopy persistence of 5616 % days and a tuber FW yield of 46.3 t/ha. A modelling study showed that if were possible to increase the total N uptake by 27 kg N/ha then, in principle, canopy persistence should be increased *c.* 1000 % days (i.e. an extra 10 days at complete ground cover) and the tuber FW yield should increase by 7 t/ha. A similar result was found for a crop of Russet Burbank grown at Cambridge in 2006.

Table 83. Relationship between N uptake, canopy persistence and yield for crops of Lady Rosetta and Russet Burbank

	Crop 1	Crop 2
Variety	Lady Rosetta	Russet Burbank
Site and year	JW 2007	CUF 2006
Total N applied as fertilizer (kg N/ha)	252	125
Measured integrated GC (% days)	5616	6995
Measured radiation absorption (TJ/ha)	10.07	12.66
Measured tuber FW yield (t/ha)	46.3 (± 0.74)	57.8 (± 2.17)
Asymptotic value for total N uptake (kg N/ha)	137	250
Simulated integrated GC (% days)	6637	8000
Simulated radiation absorption (TJ/ha)	12.18	13.80
Simulated tuber FW yield (t/ha)	53.3	64.9
Asymptotic value for total N uptake (kg N/ha)	164	269
Increase in yield (t/ha)	7.0	7.1
Increase in total N uptake needed to increase yield (kg N/ha)	27	19

The modelling study makes several assumptions. An important assumption was that the rate of transfer of N from haulm to tubers was independent of the size of total N uptake, however data shown in Figure 26 suggest this is probably an over-simplification. Despite this the modelling study suggests that relatively small increases in total N uptake (20-30 kg N/ha) can increase the yield potential and change a mediocre crop into a crop with a yield and financial potential that is above average. The key question, which in not yet fully resolved, is how best to increase the N uptake and future work should concentrate on the relationship between soil N supply, soil condition and N uptake.

SECTION 4

Conclusions and areas for further development

British Potato Council project R273, *Improved Nitrogen Management for Potato Crops* had a remit to evaluate an N management system. The N management system was underpinned by research that described 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. The project had two distinct but complimentary objectives. The first was to test aspects of the CUF N model under UK and more extreme, USA conditions. This testing was to involve detailed measurements of crop growth and N uptake in randomised and replicated experiments. The second objective was to test the practicalities of using the N management model in closely-monitored commercial crops.

The studies in 2005 to 2007 have shown that that there was a clear link between yield potential and total N uptake of the potato crop. Thus, large N uptakes were usually associated with large tuber yields and small tuber yields were associated with small N uptakes (for example compare yields and total N uptakes in Table 53 and Table 55). The CUF N management system provides an explanation for varietal differences in N fertilizer requirement. Thus, at a given N application rate, determinate varieties (such as Estima) will tend to have smaller total N uptakes but will transfer N at a faster rate from haulm to tubers than more indeterminate varieties such as Maris Piper or Russet Burbank (Table 77). The two factors are consistent with the relative haulm longevity of these varieties.

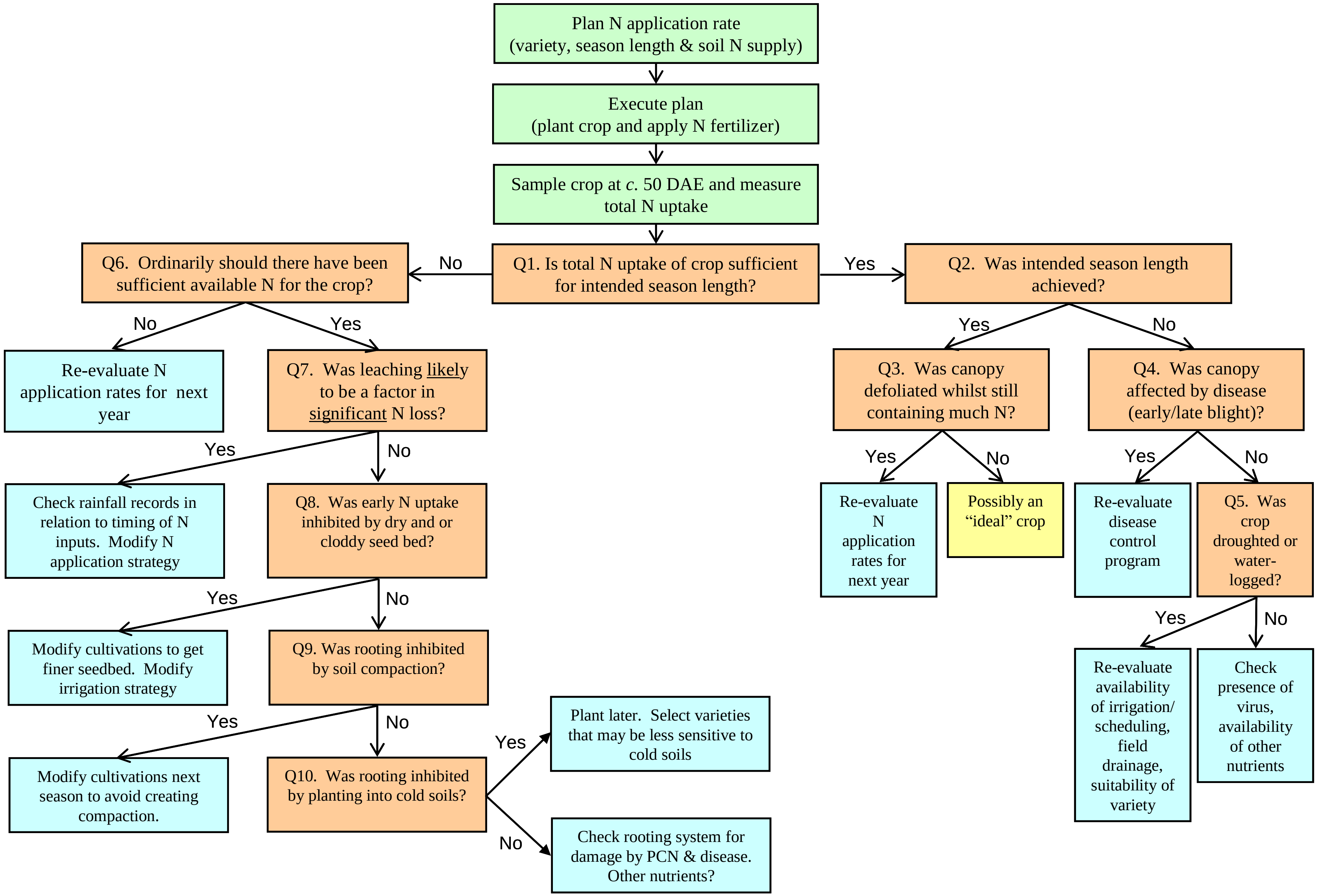
The project has consistently shown that crops take up most of their N during a relatively short period and for some crops N uptake effectively ceases 50 DAE (Table 19). For many crops, yield formation is not occurring during periods of rapid N uptake from the soil but is concurrent with the transfer of N reserves from the haulm to the developing tubers. Since N uptake and tuber yield potential are linked, crop yield potential must also be set early in the season and any factors that may temporarily impede N uptake early in the season are likely to reduce yield potential. Experimental evidence shows (Table 48) it is difficult to change crop yield potential by applying more N fertilizer late in the season and there is now a growing body of evidence that all the crop's N requirement should be applied early (i.e. between planting and *c.* 30 DAE) so that yield potential is not forfeited by restricting early N uptake.

The CUF N management model permits predictions to be made of crop yield potential. However, the model assumes that the radiation-driven transfer of N from haulm to tuber proceeds in an orderly manner. Failure to achieve potential can therefore occur in several ways. For example, many commercial crops are defoliated whilst their canopies still contain significant amounts of N. Under favourable condition and given sufficient time (or incident radiation) this haulm N could have converted into tuber N and thus the crops were defoliated before they had achieved their full biological potential. Similarly, de-foliating diseases such as early blight (*Alternaria solani,* see Shade and N experiment in 2006 p. 16) or late blight (*Phytophthora infestans*) will disrupt the smooth transfer of N from haulm to tubers and reduce yield potential. Indeed the model is useful in quantifying the effects of these diseases on loss of tuber yield.

The CUF N management model has shown that total N uptake is related to yield potential but, sometimes, this potential is not realised. The N model therefore provides a convenient framework with which to analyse crop performance in terms of creation of potential and then realisation of that potential. This approach is shown schematically in Figure 34. The start of the process (green boxes) is the planning of the N management of the crop, the execution of the plan and the subsequent monitoring of the crop. The first question (Q1) is whether, on the basis of measured total N uptake the crop has sufficient N to achieve its intended season length (and by implication yield). If the N uptake was sufficient, the question then becomes whether the estimated crop potential was actually achieved (Q2). If the crop failed to achieve its potential then the decision tree helps to identify possible causes of this failure. If the initial sampling had revealed that N uptake was insufficient for the intended season length then subsequent questions aid diagnosis of possible causes. Using this system on some of the commercial crops listed in Table 80 has shown that large N application rates do not necessarily result in large N uptakes and persistent canopies (Figure 32). Similarly, analysis of crop development in relation to the timing of N application, soil type and rainfall suggest that N leaching was not a significant factor in poor crop performance. It is probable that in many cases N uptake was hampered by poor soil physical conditions (too dry, cloddy compacted) or by some of the N being applied too late to be taken up by the crop.

Future development of the CUF N management model should concentrate on those factors that impede N uptake and the creation of yield potential and those factors that prevent the crop's yield potential being fulfilled. Thus, detailed experiments are needed on the relationship between soil physical conditions (cloddiness, compaction and water content), root distribution and function, soil N supply and crop N uptake. A better understanding of these factors may help improve N recommendations by making them more site specific and, in turn, increase the yield potential of the UK potato crop.

Figure 34. Flow diagram illustrating use of CUF N management model as a diagnostic tool.



Practical recommendations derived from project

Listed below are some key practical recommendations derived from project R273.

1. The potato crop usually takes up most of its N within seven weeks of emergence and there is a clear link between the amount of N taken up and the yield potential of the crop.

2. To maximise crop yield potential it is important to facilitate early N uptake. Soils should be uncompacted and seed-beds have a fine tilth. Ideally, early crop development should not be hampered by excessively dry or wet soil conditions.

3. Some crops fail to achieve their full yield potential since canopy health is impaired by factors such as heat and or water stress, pests and disease. Failure to adequately control these factors will reduce crop yield and represents a waste of inputs.

4. Late applications of N (after *c.* 40 DAE) are not used very efficiently by the potato crop and do not materially increase canopy persistence and tuber yield. If possible, the entire fertilizer N requirement should be applied between planting and tuber initiation (*c.* 25 DAE) at the latest.

5. On a limited number of soil types, applications of large amount of N (> *c.* 200 kg N/ha) at planting have been shown to cause erratic emergence. This adversely affects early crop development and may cause problem in scheduling irrigation for scab control. In these circumstances a split application may be advisable but with the entire fertilizer dose applied by tuber initiation (see above).

6. Some of the commercial crops were defoliated whilst the haulm contained substantial amount of N (i.e. canopies were near complete and green). This suggests that these crops had received an excess of N fertilizer and there may be opportunities to reduce N applications in subsequent seasons without compromising yield.

7. When potato crops are grown in compacted soils there may be some benefit from applying more N fertilizer than when grown on uncompacted soils. However,

water supply and the correct irrigation scheduling of irrigation has a larger effect than N when soils are compacted.

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Appendix 1a **Number of plants, stems and tubers; tuber FW yield; tuber, haulm and total DM yield and N uptake for five commercial crops sampled on two occasions**

Crop variety, location and date of harvest		No of plants (000/ha)	No of stems (000/ha)	No. of tubers (000/ha)	Tuber FW yield (t/ha)	Tuber DW yield (t/ha)	Haulm DW yield (t/ha)	Total DW yield (t/ha)	Tuber N uptake (kg N/ha)	Haulm N uptake (kg N/ha)	Total N uptake (kg N/ha)
Russet Burbank (MC), Norfolk 2006											
3 July	Mean	38.3	113	476	20.9	3.51	3.51	7.02	54	115	169
	S.E.	2.35	16.2	65.0	1.29	0.241	0.285	0.369	3.9	12.7	12.1
24 August	Mean	34.6	112	494	65.4	14.26	3.14	17.40	163	33	196
	S.E.	1.05	4.6	5.7	2.70	0.489	0.317	0.776	12.4	5.2	16.8
Russet Burbank (VF), Norfolk 2006											
3 July	Mean	37.4	159	759	28.2	4.81	3.46	8.27	69	98	167
	S.E.	0.91	6.2	42.1	0.90	0.249	0.105	0.165	5.0	9.6	9.3
24 August	Mean	35.6	142	740	60.7	12.59	2.52	15.10	167	31	198
	S.E.	0.91	13.4	47.9	2.83	0.438	0.161	0.487	8.4	4.2	5.6
Lady Rosetta (EU), Suffolk 2006											
4 July	Mean	35.6	143	841	30.0	7.05	3.02	10.07	74	68	142
	S.E.	0.91	7.0	73.8	2.39	0.740	0.292	0.977	7.8	9.8	16.9
22 August	Mean	34.6	127	773	68.4	16.05	1.66	17.71	208	24	232
	S.E.	1.05	13.7	72.2	5.71	1.066	0.142	1.184	22.5	2.1	24.3
Lady Rosetta (BO-1), Suffolk 2006											
4 July	Mean	34.6	154	867	34.6	7.43	3.07	10.51	86	74	161
	S.E.	1.05	9.0	38.4	0.70	0.199	0.180	0.132	4.3	6.3	10.1
22 August	Mean	33.7	127	850	66.1	14.68	1.41	16.08	152	18	170
	S.E.	0.91	9.2	32.6	4.13	0.762	0.281	1.031	14.2	4.1	16.2
Lady Rosetta (BO-2), Suffolk 2006											
4 July	Mean	33.7	124	796	32.6	6.97	3.12	10.09	94	79	174
	S.E.	0.91	7.4	28.3	0.55	0.219	0.289	0.484	5.6	6.9	9.4
22 August	Mean	34.6	138	905	70.2	15.54	1.32	16.86	156	18	174
	S.E.	1.05	5.2	43.6	1.82	0.439	0.130	0.539	11.4	1.6	12.8

***Appendix 1b*.** **Number of plants, stems and tubers; tuber FW yield; tuber, haulm and total DM yield and N uptake for four commercial crops sampled on two occasions**

Crop variety, location and date of harvest		No of plants (000/ha)	No of stems (000/ha)	No. of tubers (000/ha)	Tuber FW yield (t/ha)	Tuber DW yield (t/ha)	Haulm DW yield (t/ha)	Total DW yield (t/ha)	Tuber N uptake (kg N/ha)	Haulm N uptake (kg N/ha)	Total N uptake (kg N/ha)
Marfona (LH), Suffolk 2006											
22 June	Mean	32.1	93	520	26.3	3.55	3.01	6.56	62	113	175
	S.E.	0.73	4.7	30.3	1.95	0.277	0.062	0.302	4.4	5.9	9.3
26 July	Mean	26.3	87	479	65.8	11.29	2.07	13.36	125	33	158
	S.E.	0.73	3.9	26.3	1.80	0.229	0.078	0.270	4.0	1.6	3.5
Sante (LE), Somerset 2006											
26 July	Mean	40.8	90	424	30.2	5.47	3.35	8.82	66	131	196
	S.E.	1.36	5.2	20.2	0.60	0.098	0.178	1.191	2.1	5.1	4.5
15 August	Mean	32.8	71	415	48.6	10.25	3.11	13.36	128	97	226
	S.E.	1.63	6.9	31.7	1.20	0.352	0.184	0.425	3.8	5.3	6.6
Marfona (BW), Suffolk 2006											
3 July	Mean	56.9	124	486	35.6	5.74	2.33	8.06	69	61	130
	S.E.	2.47	5.5	37.9	1.59	0.179	0.152	0.287	2.6	4.2	5.6
26 July	Mean	49.6	125	492	61.0	11.74	2.05	13.79	144	58	203
	S.E.	1.46	8.4	17.0	1.89	0.478	0.044	0.520	7.7	3.7	11.1
Maris Piper (GE), Suffolk 2006											
4 July	Mean	48.9	185	536	45.8	8.55	3.83	12.38	109	109	217
	S.E.	4.25	13.1	31.6	2.43	0.463	0.177	0.515	7.1	10.4	13.2
17 July	Mean	31.4	211	588	59.5	10.94	4.14	15.08	132	92	224
	S.E.	3.18	6.9	33.0	2.89	0.747	0.179	0.822	9.1	10.9	10.7

Appendix 1c. **Number of plants, stems and tubers; tuber FW yield; tuber, haulm and total DM yield and N uptake for four commercial crops sampled on two occasions**

Crop variety, location and date of harvest		No of plants (000/ha)	No of stems (000/ha)	No. of tubers (000/ha)	Tuber FW yield (t/ha)	Tuber DW yield (t/ha)	Haulm DW yield (t/ha)	Total DW yield (t/ha)	Tuber N uptake (kg N/ha)	Haulm N uptake (kg N/ha)	Total N uptake (kg N/ha)
Lady Rosetta (US), Norfolk 2007											
20 July	Mean	44.7	130	613	37.7	9.49	1.84	11.33	112	33	146
	S.E.	1.75	4.3	30.0	2.42	0.403	0.168	0.566	16.7	5.4	16.7
29 August	Mean	46.5	140	630	48.6	12.86	0.73	13.59	115	6	120
	S.E.	0.91	3.8	26.9	1.65	0.536	0.090	0.607	3.9	0.7	4.3
Lady Rosetta (JW), Norfolk 2007											
20 July	Mean	46.5	140	602	38.7	9.81	0.96	10.77	117	16	133
	S.E.	1.75	4.3	25.4	2.41	0.376	0.029	0.393	22.1	0.8	22.1
29 August	Mean	45.6	155	628	46.3	11.78	0.66	12.44	123	5	128
	S.E.	1.05	10.6	33.6	0.74	0.088	0.068	0.086	5.1	0.4	5.2
Russet Burbank (BR), Norfolk 2007											
23 July	Mean	37.4	122	622	42.3	8.86	3.21	12.07	94	51	146
	S.E.	2.74	7.5	67.3	2.44	0.560	0.225	0.784	9.9	7.5	16.1
28 August	Mean	37.4	151	493	54.3	13.08	1.71	14.80	129	16	144
	S.E.	5.24	30.3	34.8	3.01	0.719	0.305	0.659	11.6	4.4	12.4
Russet Burbank (MQ), Norfolk 2007											
23 July	Mean	39.2	114	503	38.9	8.35	2.82	11.17	81	45	127
	S.E.	2.29	4.8	25.5	2.51	0.448	0.441	0.874	6.0	6.6	11.7
28 August	Mean	34.6	129	460	48.3	11.36	1.29	12.65	125	11	136
	S.E.	1.05	16.3	36.9	2.93	0.758	0.140	0.884	9.5	0.9	10.3

***Appendix 1d*.** **Number of plants, stems and tubers; tuber FW yield; tuber, haulm and total DM yield and N uptake for four commercial crops sampled on two occasions**

Crop variety, location and date of harvest		No of plants (000/ha)	No of stems (000/ha)	No. of tubers (000/ha)	Tuber FW yield (t/ha)	Tuber DW yield (t/ha)	Haulm DW yield (t/ha)	Total DW yield (t/ha)	Tuber N uptake (kg N/ha)	Haulm N uptake (kg N/ha)	Total N uptake (kg N/ha)
Maris Peer (MI), Norfolk 2007											
23 July	Mean	91.1	309	777	34.5	6.59	2.62	9.21	53	43	96
	S.E.	2.10	25.3	54.8	1.70	0.263	0.139	0.273	2.4	4.2	6.5
28 August	Mean	88.4	317	752	48.5	9.70	-	9.70	100	-	100
	S.E.	3.45	26.6	56.7	3.67	0.783	-	0.783	9.3	-	9.3
Estima (GC), Somerset 2007											
25 July	Mean	38.3	103	359	36.1	5.80	2.85	8.65	86	95	182
	S.E.	1.82	9.7	34.7	1.79	0.251	0.211	0.449	4.8	10.6	14.4
23 August	Mean	38.3	109	430	62.7	10.94	2.22	13.16	158	48	206
	S.E.	1.82	7.7	36.6	4.63	0.876	0.208	1.067	21.0	6.6	23.0
Estima (NA), Somerset 2007											
23 July	Mean	38.3	77	288	43.0	6.75	3.33	10.08	100	98	198
	S.E.	1.05	5.4	15.5	2.02	0.387	0.179	0.466	4.0	8.3	10.2
28 August	Mean	39.2	75	327	55.2	8.67	-	8.67	125	-	125
	S.E.	0.91	5.3	17.3	1.83	0.384	-	0.384	9.8	-	9.8
Hermes (CO), Yorkshire 2007											
12 July	Mean	43.7	75	380	35.3	5.99	3.46	9.45	72	72	144
	S.E.	0.00	2.4	48.8	1.90	0.337	0.132	0.446	8.2	10.1	12.2
5 Sept	Mean	43.7	95	427	53.0	13.13	-	13.13	196		196
	S.E.	0.00	7.3	32.4	3.91	1.240	-	1.240	10.2		10.2

***Appendix 1e*.** **Number of plants, stems and tubers; tuber FW yield; tuber, haulm and total DM yield and N uptake for four commercial crops sampled on two occasions**

Crop variety, location and date of harvest		No of plants (000/ha)	No of stems (000/ha)	No. of tubers (000/ha)	Tuber FW yield (t/ha)	Tuber DW yield (t/ha)	Haulm DW yield (t/ha)	Total DW yield (t/ha)	Tuber N uptake (kg N/ha)	Haulm N uptake (kg N/ha)	Total N uptake (kg N/ha)
Hermes (RG), Shropshire 2007											
11 July	Mean	43.7	163	640	31.3	5.14	6.34	11.49	107	266	373
	S.E.	0.00	2.4	38.4	3.53	0.612	0.428	0.827	14.5	17.4	15.5
4 Sept	Mean	43.7	149	678	62.8	13.50	-	13.50	253	-	253
	S.E.	0.00	5.6	58.1	2.17	0.588	-	0.588	8.1	-	8.1
Saturna (RG), Shropshire 2007											
11 July	Mean	43.7	126	620	27.2	5.02	5.24	10.26	83	200	283
	S.E.	0.00	6.8	46.4	3.49	0.686	0.252	0.828	7.0	14.0	16.0
4 Sept	Mean	43.7	111	600	57.7	14.10	-	14.10	238	-	238
	S.E.	0.00	2.4	38.9	3.57	0.861	-	0.861	17.6	-	17.6
Russet Burbank (UT-1), Staffordshire 2007											
31 July	Mean	30.1	109	467	42.0	7.81	3.72	11.53	110	103	214
	S.E.	1.75	6.9	13.6	1.10	0.253	0.151	0.366	6.9	8.8	12.4
12 Sept	Mean	28.3	94	381	58.6	13.59	2.27	15.87	173	34	208
	S.E.	0.91	5.0	15.9	0.66	0.353	0.091	0.379	6.1	2.6	4.3
Russet Burbank (UT-2), Staffordhire 2007											
31 July	Mean	30.1	124	452	42.2	8.14	3.91	12.05	92	85	177
	S.E.	0.91	7.1	36.1	1.72	0.253	0.117	0.365	5.1	5.6	5.2
12 Sept	Mean	30.1	118	488	66.5	16.00	2.06	18.06	164	20	184
	S.E.	0.91	7.9	18.7	1.99	1.015	0.274	1.269	11.8	2.5	13.9

Appendix 1f. **Number of plants, stems and tubers; tuber FW yield; tuber, haulm and total DM yield and N uptake for five commercial crops sampled on two occasions**

Crop variety, location and date of harvest	No of plants (000/ha)	No of stems (000/ha)	No. of tubers (000/ha)	Tuber FW yield (t/ha)	Tuber DW yield (t/ha)	Haulm DW yield (t/ha)	Total DW yield (t/ha)	Tuber N uptake (kg N/ha)	Haulm N uptake (kg N/ha)	Total N uptake (kg N/ha)
Cambridgeshire, 2 July 2007										
Hermes	52.5	57	315	23.7	4.00	3.66	7.66	54	111	165
Lady Rosetta	52.5	84	458	31.9	6.40	3.31	9.71	89	102	190
Saturna	52.5	139	633	34.4	6.70	4.27	10.97	91	120	211
Smiths Comet	52.5	98	549	28.5	6.20	3.75	9.95	92	113	205
S.E. (9 D.F.)	0.00	4.0	41.1	1.20	0.379	0.141	0.412	6.7	7.4	8.2
Cambridgeshire, 21 August 2007										
Hermes	52.5	57	310	54.1	12.51	-	12.51	156	-	156
Lady Rosetta	52.5	86	424	58.0	15.14	-	15.14	190	-	190
Saturna	52.5	156	721	60.6	15.16	-	15.16	183	-	183
Smiths Comet	52.5	109	506	49.5	13.16	-	13.16	162	-	162
S.E. (9 D.F.)	0.00	7.8	20.7	2.02	0.683		0.683	8.0	-	8.0