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Effects of crop husbandry and growing conditions on storage losses of Pentland Crown potatoes

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SUMMARY

Over five growing seasons (1976–80) experiments were carried out using at least three contrasting sites per season to study the relationship between growing conditions and storage losses in Pentland Crown potatoes. Crops were harvested by hand and storage was carried out in a single environment over a period of 6–7 months without sprout suppressants. The range in growing conditions was great and reflected in the pattern of leaf growth and range in yields of the stored crops (30–90 t/ha). Crops from Tenby (S. W. Wales) produced the most consistent and frequently the highest yields and usually lost the least weight during storage. Although the range in total weight loss over all experiments was large from 5·4 to 16·3%, treatment effects were much smaller than in field growth and yield. Delaying the date of harvest usually increased weight loss and tubers harvested in early August stored at least as well as late-harvested tubers. Tubers harvested without prior defoliation stored as well as tubers harvested on the same day from crops defoliated at least 2 weeks previously. Lengthening the interval from defoliation to harvest usually increased weight loss in storage. Although the tubers were hand harvested effects on saleability were found at the end of storage and there was no evidence that earlier harvesting, which may involve some loss of field yield, would result in any loss of saleable yield out of store.

The results provided no evidence to support the widely-held view that the suitability of a tuber for harvesting improves during maturation associated with natural or imposed crop senescence. It is therefore suggested that the use of the term maturity be avoided as it is wholly unhelpful in studies of the relationship between field growth and storage losses in potatoes.

INTRODUCTION

About 85% of maincrop potatoes harvested in Great Britain are loaded directly into store to meet the demands of the market during winter, spring and early summer (Potato Marketing Board, 1979*a*). Natural wastage or shrinkage caused by evaporative moisture loss, respiration and sprouting are inevitable during storage and pathological wastage will also occur to a greater or lesser extent, mainly as a result of those tuber diseases which are associated with mechanical damage. As well as causing weight loss directly, wastage may also render a proportion of the tubers unsaleable because of severe disease infection or wilting.

Burton (1978*a*) suggested that with the ideal combination of perfect potatoes, unlimited technical facilities and complete suppression of sprout growth, natural wastage might be kept down to 0·15% or less of the original weight per week of storage. In commercial situations where damage and disease are kept to a minimum and storage conditions are controlled by forced draught ventila-

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tion, Wilson, Twiss & Lessells (1962) suggested that for maincrops stored in stacks, shrinkage may account for a 7% loss of the original weight of tubers put into store by the end of May which is equivalent to about 0·22% per week. If not suppressed, sprouting might be expected to cause an additional 4% loss over the same period of storage (Burton, 1978*a*) giving a total loss of about 11%.

The major storage diseases, gangrene, dry rot and bacterial soft rot will also increase weight loss by causing more rapid dehydration of affected tubers, but this effect is relatively small compared with those on the fraction of the bulk which is finally saleable. In the absence of these diseases, tuber damage caused by harvesting and handling also leads to more rapid loss of moisture until the wounds have healed, but again, this is trivial compared with the weight of tubers which may have to be discarded because they are unacceptable for the domestic ware market. Data from Sutton Bridge Experimental Station suggest that damage and disease may cause a loss in ware percentage of about 5% in potatoes stored in a reasonably good condition and with good store management, but disastrous losses of 10–20% can occur if there is widespread development of rotting diseases. Combining ware loss from shrinkage, damage and disease gives an expected minimum fall in the ware yield of 6–7% of potatoes stored until the beginning of January and a total fall of between 10 and 15% for potatoes in good condition stored until March or later (Potato Marketing Board, 1970).

It is well known that losses in store are strongly dependent upon storage conditions (Burton, 1978*a*) and generally agreed that they may also reflect treatments from as early as seed storage and are certainly influenced by the way in which the ware crop is grown and treated at harvest. However, in the past, investigations concerning growing, storing and marketing the potato crop have been largely compartmentalized. Potato agronomists have mainly been interested in effects of treatments on final yield in the field and post-harvest physiologists more usually concerned with the response of tubers to the storage environment but often with little regard to their previous history. Unfortunately, these independent approaches have inevitably resulted in an incomplete picture of the links between crop growth and out-turn from store. The aim of the experiments reported here was to examine more fully these inter-relationships by monitoring the field and storage performance of crops grown at three contrasting sites over five consecutive seasons and which received a series of pre-harvest defoliation treatments. The design of the experiments also made it possible to test for any conflict between high tuber yields and good storage performance which some growers suspect and to re-examine the general recommendation that crops intended for storage should be defoliated 2 or 3 weeks before harvest. The benefits of deliberate haulm removal for the control of blight spread from foliage to tubers, the facilitation of mechanical harvesting, both by decreasing the amount of trash and encouraging tubers to break from their subtending stolons and allowing the tuber skins to set, are well established. However, the effects of the treatment on fitness for storage are not established for there are no data which show that harvesting crops which are still actively growing will result in disastrous storage losses. Tuber yield may be gained by delaying the cessation of growth although some aspects of quality may suffer. The relative importance of these two effects in determining saleable yields at the end of storage appear to be unknown.

EXPERIMENTAL PROCEDURES

Crop husbandry

Pentland Crown was the variety used in this series of experiments. It is the highest yielding maincrop currently recommended by the National Institute of Agricultural Botany (1984) and was the most popular one grown (and presumably stored) in Great Britain throughout the 1970s, accounting for approximately 25% of the maincrop area annually. Seed was grown in Wales and sprouted in the same glasshouse to ensure that tubers planted at each site were the same physiological age. There were always three sites and cultural conditions were standardized as far as possible (Table 1).

In 1976, the aim was to provide a limited but extreme set of field treatments to characterize the range of effects that might be detected in store. There were two harvests 8 weeks apart and each was made 2 weeks after mechanical defoliation of the haulm. The range of treatments was extended in succeeding years and timing and method of defoliation were included as the main husbandry variables because they are perhaps the most obvious, and arguably the most important, cultural practices which affect tuber yield, quality and fitness for storage. From 1977 to 1979 inclusive, crops were defoliated either chemically with diquat or mechanically by cutting off the foliage prior to harvest. This is in common with commercial practice, as survey data show that in 1977, 72% of the national crop was sprayed with chemical defoliants, 34% was topped mechanically and 17% received both chemical and mechanical treatments (Potato Marketing Board, 1979*a*). Thus, it was possible to compare the effects of slow and rapid methods of severing the link between foliage and tubers. With chemical defoliation with diquat there

Table 1. *Cultural conditions at each site*

Husbandry

	1976	1977	1978	1979	1980
Seed size (g)	50 110–140	60–80	40–60	60–90	100–140
Row width × spacing (cm)	76 × 28 76 × 38	76 × 30	76 × 28	76 × 34	76 × 40
Planting date	8. iv	22. iv	19. iv	27. iv	22. iv (early) 20. v (late)
Fertilizer (kg/ha)	180 N 77 P 188 K	198 N 106 P 204 K			
Method of defoliation	Mechanical	Control (natural senescence) Mechanical Chemical (diquat)			Mechanical

Dates of defoliation and harvesting

			Harvest	
		Defoliation	Early	Late
1976	Early	20. vii	3. viii	—
	Late	14. ix	28. ix	—
1977	Early	1. viii	15. viii	31. viii
	Late	31. viii	15. ix	27. ix
1978	Early	14. viii	30. viii	11. ix
	Late	11. ix	25. ix	9. x
1979	Early	13. viii	27. viii	10. ix
	Late	10. ix	24. ix	8. x
1980	Early	18. viii	1. ix	—
	Late	13. x	27. x	—

is an opportunity for re-translocation of dry matter from the dying haulm to the tubers, but not with the mechanical method.

Defoliation was done at two distinct phases in the growth of the crop rather than on the basis of calendar date which is of no physiological significance. The first was timed to occur during the prolonged period when tuber bulking rate was relatively constant and the second when the haulm was senescing rapidly and the rate had fallen and tuber yields were hardly increasing (Scott & Wilcockson, 1978). At 2 and 4 weeks after crop defoliation tubers were carefully hand-dug with a fork, in order to examine the effects of extending the interval between killing the tops and harvesting. This gave a total of four harvests. Control crops which had not been defoliated were also harvested to study how the storage characteristics of crops changed as natural senescence progressed. The schemes of harvesting also made it possible to compare harvesting for storage with and without prior defoliation. In 1980, an attempt was made to widen further the spectrum of crops available for storage by a slightly different approach. Two planting dates, one in late April and the other a month later, were included which together with three sites created six contrasting environments for growth within a single season. The interval between the dates of defoliation was wider than in previous years (2 months rather than 1) and the last defoliation was made later than before to coincide with the time that the majority of the national crop is defoliated and harvested (mid-late October) (Potato Marketing Board, 1979*a*).

Simplified growth analysis of four plants per site was done at 2-weekly intervals throughout all seasons to compare crop growth at the sites. Measurements of tuber periderm thickness (Nielsen, 1973) were made at final harvest in 1976, 1977 and 1978 as this was considered to be a potentially important factor affecting storage losses (Burton, 1978*b*).

Storage treatments

Tuber samples were stored at the Potato Marketing Board's Sutton Bridge Experimental Station

Table 2. *Details of the storage conditions*

Curing temperature	15 °C
Curing duration	14 days
Holding temperature	7 °C
Relative humidity	90–95 % at all times

Duration of storage (weeks)*	
1976	30
1977	31
1978	25
1979	25
1980	26

* Storage period from the date of loading of each treatment into store. Dates of store loading were date of harvest + 2.

in an experimental bin in 6 kg capacity boxes (held in racks) and there were three replicates (boxes) per treatment. The storage environment was controlled and a single management regime imposed which was considered to be optimum for ware potatoes for domestic consumption (Burton, 1978*b*). This included an initial curing period to encourage wound healing prior to the main holding period and details are shown in Table 2. Weight loss during storage was recorded by weighing all samples on entry and removal from storage. The weight of any sprouts was recorded on removal from storage and disease occurrence, dry-matter content and reducing-sugar content were recorded on entry and removal from storage. The appearance of the tubers was carefully recorded according to the Potato Marketing Board's grading standards (Potato Marketing Board, 1980) so that saleable tuber yields could be established. During the 1976–7 storage season it was possible to make these measurements at the end of the curing period and then at 4-weekly intervals and so follow their change with time throughout the storage period of 30 weeks. However, in subsequent seasons, the very large number of treatments meant that measurements could be made on only two occasions. The first was approximately halfway through the storage period at 19, 12, 12 and 13 weeks in 1977, 1978, 1979 and 1980 respectively. The second was at the end of the storage period (Table 2).

Because the tubers were harvested carefully by hand to minimize damage, from 1977 onwards subsamples were given a standard damage treatment prior to storage to test the extent to which losses were affected by damage which may be inflicted during commercial harvesting and handling. The damage treatment or 'drop test' involved dropping each tuber from a height of 0·61 m onto an expanded metal plate inclined at 45 °C. In 1980, by storing further samples of undamaged and damaged tubers which had been either cured or not cured prior to the holding period, the extent to which the adverse effects of damage might be overcome by encouraging wound healing were determined. In 1976, 1977 and 1978, measurements of rates of respiration during storage of tubers from selected treatments were made at the Food Research Institute, Norwich. The amount of carbon dioxide provided by samples was determined gravimetrically by periodically recording the increase in weight of the carbon dioxide absorbent, 'Sofnolite'. This method gave an assessment of the effects of site and cultural conditions on respiration rate and the contribution of respiration to natural wastage.

The sites

The inclusion of different sites was an essential feature of the experiments as it was clearly necessary to grow crops under as many diverse experimental conditions as possible if there was to be a chance of understanding the relationship between growth and storage performance. The use of contrasting sites is a simple way of achieving environmental variation within a year and standardization of husbandry conditions at each of them allowed differences in performance to be attributed to

Table 3. *Details of the experimental sites*

Site	Longitude	Latitude	Altitude (m)	Soil series	Years
Tenby (Dyfed)	04° 42′ W	51° 41′ N	15	Pembroke (Soil Survey Record No. 24, 1974)	1976–80
Sutton Bonington (Nottinghamshire)	01° 15′ W	52° 50′ N	48	Astley Hall (Thomasson, 1971)	1976–9
Wellesbourne (Warwickshire)	01° 36′ W	52° 12′ N	47	Wick (Whitfield, 1974)	1976–8
Cockle Park (Northumberland)	01° 41′ W	55° 13′ N	91	Dunkeswick (Jarvis, R. A., Hartnup, R. and Allison, J. W., unpublished)	1979–80
Reading (Berkshire)	00° 56′ W	51° 26′ N	66	Sonning (Jarvis, 1968)	1980

differences in environmental factors operating at each location. The sites (Table 3) were situated in areas which are commercially important for potato production. They included one (Tenby) in a western coastal district notable for earlies, whilst the others are typical of more easterly sites where maincrops for storage predominate.

Tenby in south-west Wales is characterized by the early and more consistent rise in temperature in spring, relative freedom from frost and on average 20% higher solar radiation compared with eastern England (Allen & Scott, 1980). These conditions favour early leaf growth and radiant energy interception and are ideal for the production of first earlies for harvesting in late May and early June. The same conditions combined with generally higher rainfall and more moderate summer temperatures also make this an environment capable of producing very high yields of maincrops which are consistently greater than those achieved at eastern sites (Ifenkwe, 1975).

Sutton Bonington, Wellesbourne and Reading are more typical of light-textured soils likely to produce maincrop potatoes for storage. They have lower spring and higher summer temperatures than western coastal regions and are usually duller, especially in late spring and early summer. Their outstanding feature is susceptibility to drought: from April to October potential transpiration exceeds rainfall by about 100–125 mm on average and unless irrigation is used water stress frequently occurs. When water is not limiting, maincrop yields at these sites may be similar to those produced at Tenby.

Cockle Park is the latest and perhaps potentially least productive of all of the sites for potatoes. It is the most northerly, situated 9 km from the North Sea coast and exposed to the north and east and typical of the infertile, heavy, poorly drained clay areas of south-east Northumberland (Pawson, 1960). It is generally cooler, particularly in summer, and also wetter (20%) than the other sites. July and August are usually duller and wetter on average and 50 mm of soil moisture deficit may be expected to occur between the end of June and mid-August only 10 years in 20. The start of crop growth in spring is generally rather late partly on account of the occurrence of frost in late spring but also because the predominantly heavy soil is very water retentive.

The seasons

The five seasons provided exceptional contrasts in weather and included the best (1978 and 1980) and worst (1976) on record in terms of performance of the national potato crop (Potato Marketing Board, 1981). A summary of conditions prevailing during the growing seasons (April–October) at each site is shown in Table 4. Tenby was invariably the brightest and wettest but average temperatures were quite similar to those prevailing at Sutton Bonington, Wellesbourne and Reading. Weather conditions at both Sutton Bonington and Wellesbourne were similar as might have been expected from their proximity. Cockle Park in the north-east was clearly the coolest and dullest location though rainfall was similar to that at Sutton Bonington and Reading in 1979 and 1980 respectively. In 1980, conditions at Reading were similar to those experienced at Tenby.

1976 was remarkable for the hot, dry, sunny summer and the severe drought conditions which were widespread in most of Europe in that year. At all sites, the relative dry and warm conditions in spring allowed earlier planting than usual and rapid early growth gave indications of potentially high-yielding crops. However, June, July and August were very dry at Sutton Bonington, Wellesbourne and Tenby and exceptionally high air temperatures were recorded at the inland sites. Maximum temperatures over 30 °C were recorded at all sites in June and at Wellesbourne and Sutton Bonington in July. Temperatures were lower in August at all sites and Tenby was 2–3 °C cooler than the more easterly sites. In the Midlands, unirrigated crops wilted heavily by mid-July and began to senesce prematurely by late June.

1977 and 1978 were cooler, duller and wetter than 1976 had been, with weather conditions much closer to the long-term averages. Near average sunshine in 1978, coupled with frequent rainfall throughout the summer and the absence of extremes of temperature, meant that the crop was rarely water stressed and tuber yields were high. 1978 was a record year nationally with average yields of 34·9 t/ha, 63% higher than in 1976.

1979 was generally a poor year for potato crops. Wet, cold weather in March and April delayed planting of both the experiments and commercial crops and seed beds were rather poor. The crop was late to emerge and, with limited rainfall in June and July, it was never able to overcome the early set back to growth at Sutton Bonington and Cockle Park but brighter, wetter conditions at Tenby ensured better growth and higher yields. Conditions in 1980 were in complete contrast. April and May were dry, warm and sunny which gave crops a good start. Although the rest of the summer was rather cool and duller, rainfall was heavier and more evenly distributed. Record yields of 35·1 t/ha nationally were recorded (Potato Marketing Board, 1981).

Table 4. *Weather conditions at the experimental sites*

	1976			1977			1978			1979			1980		
	SB	T	W	SB	T	W	SB	T	W	SB	T	CP	CP	T	R
							Rainfall (mm)								
April	10	15	9	37	(75)	32	25	47	28	66	85	50	3	24	19
May	41	59	43	45	32	44	39	25	37	95	122	96	26	32	32
June	10	24	21	80	47	144	77	51	36	15	42	28	132	88	72
July	31	17	15	15	21	4	55	91	112	65	17	36	65	51	56
August	7	3	52	73	107	130	60	51	48	62	112	59	89	(87)	88
September	92	176	112	23	59	17	27	39	38	29	65	42	31	113	80
October	87	245	68	31	(164)	33	8	27	7	52	197	72	57	156	75
Total	278	539	320	304	505	374	291	331	306	332	640	383	403	551	422
							Sunshine (h)								
April	130	210	143	146	191	166	134	186	109	113	146	118	151	217	161
May	153	196	169	207	277	231	176	257	194	171	191	153	223	241	219
June	229	233	268	158	(206)	138	187	214	160	171	185	172	141	181	183
July	252	255	253	180	(246)	188	177	157	165	194	218*	170	122	186	172
August	222	299	243	147	224	145	161	195	150	162	170	127	124	(170)	177
September	107	106	100	119	129	115	125	184	161	170	149	157	100	123	145
October	66	(97)	59	97	(115)	103	92	79	76	102	104	78	88	100	124
Total	1159	1396	1235	1054	1388	1086	1052	1272	1015	1083	1163	975	959	1218	1181
							Average air temperature °C $\left(\frac{\text{max}+\text{min}}{2}\right)$								
April	7·8	(8·7)	8·0	7·2	(7·5)	7·3	5·9	6·9	6·5	7·5	7·7	5·9	7·3	8·7	8·9
May	11·9	(11·1)	12·1	10·1	11·1	10·4	10·7	11·3	10·9	9·9	8·5	8·3	8·9	11·3	11·4
June	17·7	(15·3)	17·1	12·3	12·3	11·8	13·1	12·9	13·6	13·5	13·1	12·3	12·1	13·3	14·3
July	18·3	(17·3)	18·6	15·6	15·8	15·9	14·1	14·1	15·2	15·8	15·3	14·5	12·9	14·1	14·8
August	17·0	(18·1)	16·8	15·3	14·9	15·2	14·7	14·5	15·3	15·0	14·3	13·1	14·1	(15·2)	16·5
September	13·2	(13·4)	13·4	13·5	13·2	13·6	13·5	13·6	14·2	13·1	12·9	11·8	13·3	14·5	15·1
October	10·4	(11·3)	10·7	11·3	(12·9)	11·6	11·3	12·5	11·8	10·7	11·9	9·9	7·7	9·9	9·1

Sutton Bonington (SB); Tenby (T); Wellesbourne (W); Cockle Park (CP); Reading (R).
( ) Data for Milford Haven; * Data for Aberporth.

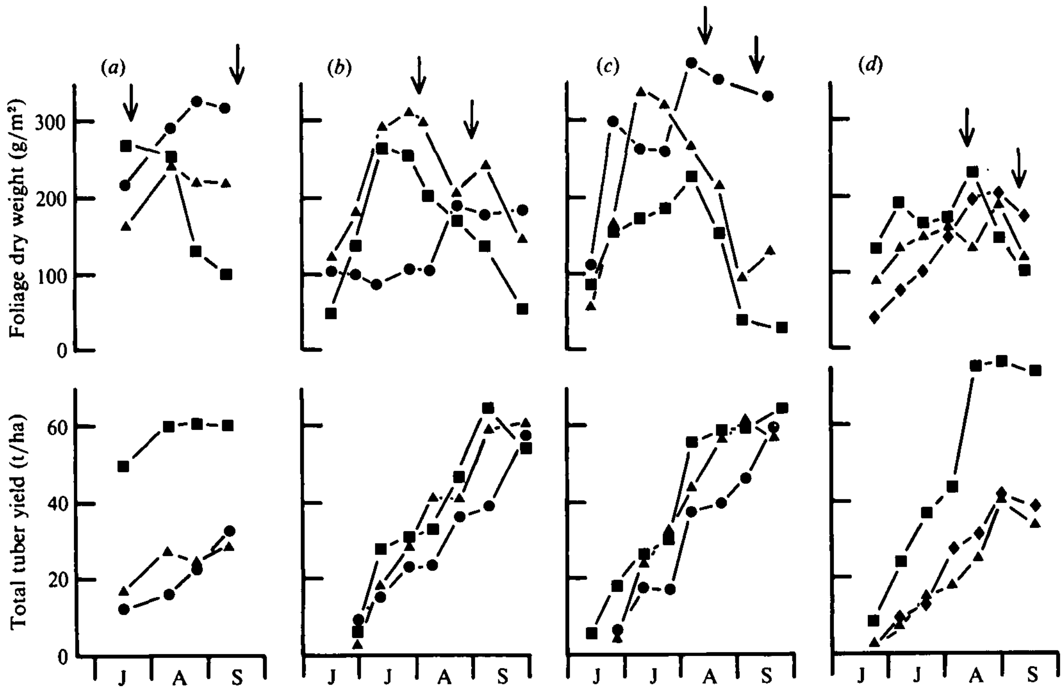

Fig. 1. The effects of site on the change with time in foliage dry weight and tuber yield in (*a*) 1976; (*b*) 1977; (*c*) 1978 and (*d*) 1979. Cockle Park (◆), Sutton Bonington (▲), Tenby (■), Wellesbourne (●). The arrows mark the dates when crops were defoliated.

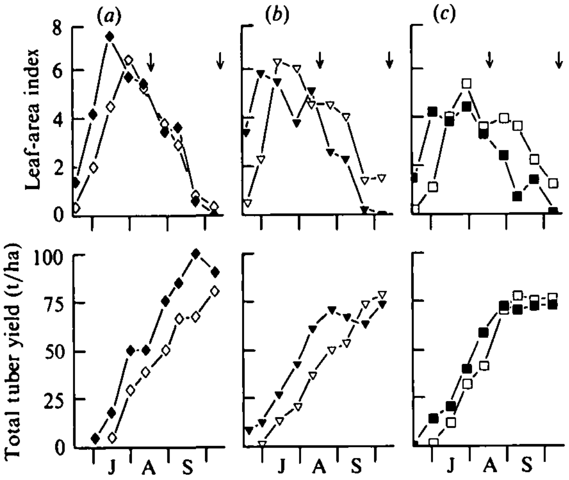

Fig. 2. The effects of date of planting on the change with time in leaf area index and tuber yield at (*a*) Cockle Park (◆, planted 22 April; ◇, planted 20 May) (*b*) Reading (▼, planted 22 April; ▽, planted 20 May) and (*c*) Tenby (■, planted 22 April; □, planted 20 May) in 1980. The arrows mark the dates when crops were defoliated.

RESULTS

Crop growth

Patterns of haulm and tuber growth are shown in Figs 1 and 2. As expected Tenby was the earliest and highest-yielding site and, moreover, yields were always high ranging from 60 to 75 t/ha over the five seasons. However, haulm growth was never more prolific or persistent than at other sites and crops at Tenby were often first to senesce and tuber bulking rate began to decrease by mid-August. Thus, the consistently high yields were achieved by rapid rates of bulking over a relatively short period and in the dry years reflected the large water-holding capacity of the soil (Jones & Allen, 1983). At the other sites, the rate of tuber bulking was slower but sometimes continued for a longer period.

In 1976, tuber yields at Sutton Bonington and Wellesbourne were only about half those recorded at Tenby because of the absence of rainfall, the limited contribution of soil water and higher temperatures. Weather conditions were more favourable at all sites in 1977 and 1978 than they had been in 1976 and tuber yields at Sutton Bonington and Wellesbourne were about twice those produced in 1976 and similar to the yield at

Tenby. In 1977 the pattern of tuber growth was broadly similar at Sutton Bonington and Tenby despite more vigorous haulm growth from the beginning of June until mid-August. Heavy June rainfall (114 mm, Table 4) may have resulted in severe leaching of nitrogenous fertilizer which inhibited growth of the foliage. To rectify this, an extra 150 kg N/ha was applied as a top-dressing on 28 June but July was very dry with only 4 mm rain and so the effects of this supplementary nitrogen did not become evident until after substantial rain in August. Yields then continued to increase until mid-September because haulm growth was maintained. In contrast, bulking ceased by the end of August at Tenby and Sutton Bonington with the net result that final yields were similar at all three sites.

The pattern of tuber bulking at Wellesbourne was very similar in 1978 also with a slower rate but longer duration than at either Tenby or Sutton Bonington but the reasons for this are unclear, especially as haulm growth was most prolific at Wellesbourne. Blight (*Phytophthora infestans*) was certainly involved in the very rapid senescence of foliage at Tenby in 1978 despite regular applications of fungicide. By 21 August all of the leaves had at least 50% of their area infected with blight. The disease was also evident in the crop at Sutton Bonington.

In 1979, late planting at the end of April combined with predominantly cool, wet and dull conditions and poor seed beds resulted in very poor growth at both Sutton Bonington and Cockle Park. Haulm growth was restricted and the rate of tuber bulking was slow, so that yields reached only about 40 t/ha. On the other hand, haulm and tuber growth were again unrestricted at Tenby and yield reached 75 t/ha, approximately 10 t/ha greater than it had done in previous years. Tuber yields in 1980 were the highest recorded in the series of experiments and reached 75 t/ha at all sites. Although it was not the brightest of the five seasons the early spring was warmer than in most previous years and the development of a complete leaf cover was achieved by mid-June at all sites. Although the highest tuber yield of all was recorded for the early planting at Cockle Park (90 t/ha), yield differences between sites largely disappeared when considered on a dry-weight basis, as dry-matter content of tubers from Cockle Park was only 18% compared with 20% at Tenby and 22% at Reading. Nevertheless, the yield at Cockle Park was higher than might have been expected on the basis of incident solar radiation since it was the dullest of the three sites with about 20% less sunshine over the April to October period than Tenby and Reading. This short-fall was to a large extent compensated for by the maintenance of a leaf area index above 3 until mid-September which could have intercepted most of the late summer and autumn radiation and prolonged tuber bulking. At Tenby and Reading, however, leaf area index fell below 3 from mid-August onwards and tuber bulking ceased shortly afterwards. It is also likely that intercepted radiation was used more efficiently at Cockle Park as the crop was grown on a fertile, water-retentive soil and rainfall from May to August was substantially greater than at other sites. The effects of planting date on crop growth in 1980 were as expected. Late planting merely displaced the growth cycle and because the growing season was long enough, the late crops achieved the same yield as those planted early.

The combination of several sites and a number of seasons produced the required range in tuber growth patterns for a satisfactory test of the effects of field conditions on storage potential. Crops from Tenby had the most consistent pattern of growth and final yield and had created large soil moisture deficits at the first defoliation in most years. At Sutton Bonington and Wellesbourne crop (and tuber) growth was restricted at much smaller soil moisture deficits and final yields fluctuated according to annual rainfall. The 1977 and the 1978 crop at Wellesbourne grew very rapidly at the end of the season after a period of restricted growth. There were differences between sites in the timing of peak leaf area and the rate of decrease so that overall the first defoliation was carried out on crops of a wide range of yield (and hence tuber size), foliage size, bulking rate and water status. In almost all cases the first defoliation was carried out on actively-growing foliage which was adequate to maintain tuber growth rates close to the potential given adequate water.

The pattern of change with time in the number of tubers varied from site to site and season to season. However, in most cases, peak numbers were achieved shortly after the start of the period during which tuber bulking was virtually constant. Thereafter, they decreased and at the final growth analysis harvest in each year the number of tubers in the 40–80 mm size range was remarkably similar at 30–40/m^2. The total number of tubers, however, was more variable. The average weight of individual tubers increased in all crops as the season progressed until tuber bulking ceased. Tubers from crops at Tenby were markedly larger than at the other two sites in 3 of the 5 years (1976, 1978 and 1979) (Fig. 3). The differences in 1976 and 1979 were simply a reflexion of the very large differences in yields at Tenby (60–75 t/ha) and the other sites (30–40 t/ha) whilst in 1978, the combination of slightly higher yields and fewer tubers was responsible. By the end of the 1980 season, the average size of tubers from both early and late

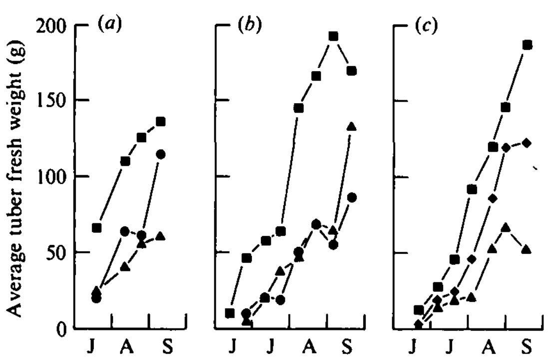

Fig. 3. The effects of site on the change with time in average tuber weight in (*a*) 1976; (*b*) 1978 and (*c*) 1979. Cockle Park (◆), Sutton Bonington (▲), Tenby (■), Wellesbourne (●).

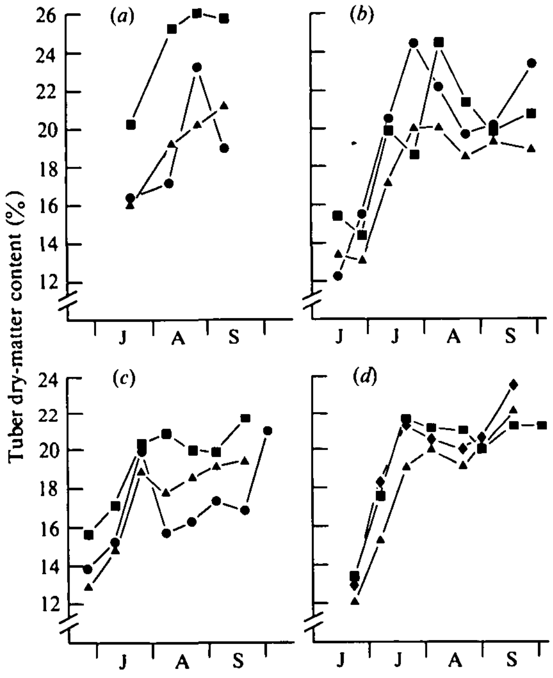

Fig. 4. The effects of site on the change with time in dry-matter content of tubers in (*a*) 1976; (*b*) 1977; (*c*) 1978 and (*d*) 1979. Cockle Park (◆), Sutton Bonington (▲), Tenby (■), Wellesbourne (●).

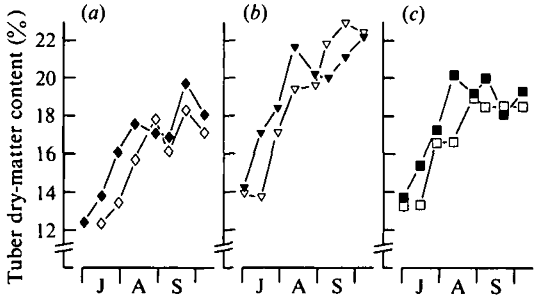

Fig. 5. The effects of date of planting on the change with time in dry-matter content of tubers at (*a*) Cockle Park (◆, planted 22 April; ◇, planted 20 May) (*b*) Reading (▼, planted 22 April; ▽, planted 20 May) (*c*) Tenby (■, planted 22 April; □, planted 20 May) in 1980.

planted crops was similar except at Cockle Park where the lower yields and higher number of tubers of the late planting resulted in smaller tubers which were on average only about half the size of those from the early crop.

The change with time in average tuber dry-matter content is shown in Figs 4 and 5. In general, it increased from about 12 or 14% shortly after the start of the period of rapid tuber bulking (end of June) up to maxima of 20–22%. However, in 1976 the average dry-matter content of tubers from Tenby reached the exceptionally high value of 25%. Maximum tuber dry-matter content was usually achieved between the end of July and mid-August when tuber bulking was still actively underway. From then on, it was very variable from one harvest to the next. Heavy rainfall in late summer and autumn was almost certainly responsible for depressions of tuber dry-matter percentage. The marked decreases at both Trefloyne and Wellesbourne in late August 1977 and at Wellesbourne in mid-August 1978 were closely associated with heavy rainfall (Table 4) which preceded these particular growth analysis harvests.

Storage

The pattern of weight loss in store

In all years, development of serious storage diseases, gangrene, dry rot and soft rot, was minimal although in 1980, gangrene was prevalent in a limited number of treatments. Thus, weight loss recorded in these experiments was mainly the result of natural wastage although Silver scurf (*Helminthosporium solani*) which affected the periderm of all tubers to some extent may have contributed to increased moisture loss compared with uninfected tubers. Total weight loss was defined as the difference between the total weight of tubers loaded into store and the total weight of desprouted tubers taken out of store expressed as a percentage of the original weight of tubers stored.

The effects of site and date of harvest on the time course of weight loss in 1976 are shown in Fig. 6 and the basic pattern is typical of those published by other workers (Ophuis, 1957; Schippers, 1971;

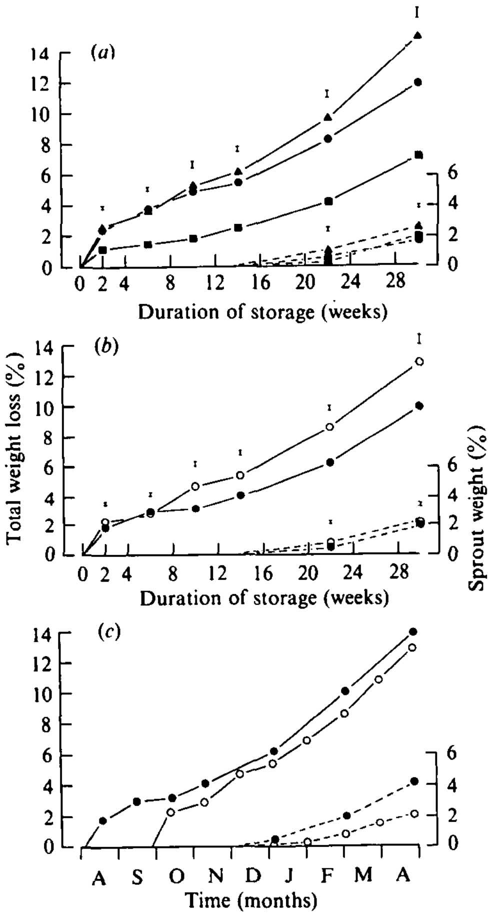

Fig. 6. The main effects of (*a*) site and (*b*) and (*c*) harvest date on the change with time in total weight loss of tubers (solid lines) and sprout weight (broken lines) during storage in 1976–7. (*a*) Sutton Bonington (▲), Tenby (■) and Wellesbourne (●). (*b*) and (*c*) harvested 4 August 1976 (●) and harvested 28 September 1976 (○). Total weight loss and sprout weight are expressed as a percentage of the original weight of tubers put into store. Total weight loss includes sprout weight.

Iritani, Pettibone & Weller, 1977; Hampson, Dent & Ginger, 1980). During curing the rate of evaporative loss was more rapid than during the holding period. To some extent, this was because temperatures were higher, 15 compared with 7 °C, resulting in a higher saturation vapour pressure deficit of the store atmosphere at the same humidity of 95 %, but breaks in the periderm caused by harvesting and handling may have been more important. According to Burton (1978*a*), these can result in potential evaporative losses which are two or three times those of undamaged tubers until wound healing is complete. During the holding period, at least until sprouting began, a relatively constant rate of weight loss was established for individual treatments. This is because there is no regulatory mechanism over water loss from tubers by evaporation, and so the rate of loss for any particular sample of potatoes is proportional to the vapour pressure deficit of the surrounding air (Burton, 1966). The rate of weight loss then increased when sprout growth commenced because sprouts themselves represent a direct loss of weight and also because the rate of water loss per unit area of sprout epidermis is much greater (30–40 times) than is that from the thickened periderm of the tuber (Burton & Hannan, 1957). Thus differences in final weight loss were largely created by the duration of the period of increased weight loss until all wounds were healed. In this year, on average, tubers from Tenby lost substantially less weight than tubers from the other sites and this difference was detectable within 2 weeks of tubers entering storage. Date of harvest had a much smaller effect and there was some evidence that the period of increased loss continued with the later harvested

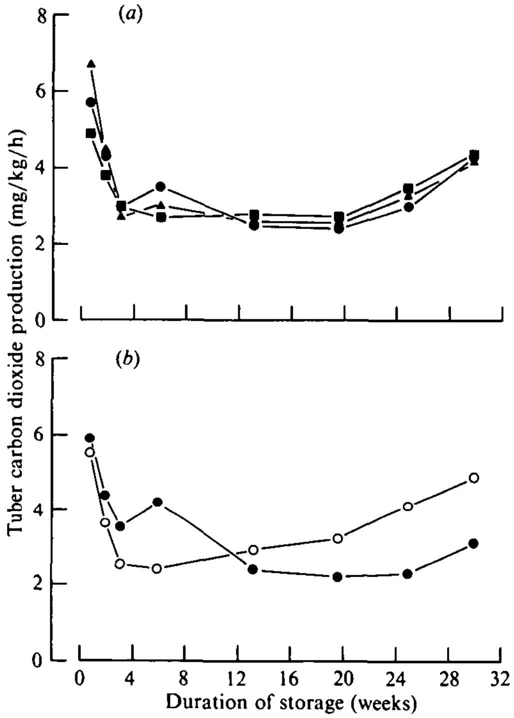

Fig. 7. The main effects of (*a*) site and (*b*) harvest date on the change with time in the respiration rate of tubers during storage in 1976–7. (*a*) Sutton Bonington (▲), Tenby (■) and Wellesbourne (●). (*b*) Harvested 4 August 1976 (●) and harvested 28 September 1976 (○).

Table 5. *Components of weight lost by tubers during storage expressed as a percentage of the original weight of tubers stored (based on data recorded at the Food Research Institute, Norwich)*

	1976						1977					
	Early harvest*			Late harvest‡			Early harvest†			Late harvest‡		
	SB	T	W	SB	T	W	SB	T	W	SB	T	W
Moisture loss (by difference)	9·0	5·1	7·5	11·3	5·7	9·8	8·1	8·3	10·5	7·7	9·0	8·1
Sprout weight	5·0	5·3	5·7	3·7	4·3	4·8	4·6	4·3	3·9	3·9	4·3	3·1
Respiration	1·4	1·5	1·5	1·3	1·4	1·3	1·4	1·6	1·6	1·3	1·3	1·2
Total weight loss	15·4	11·9	14·7	16·3	11·4	15·9	14·1	14·2	16·0	12·9	14·6	12·4

Duration of storage: * 38 weeks; † 36 weeks; ‡ 32 weeks. Sutton Bonington (SB), Tenby (T), Wellesbourne (W).

tubers. Thus, tubers harvested in early August from crops defoliated in full growth in late July stored as well as tubers harvested at the generally accepted appropriate time (September).

In 1976, 1977 and 1978, measurements were made of the rates of respiration of tubers from the crops mechanically defoliated at both the early and late stages of growth and harvested 2 weeks later. The effects of site and harvest date were broadly similar in each year and data for 1976 are shown in Fig. 7. In general, the rate of tuber respiration decreased as harvest was delayed and decreased rapidly during the curing period in all treatments. Tubers from Tenby always respired at a lower rate than those from the other two sites during curing and the initial stage of holding. Later in the storage period, once sprouting began, the rate of respiration increased markedly and this occurred sooner with late-harvested tubers (Fig. 7*b*). It was estimated that weight loss due to respiration in tubers stored for approximately 8 months amounted to between 1 and 1·5% of the original weight of tubers stored and estimates of the relative importance of the different components of natural wastage in 1976 and 1977 are shown in Table 5. Clearly, evaporation was the major source of loss followed by sprouting whilst respiration accounted for only about a tenth of total weight loss.

Range of weight loss

The range of weight losses recorded after long-term storage was very great in every year, but particularly so in 1976, 1977 and 1980 (Table 6), confirming the expectation that the way in which the crop is grown and treated at harvest has very significant effects on storage losses. Main effects of treatments are shown in Table 7. With the exception of 1977, tubers grown at Tenby stored with the lowest losses of weight and this was particularly marked in 1976 which was the most extreme season in terms of weather prevailing at the different sites. In 1976, 1977 and 1980 crops defoliated early had smaller weight losses than crops defoliated later and in 1980 the very late defoliation and harvest resulted in a doubling of weight loss in store. On the other hand, there was no difference between the performance of tubers from crops harvested either early or late in 1978 and 1979. This was related to the stage of crop growth at defoliation. Crop growth patterns (Figs 3 and 4) show that in 1976, 1977 and 1980, the first defoliation occurred when tuber bulking was still actively underway and the haulm was at or just beyond maximum weight. In contrast, in 1978 and 1979, even at the first defoliation, tuber bulking had already ceased and senescence of the haulm was well advanced. Thus, there was a suggestion that crops which were defoliated during the phase of rapid tuber growth had better storage characteristics than those defoliated and harvested after it had ceased. This also seemed to be true for crops which were harvested without prior defoliation. However, once tuber growth had ceased the timing of defoliation and harvest was of less importance.

Crops harvested without prior defoliation generally stored at least as well as those which were deliberately defoliated on the same date but harvested 2 or 4 weeks later. It was also clear that the

Table 6. *The range of total weight loss* (%) *in store recorded for undamaged samples of tubers*

Year	Duration of storage (weeks)	Total weight loss (%)
1976	30	5·5–16·3 (5·5–16·3)*
1977	31	6·3–16·1 (6·0–15·4)
1978	25	5·7–10·8 (6·9–13·1)
1979	25	6·1–9·7 (7·3–11·8)
1980	26	5·4–13·1 (6·2–15·1)

* Figures in parentheses are the estimated values for a 30-week storage period, assuming a constant rate of total weight loss.

Table 7. *The effects of site and cultural conditions on storage losses of Pentland Crown* 1976–80

	Total weight loss (%)*					Sprout weight (%)*				
	1976	1977	1978	1979	1980	1976	1977	1978	1979	1980
Site										
Sutton Bonington	15·0	9·6	7·4	8·9	—	2·4	1·6	0·4	0·6	—
Tenby	7·2	11·3	6·6	8·0	8·7	1·9	2·0	0·5	0·3	0·9
Wellesbourne	11·9	11·3	8·9	—	—	1·8	1·3	0·4	—	—
Cockle Park	—	—	—	—	10·2	—	—	—	—	1·1
Reading	—	—	—	—	9·3	—	—	—	—	1·1
S.E.	0·70	0·18	0·37	0·38	0·15	0·21	0·06	0·02	0·02	0·05
Method of defoliation										
Control	—	11·0	7·4	8·6	—	—	1·4	0·4	0·4	—
Mechanical	11·4	10·7	7·9	8·0	9·4	2·0	1·8	0·5	0·5	1·0
Chemical	—	11·2	7·6	8·8	—	—	1·7	0·5	0·5	—
S.E.	—	0·18	0·37	0·46	—	—	0·06	0·02	0·02	—
Time of defoliation										
Early	10·0	9·8	7·6	7·2	6·2	2·0	1·8	0·4	0·5	0·2
Late	12·8	12·2	7·3	7·9	11·8	2·1	1·7	0·5	0·6	1·9
S.E.	0·57	0·15	0·30	0·38	0·12	0·17	0·05	0·02	0·02	0·04
Time of harvest relative to defoliation										
Early	—	10·2	7·0	7·4	—	—	1·5	0·3	0·5	—
Late	—	11·7	7·9	7·7	—	—	1·9	0·6	0·6	—
S.E.	—	0·15	0·30	0·38	—	—	0·05	0·02	0·02	—

* Recorded after 30, 31, 25, 25, 26 weeks of storage in 1976, 1977, 1978, 1979, 1980 respectively.

earliest harvested crops almost invariably stored with lower losses of weight than late harvested ones. There were no consistent differences between the chemical and mechanical methods of defoliation in weight loss and neither was superior to harvesting directly without removing the haulm. In general, extending the interval between defoliation and harvest from 2 to 4 weeks resulted in slightly greater storage losses (Table 7). However, in 1977, harvesting 4 weeks after the early defoliation was considerably worse than at 2 weeks at all sites and resulted in at least a 25% increase in weight losses. This effect seems to have been associated with the very high rainfall in the 2-week period intervening between the first and second harvests of the early-defoliated crop in this season.

Influence of tuber damage, curing and disease

Damage has two effects on weight loss. Cuts and breaks in the periderm result in greater evaporative loss compared with undamaged tubers which have intact skins. Burton (1978*a*) suggested that the difference could be two- or three-fold initially but declines rapidly as wound healing progresses. Secondly, damage provides sites for the invasion and proliferation of wound pathogens which result in severe dehydration of infected tubers.

In these experiments, all tubers were harvested carefully by hand to minimize damage, but in 4 years (1977–80) subsamples of each treatment were damaged prior to storage by using the Sutton Bridge 'standard drop test' which is designed to simulate impact during harvesting. This allowed determination of the contribution of damage to weight loss and if contrasting treatments responded differently to it. Damage increased total weight loss of all treatments by about an eighth to a tenth on average, equivalent to about 1–2% of the original weight of tubers stored, which is similar to the results of other experiments that have compared weight loss from damaged and undamaged tubers (Hampson *et al.* 1980; Ophuis, 1957; Green, 1956). There was no evidence to show that damage had more severe effects on some treatments than on others. However, this may have been because the 'drop test' is too crude to discriminate relatively small differences between the susceptibility to damage of different tubers or their response to damage.

The overall level of disease was low in this series of experiments and the incidence of major storage rots (soft rot, dry rot, gangrene) was not markedly increased by damage, with one exception: in 1980 the number of tubers infected with gangrene was

Table 8. *The main effects of tuber damage and curing on total weight loss (%) after* 26 *weeks storage* 1980

	Undamaged	Damaged	Mean	S.E.
Cured	9·0	10·3	9·7	0·12
Uncured	9·8	11·3	10·6	
S.E.	0·18			
Mean	9·4	10·8		
S.E.	0·12			

increased in tubers from Tenby and Reading. However, in most cases, it seems that extra weight loss due to damage was not associated with an increase in disease and so was probably the direct result of damage to the periderm causing increased moisture loss.

Curing encourages wound healing and shortens the duration of excessive moisture loss from wound sites. It also prevents the ingress of pathogens which not only increases weight loss but also decreases the weight of marketable tubers. In 1980, failure to cure tubers prior to the main holding period increased total weight loss of both damaged and undamaged samples by about a tenth. However, tubers which were damaged and not cured lost about 25% more weight than undamaged cured ones and it was clear that the effects of damage and curing on total weight loss were additive (Table 8). It was also apparent that not curing a stock of tubers prior to storage had similar effects on total weight loss to damaging tubers. Both young and old tubers (harvested early and late respectively) were given the damage and curing treatments but the data on weight loss revealed no effects of tuber age on the importance of curing. Curing also had a notable effect on the incidence of one of the major wound pathogens, gangrene. This invades wounds effectively only under conditions which adversely affect the formation of wound cork and so is suppressed by curing. Thus, without curing, gangrene was markedly increased, but only following late harvesting, particularly in samples from Tenby (Table 9).

Table 9. *The effects of damage and curing on the percentage (by number) of late-harvested tubers infected with gangrene after* 26 *weeks storage* 1980

	Tenby		Cockle Park		Reading	
	Undamaged	Damaged	Undamaged	Damaged	Undamaged	Damaged
Cured	0·8	9·5	1·5	0	2·5	4·1
Not cured	4·3	62·3	0·7	2·1	3·0	10·3

Table 10. *The effects of tuber damage on the percentage (by number) of tubers infected with the major storage diseases*

	Soft rot*		Dry rot*		Gangrene*	
	Undamaged	Damaged	Undamaged	Damaged	Undamaged	Damaged
1977						
Sutton Bonington	0·13	0·08	2·97	3·68	0	0·43
Tenby	0	0·26	0·71	1·97	0·06	0·50
Wellesbourne	0·05	0·49	0·65	0·85	0·16	0·13
1978						
Sutton Bonington	0·50	0·20	0·07	0·24	0·11	0·16
Tenby	0·67	0·83	0·21	0·83	0·29	0·83
Wellesbourne	0·75	0·92	0·20	0·28	0·39	0·63
1979						
Sutton Bonington	0·45	0·99	2·19	1·93	0·84	0·33
Tenby	0·53	0·73	0·23	0·28	0·10	0·43
Wellesbourne	1·02	1·30	0·17	0·32	0·86	0·97
1980						
Tenby	0·10	0·25	0	0·08	1·30	18·10
Cockle Park	1·29	0·50	0	0·21	0·80	0·70
Reading	0·08	0·10	0	0	1·36	3·60
Cured	0·68	0·28	0	0·08	0·85	2·26
Not cured	0·30	0·29	0	0·14	1·43	12·62

* Recorded after 31, 25, 25, 26, weeks of storage in 1977, 1978, 1979, 1980 respectively.

Table 11. *The effects of site and cultural conditions on silver scurf infection* 1976–80

	Silver scurf infection (code)*†				
Site	1976	1977	1978	1979	1980
Sutton Bonington	1·89	1·10	1·32	1·31	1·17
Tenby	1·63	1·44	1·33	1·45	1·26
Wellesbourne	0·97	1·29	1·41	—	—
Cockle Park	—	—	—	—	1·04
Reading	—	—	—	—	—
S.E.	—	0·017	0·027	0·024	0·020
Method of defoliation					
Control	—	1·30	1·43	1·42	—
Mechanical	1·50	1·25	1·31	1·33	1·16
Chemical	—	1·27	1·32	1·40	—
S.E.	—	0·017	0·027	0·024	—
Time of defoliation					
Early	1·07	1·12	1·16	1·05	1·04
Late	1·92	1·43	1·55	1·70	1·28
S.E.	—	0·014	0·019	0·020	0·017
Time of harvest relative to defoliation					
Early	—	1·19	1·29	1·17	—
Late	—	1·36	1·42	1·58	—
S.E.	—	0·014	0·019	0·020	—

* Silver scurf code: 0, no infection; 1, under 10% of surface area of tuber infected; 2, 10 to 25% of surface area of tuber infected; 3, over 25% of surface area of tuber infected.

† Recorded after 30, 31, 25, 25, 26 weeks of storage in 1976, 1977, 1978, 1979 respectively.

Three major storage rots, dry rot, gangrene and bacterial soft rot which have large effects on losses in commercial stores, were recorded in the experiments. However, their incidence was so rare (for most treatments less than 1% of tubers showed signs of rots, even when deliberately damaged (Table 10)) that they made relatively little contribution to weight loss except in one or two cases. It was also difficult to establish any clear relationship between field treatments and disease levels for the same reason. However, those few samples which were infected with the rotting diseases were invariably those which lost most weight during storage. As expected, damage tended to increase the incidence of these rots because infection of the tuber flesh takes place through breaks in the periderm and outer cortex. However, the effect was much smaller than would have been expected in a commercial situation where tubers are stored in bulk or large capacity boxes.

Silver scurf is a superficial blemish disease which may influence the permeability of the periderm and result in enhanced water loss compared with uninfected tubers and was prevalent in all samples. The disease was already evident at harvest and the severity of infection increased as storage was prolonged. Defoliation and harvesting treatments had clear and consistent effects: infection increased both as the date of defoliation and harvest was delayed (Table 11). This may be responsible at least in part for the generally observed increase in total weight loss in store associated with late harvesting and in 1977 there was a close relationship between total weight loss and silver scurf infection (Fig. 8) but not in other years.

The relationship between tuber characteristics and storage losses

The data allow examination of the link between tuber yield and weight loss and some of the morphological, biochemical, and physiological characteristics of tubers and their storage potential.

Yield. Contrasting sites, seasons and defoliation treatments resulted in very large differences in yield both within and between years. There was always at least a two-fold difference between the highest and lowest-yielding treatments in each season but differences in weight loss were much smaller and there was no correlation between yield and storage losses.

Average tuber size. This was often affected by site and harvest date because of effects on number of tubers and yield. It increased during the period of tuber bulking at all sites and tubers from Tenby were almost invariably the largest on any harvest

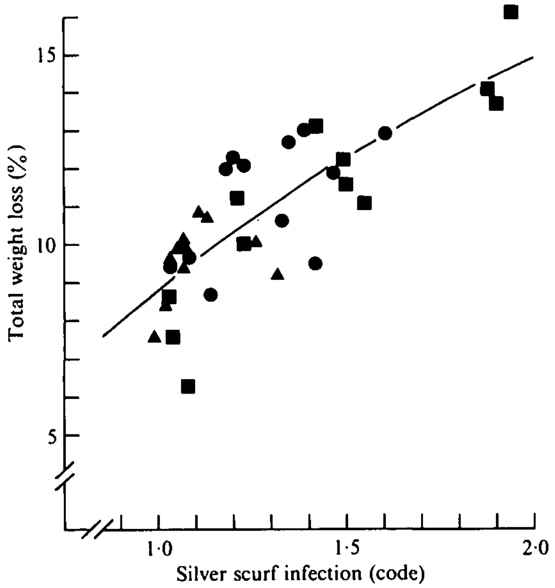

Fig. 8. The relationship between total weight loss of tubers and silver scurf infection after 31 weeks of storage in 1977–8. Sutton Bonington (▲), Tenby (■), Wellesbourne (●). Regression line:

$$Y = 11{\cdot}36X - 1{\cdot}78X^2 - 0{\cdot}77; \quad R^2 = 0{\cdot}643.$$

Silver scurf code: 0, no infection; 1, under 10 % of surface area of tuber infected; 2, 10–25 % of surface area of tuber infected; 3, over 25 % of surface area of tuber infected.

date (Fig. 3). Tuber size distribution can have marked effects on weight loss of a particular sample as it will influence the total surface area of periderm through which evaporative water loss occurs. For example, unit weight of small tubers has a higher potential for weight loss than unit weight of larger tubers under the same conditions of storage because there is greater surface area available for evaporation. Thus, although the rate of evaporation per cm^2 of periderm per hour per mm Hg VPD may be independent of tuber size (Burton, 1966; Schippers, 1971), the rate of weight loss is not, small tubers losing water at a faster rate. To some extent, this may help to explain the large difference between sites in average weight loss in 1976. After 30 weeks of storage, weight losses recorded for Tenby, Sutton Bonington and Wellesbourne were 7·2, 15·0 and 11·9 % respectively and corresponding average tuber weights were 101, 41 and 68 g. On the other hand, increases in tuber size with delayed harvest at individual sites were not associated with lower weight losses in store. Possibly, this is because the situation is complicated by increased damage to large tubers even during hand harvesting and handling by virtue of their size and greater kinetic energy on impact compared with small tubers. This could result in a greater rate of moisture loss initially from the wound sites until healing was complete.

Periderm thickness. Evaporative water loss is the major component of natural wastage and since the periderm is the physical barrier through which 98 % of moisture is lost (Burton, 1978*b*) it is possible that its thickness may influence weight loss in store. Effects of treatments on periderm thickness in 3 years are shown in Table 12. Differences within years were small but the thicker periderm of tubers grown at Tenby in 1976 may have restricted moisture loss below that of tubers from Sutton Bonington or Wellesbourne. However, since both periderm thickness and weight loss increased as defoliation was delayed at individual sites in all 3 years, it seems that in these experiments, the small improvements in periderm thickness were more than offset by other factors.

Tuber dry-matter content. Dry-matter content is an important quality attribute, particularly of crops destined for processing, because it affects yield and quality of the end product. Over the experiments as a whole, dry-matter content of tubers put into store ranged from 14 to 25 % and a typical example of the effects of treatments is shown in Table 13. In general, maximum dry-matter content in any year was usually achieved before the latest harvest. Prior defoliation decreased dry-matter content compared with control crops harvested 'green-top' on the same date. Where diquat was used as the defoliant, tuber dry-matter content was on average 0·5–1 % higher than where mechanical defoliation was done, presumably because of retranslocation of dry matter from the dying haulm to tubers. However, in most cases, delaying harvest of chemically defoliated crops from 2 to 4 weeks after diquat application resulted in a slight decrease in dry-matter content of tuber probably because water uptake continued after foliage death. There was no relationship between dry-matter content of tubers and storage losses.

Reducing-sugar content. Reducing-sugar content is another important quality attribute of tubers for processing as it affects the colour of the final product in crisps and french fries. Although treatments had a large effect giving a range of 0·1 to 0·95 % over the years, there were no consistent trends and no correlations between reducing-sugar content and storage losses.

Rates of tuber respiration. Table 5 and Fig. 7 showed that site and time of defoliation affected the rate of tuber respiration. However, the contribution of respiration to storage losses was so small that a relationship between total weight loss and respiratory losses in store is very unlikely. This result is in complete agreement with Schippers (1977) who working with a range of American varieties also

Table 12. *The effects of site and cultural conditions on periderm thickness (μm)* 1976–8

	Periderm thickness (μm)		
Site	1976	1977	1978
Sutton Bonington	128·5	160·0	189·3
Tenby	158·4	160·9	193·2
Wellesbourne	133·7	164·9	179·9
s.e.	3·69	1·19	1·61
Method of defoliation			
Control	—	164·7	193·3
Mechanical	—	163·1	187·4
Chemical	—	158·2	181·8
s.e.		1·19	1·61
Time of defoliation			
Early	138·6	157·1	186·2
Late	141·4	166·9	188·6
s.e.	3·01	0·97	1·32
Time of harvest relative to defoliation			
Early	—	157·6	187·4
Late	—	166·4	187·5
s.e.		0·97	1·32

Table 13. *The effects of treatments on tuber dry-matter content (%) tubers before storage* 1977

		Early defoliation (1. viii)		Late defoliation (31. viii)	
Site	Method of defoliation	Early harvest (15. viii)	Late harvest (31. viii)	Early harvest (15. ix)	Late havest (27. ix)
Sutton Bonington	Control	21·4	19·7	20·3	20·3
	Mechanical	18·4	18·0	19·7	19·1
	Chemical	19·0	18·4	19·9	19·2
Tenby	Control	24·8	21·7	22·0	22·0
	Mechanical	21·0	21·1	20·8	20·7
	Chemical	22·3	22·3	21·4	21·1
Wellesbourne	Control	22·2	21·2	22·5	23·5
	Mechanical	19·6	18·4	19·8	19·9
	Chemical	20·3	19·2	20·2	19·7

s.e.: sites, 0·06; method of defoliation, 0·06; time of defoliation, 0·05; time of harvest relative to defoliation, 0·05; body of Table, 0·22.

suggested that differential rates of respiration early in storage are no guide to potential storage losses.

Sprouting

The importance of the contribution of sprouting to total weight loss in store has already been considered. On average, sprout weights were greater in 1976 and 1977 than in other years because of the extended period of storage and were about 2% of the original weight of tubers put into store. Differences between treatments within a year were usually small and infrequent sampling during storage made it impossible to determine if the dates at which sprout growth commenced were different. However, date of harvest had a very significant effect on sprout growth in 1980 (Table 7) when the late harvest was delayed well into the autumn. Presumably this was because the period between loading into store and the time when sprouts began to grow was much shorter for the late harvest, but the rate of sprout growth might also have been affected.

After 6 or 7 months storage, treatments which lost most weight were those with most prolific

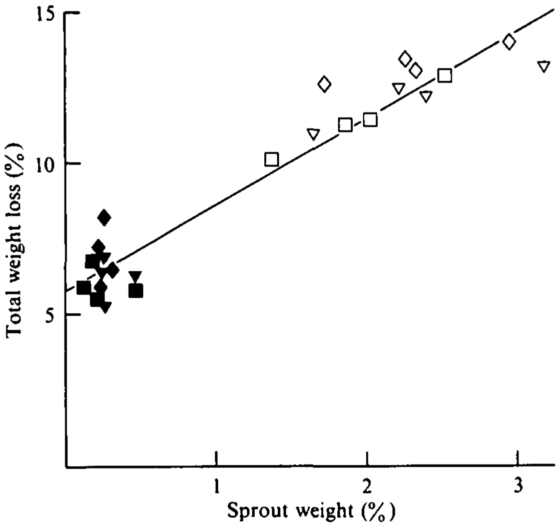

Fig. 9. The relationship between total weight loss of tubers during storage and sprout weight expressed as a percentage of the original weight of tubers put into store in 1980. Cockle Park (◆, 13-week storage period; ◇, 26-week storage period). Reading (▼, 13-week storage period; ▽, 26-week storage period), Tenby (■, 13-week storage period; □, 26-week storage period). Regression line: $Y = 5{\cdot}85+2{\cdot}84X$; $R^2 = 0{\cdot}921$.

sprout growth, particularly in 1980 (Fig. 9). This was to be expected as Burton & Hannan (1957) demonstrated an approximately linear relationship between the percentage by weight of sprout growth and the rate of weight loss from tubers exposed to free air movement. However, the differences between storage losses of contrasting treatments were evident before sprout growth had commenced which suggests that the ranking order of storage potential is set early in the storage period. Clearly then, the effects of different environmental conditions at the sites and contrasting husbandry treatments on weight loss were not simply the result of differences in sprout growth and would still be evident even where effective chemical suppressants are used.

DISCUSSION

Crop growth

The contrasting sites, seasons and times and methods of defoliation produced a very wide range of crop performance. The two most dominant features of the series of experiments in terms of crop growth were the drought of 1976 and the potential of Tenby to produce consistently higher yields of tubers by the end of August. Although 1976 was a very bright year with the potential to produce high yields of tubers this was not reached with crops at other sites which were water stressed because of drought (Scott & Wilcockson, 1978; Allen & Scott, 1980). There could be two basic reasons for this. First, the size of the leaf canopy was restricted because of premature senescence encouraged by the need to conserve water and probably also excessively high leaf temperatures. Consequently, the crops would be unable to intercept fully the solar radiation incident upon them after the middle of June because leaf area index had declined below the critical value of 3, which is required to intercept at least 80% of incident radiation. Secondly water stress could have inhibited the photosynthetic activity of the surviving leaves and reduced the efficiency with which the radiation was used (Scott & Wilcockson, 1978; Allen & Scott, 1980). The net result would be a severe depression of the rate and duration of tuber bulking.

Rainfall was very similar at all three sites in 1976, and although Tenby was clearly the brightest, water stress was much less severe than at either Wellesbourne or Sutton Bonington as evidenced by yields of 60 compared with 30 t/ha. Differences in available water capacity of the soils at the sites were undoubtedly involved and more recently, Jones & Allen (1983) have reported that large limiting deficits (> 100 mm for maincrops) are a general feature of crop growth at the Tenby site. Clearly the soil at Tenby was capable of supplying much more water than at other locations. Less intense water stress even when conditions were as severe as they were in 1976 together with high solar radiation receipts and warm springs were responsible for the very high yield potential of this site for maincrop potatoes. The synchronous planting of all sites reduced the potential advantage of Tenby for rapid early leaf growth for the date of planting was determined by the first occurrence of suitable conditions at all sites. On this date planting at Tenby had often been possible for over a month and the yields from other experiments planted in March or early April show that yields are frequently greater than 60 t/ha at this site (Ifenkwe & Allen, 1978; Allen, 1977). The other main cash root crop, sugar beet, also has a much higher yield potential at Tenby than in eastern England where the majority of the commercial crop is grown. In experiments in 1979, more rapid leaf expansion of sugar beet in spring and the maintenance of a larger LAI in autumn coupled with more incident radiation and more efficient use of intercepted radiation at Tenby gave 13·1 t/ha of sugar compared with 11·2 t/ha for a crop grown with identical husbandry at Broom's Barn in East Anglia (Rothamsted Experimental Station, 1981).

Over the seasons, treatments produced a large range of yield of ware tubers from 30 to almost 90 t/ha. However, the effects of sites, seasons and

Table 14. *The effect of crop growth stage on total weight loss* (%) (*moisture loss in parentheses*)

	Least advanced*	Most advanced†	Least advanced*	Most advanced†
1976	(14 weeks storage)		(30 weeks storage)	
Sutton Bonington	5·2	7·2	13·7 (10·9)	16·3 (14·3)
Tenby	2·0	2·9	5·5 (4·4)	8·9 (6·2)
Wellesbourne	5·1	6·0	10·7 (8·6)	13·1 (11·6)
1977	(19 weeks storage)		(31 weeks storage)	
Sutton Bonington	6·3	6·0	9·4 (8·1)	10·0 (7·9)
Tenby	3·7	7·2	6·3 (4·8)	14·0 (11·9)
Wellesbourne	6·0	6·8	8·7 (7·5)	11·9 (10·6)
1978	(12 weeks storage)		(25 weeks storage)	
Sutton Bonington	3·6	4·5	6·1 (6·0)	7·3 (6·8)
Tenby	3·3	3·4	6·3 (6·0)	7·3 (6·8)
Wellesbourne	5·0	5·1	8·3 (8·0)	8·8 (8·5)
1979	(12 weeks storage)		(25 weeks storage)	
Sutton Bonington	4·6	3·6	7·3 (7·0)	6·9 (6·1)
Tenby	3·7	4·8	6·1 (6·0)	9·1 (8·6)
Cockle Park	3·8	3·4	6·4 (5·8)	6·9 (5·8)
1980	(14 weeks storage)		(26 weeks storage)	
Sutton Bonington	4·0	5·8	5·9 (5·7)	11·3 (9·1)
Tenby	5·6	7·1	7·3 (7·2)	13·1 (11·2)
Cockle Park	4·6	6·3	7·1 (6·9)	12·5 (10·2)

* Least advanced: 1977, 1978, 1979, early harvested, green top; 1980 late planted early harvested.

† Most advanced: 1977, 1978, 1979, late harvested, mechanically defoliated, 1980 early planted, late harvested.

cultural practices on yield were relatively greater than on keeping quality in store. There was certainly no suggestion of any conflict between yield and storage losses as both high and low-yielding crops stored equally well. This indicates that storage losses are not a function of tuber yield. Work at the Potato Marketing Board's Sutton Bridge Experimental Station has also confirmed this (Potato Marketing Board, 1980). Crops with a yield of 75 t/ha achieved by using very high levels of inputs (Evans, 1975) stored just as well as conventionally grown crops with lower yields but there was one marked advantage: because of high seed rates in the high-yield system, average tuber size was restricted and damage at harvest was decreased (Potato Marketing Board, 1980). Presumably the decreased damage fully compensated for the higher surface area to weight ratio of small tubers which characteristically results in higher rates of water loss compared with large tubers (Burton, 1966).

Weight loss in store

These experiments produced a series of potato crops which were more diverse in their growth patterns than those achieved by previous workers concerned with storage losses. The most notable feature was that tubers harvested before the foliage began to senesce rapidly almost invariably stored with lower losses over a given period than tubers which were harvested after the haulm had died (Table 14). The size of the differences at the end of the fixed period in storage suggested that any specific date in the storage period similar comments would apply. Thus, most of the treatments which lost least weight during storage were harvested when the tops were still green and healthy and rapid tuber bulking was still underway. Such crops are traditionally classified as earlies or immature and rarely if ever considered for long-term storage. These results contradicted our expectation that storage potential would improve with the stage of crop development because increasing periderm thickness and skin-set would limit evaporation and decrease tuber susceptibility to damage during harvest. Whilst improvements in periderm characteristics undoubtedly occur as harvest is delayed, in these experiments other factors outweighed this advantage. Sprouting was certainly involved (as no chemical suppressants were used) and the most advanced crops sprouted most prolifically during this period of storage. This is a well-known effect because the later the date of harvest, the less time remains after harvest before sprout growth begins (Burton, 1978*a*). However, sprouting which contributes directly to total weight loss and leads to higher rates of moisture loss and respiration clearly cannot be the only factor, because the data (Fig. 6) and those of Schippers (1971) show that differences in storage potential are evident long before sprout growth commences. Perhaps one of the most important characteristics is the rapidity and effectiveness of healing wounds inflicted during harvest. Wound healing is most rapid in young tubers which are harvested when still in the growth phase compared with older tubers which have ceased growing for some time prior to harvest or have been stored (Burton, 1978*a*). The rate of wound healing is also positively related to tuber temperature (Wigginton, 1974) and as temperature frequently decreases throughout harvesting this factor is probably of considerable importance in the reduced storage potential of later-harvested tubers. This decrease in rate of wound healing with age and lower harvest temperatures results in an extension of the initial phase of rapid weight loss and a higher total weight loss in store from later harvesting. Thus, storage potential seems to decrease as crops become more advanced and the magnitude of the effect in any season will be determined by prevailing temperatures and the stage of growth of the crop. The adoption of earlier harvesting would bring considerable practical advantages. A longer period is available for filling stores in higher temperatures which facilitate easy curing of the late-harvested tubers. Harvesting conditions would invariably be improved and cleaner tubers enter stores. This is important for the effective application of fungicide (e.g. thiabendazole) to tubers and also for the subsequent distribution of chemicals throughout the bulk of potatoes to inhibit sprouting. Better distribution of these materials may reduce the incidence of internal sprouting in long-term storage and allow less chemical to be used. Further, earlier harvesting would allow more time between curing and the initial application of CIPC which should minimize the occurrence of skinspot which frequently follows application of CIPC to uncured potatoes (Ministry of Agriculture, Fisheries & Food, 1984).

Optimum time of harvest of potatoes for storage

The apparent deterioration in storage potential as harvest is delayed raises the question of when is the optimum time to harvest crops for storage. Much of our data suggest that a crop harvested directly when it is still actively growing, or one which is defoliated at this stage and harvested shortly afterwards may be a better prospect for storage than one which is left until natural senescence is virtually complete. Earlier work at Sutton Bridge on a larger scale, investigating curing and storage regimes in relation to date of mechanical harvesting of the crop, led to similar conclusions (Potato Marketing Board, 1976). At the end of storage, potatoes defoliated at the beginning of September and harvested in the middle of that month showed less wastage due to moisture loss and disease than those harvested up to 2 months later in mid-November. It was also clear that the wound barrier which helps to prevent infection by soft-rot bacteria formed more quickly following early harvesting. There were other benefits too. The overall appearance and suitability of tubers for washing and prepacking was better and the incidence of skin spot and silver scurf less than from later harvests. Further work (Potato Marketing Board, 1979*b*) examined the effects of defoliating crops at intervals from the 3rd week in August to the 3rd week in September and harvesting 3 weeks following defoliation and also gave similar results. However, perhaps more importantly, although the earliest harvest resulted in lower yields, these were usually compensated for by greater outturns after storage. Thus, there is strong evidence that for long-term storage it is possible to sacrifice at least some potential yield in the field by harvesting early in the expectation of securing higher outturns after storage. In some cases, considerable sacrifice may be acceptable. For example, data from our 1980 experiments show that very large differences in yield at harvest caused by contrasting planting and harvesting dates narrow considerably when yield out of store is considered. Sometimes the differences may disappear completely or even be reversed (Table 15). This was partly because total weight loss in store was less following an early harvest, but perhaps more importantly, the proportion of the yield which qualified for the ware grade was greater because there were fewer defects. These data were obtained by the rigorous application of the Potato Marketing Board's grading standards for ware potatoes for the 1980 season (Potato Marketing Board, 1981). As the tubers were hand harvested it seems probable that similar adherence to the standard for mechanically harvested crops would severely decrease the quantity of potatoes available for sale as ware because of a greater incidence of mechanical damage. The data therefore illustrate the significance of decreased quality from later harvesting and the potential for improved quality by earlier harvesting. This potential will become more important if ware standards are tightened in practice and domestic processors follow their N. American counterparts and relate price to the extent of bruising.

Currently, October is the month when the majority of maincrops are harvested and in 1977, about 80% of the total area was harvested then

Table 15. *Total tuber yields and ware yields in the field and saleable yields after 26 weeks storage* 1980–1

	Total yield (t/ha)	% total yield in ware size range (40–80 mm)	Yield of ware size tubers (t/ha)	% yield of ware size tubers which were ware standard	Saleable yield (t/ha)	% weight loss in store	Saleable yield out of store (t/ha)
Tenby							
Early planting							
Early harvest	65·3	84·7	55·3	90·3	49·9	5·5	47·2
Late harvest	72·7	88·3	64·2	73·7	47·3	11·3	42·0
Late planting							
Early harvest	56·1	98·1	55·0	96·7	53·2	5·9	50·1
Late harvest	75·4	99·7	75·2	74·3	55·9	10·1	50·3
Cockle Park							
Early planting							
Early harvest	63·3	97·3	61·6	72·0	44·4	6·0	41·7
Late harvest	90·2	97·7	88·1	66·3	58·4	13·1	50·7
Late planting							
Early harvest	44·9	99·8	44·8	94·0	42·1	7·3	39·0
Late harvest	80·7	89·0	71·8	75·0	53·9	12·6	47·1
Reading							
Early planting							
Early harvest	65·7	86·2	56·6	75·0	42·5	5·4	40·2
Late harvest	73·6	89·5	65·9	58·3	38·4	12·5	33·6
Late planting							
Early harvest	43·4	96·2	41·8	87·0	36·4	7·1	33·8
Late harvest	78·5	95·0	74·6	65·7	49·0	11·0	43·6

(Potato Marketing Board, 1979*a*). However, the reported experiments greatly increase the evidence which suggests that there is much to be gained by advancing commercial harvesting of ware crops for storage into September. Growth data suggest that for most crops planted in April there is unlikely to be any great increase in harvestable yield during September (Figs 1 and 2) and this is likely to be the case in practice as few crops have leaf cover in this month and therefore their potential for growth is limited by this inadequate and decreasing leaf area (Allen & Scott, 1980). Those crops which do have a full leaf cover in September have frequently been planted late or are of an indeterminate late-initiating variety like Cara whose yields would be lower at this time than those of alternative varieties (Ramsbottom, 1978). Further, tuber dry-matter content, which is of interest to potato processors, will already have achieved its maximum by September (Fig. 4) and the increase in the reducing-sugar content of the tuber, which is often associated with the decrease in soil temperatures in autumn (Gray & Hughes, 1978) and causes problems for crisps and french fry manufacturers, would be avoided. Bringing harvest forward into September should therefore result in lower collective losses due to sprouting, evaporation of water and disease, over the whole of the storage period and an increase in saleable (usable) yields of high quality, blemish-free potatoes which may qualify for a premium. It would not present any clash with cereal harvesting in view of the earlier harvesting of modern varieties but may accentuate conflict with drilling of cereals. An earlier potato harvest would ensure that a greater proportion of the crop was followed with winter wheat sown nearer to the optimum time. Moreover, the risk that potato crops might not be harvested at all in autumn because of poor soil conditions would be removed and damage to soil structure caused by heavy harvesting machinery working in wet conditions largely avoided. The conclusion in principle is quite clear, harvesting should begin earlier to be complete by early October. The evidence from these experiments suggests that the adoption of the recommendation would involve little sacrifice in field yield and substantial improvements in saleable yield from store.

Methods of haulm destruction

The general recommendation to growers has been to defoliate the crop either chemically or mechanically and allow at least 14 and preferably 21 days to elapse between haulm destruction and harvest so that tuber skins are set and thereby avoid, at the very least, excessive scuffing damage. However, in these experiments, defoliation prior to harvest gave no improvement in storage potential and could if done before tuber bulking had ceased result in decreased yield and dry-matter content of tubers. This suggests that it might be possible to dispense with defoliation prior to harvest at least so far as storage potential is concerned for there appear to be no essential effects on the tuber. Such a possibility would make it easier to programme harvesting schedules within the relatively short period available for harvest as the need to wait for 2 or 3 weeks after defoliation would be removed. Yield and dry-matter content would become more consistent as the length of the growing season would be open to manipulation without any penalties from late harvesting. If direct harvesting had occurred at the end of the period of relatively constant tuber bulking in these experiments, this would have been by mid-September and there would have been no sacrifice of yield or quality and tubers would have been largely blemish-free because of less silver and black scurf, less damage and more effective wound healing. This would have achieved the ideal combination of maximum yield, quality and storage potential. A simple programme of regular crop sampling to plot the time course of tuber bulking would adequately pin-point the stage at which yield increases slow down. A visual estimate of leaf cover in conjunction with incident radiation would also suffice.

There are a number of practical and mechanical advantages of haulm destruction though which must not be overlooked. Some control of blight and late aphid infestations may be effected but the main advantage is that the volume of vegetation (including weeds) is cut down drastically which greatly facilitates harvesting and growers may not be prepared to dispense with it for this reason. There is one other advantage that perhaps applies to Pentland Crown more than any other variety. Its tubers remain firmly attached to the stolons unless the crop is completely dead at harvest so that defoliation alleviates this problem. This aids harvesting and also helps to avoid excessive damage at the heel end of the tubers. However, the belief that defoliation prior to harvest leads to a general improvement in damage resistance because of improved skin-set is highly questionable. Damage survey data of the Potato Marketing Board (1974 and 1982) showed that in commercial situations, crops harvested without prior defoliation were not associated with higher levels of damage than those harvested 2 or 3 weeks after haulm destruction. This suggests that the importance of 'skin-set' conferring damage resistance to tubers and, by inference, improvements in storage potential may have been overestimated in the past.

The possibility of dispensing with defoliation is of particular significance for the extra growing period released by direct harvesting would help ensure large field yields in most crops. However, it is not known how tubers from undefoliated crops would respond to wholly mechanical harvesting. It seems inevitable that some extra scuffing would result but the expectation would be rapid regrowth of a new skin. Such tubers may retain flaps of original skin on their surface which may detract from their appearance and reduce their suitability for pre-packing. For processing, such considerations are unimportant and providing bruising can be avoided such tubers would be acceptable for processing. It is clearly important to test these possibilities involving mechanical harvesting as soon as possible and to examine the changed priorities of the harvesting operation. In the more suitable conditions for harvesting of September it may be useful to consider windrowing the crop prior to collection as a means of minimizing scuffing of tubers and ensuring the collection of a high volume of tubers without much requirement for soil separation. The development of these ideas in further experiments should also consider the influence of the storage environment for recent developments in storage loading and temperature and ventilation control have greatly increased the capability of many growers to control precisely the environment within the bulk of potatoes. Thus, the necessary conditions for rapid re-growth of tuber skin could be produced in many new stores which would be impossible in older stores.

Our data also allow general comment on the length of time that should be allowed to expire before harvest when defoliation is practised. A delay from 2 to 4 weeks was invariably associated with an increase in total weight loss (explained partly by more sprout growth) and a decrease in tuber quality. Blemish disease and storage rots increased in severity as did the amount of damage. Reducing-sugar content of tubers increased, presumably as a result of decreasing soil temperatures whilst dry-matter content usually decreased despite the opportunity for retranslocation of dry matter from haulm to tubers when diquat was used to kill the haulm. This decrease in dry-matter content is usually most severe where rainfall re-wets the ridge shortly after defoliation and the water uptake of the still active roots leads to large reductions in dry-matter contents. This suggests that there is a danger in delaying harvest after defoliation beyond the time needed for the skins to set, which is commonly taken to be 2 or 3 weeks. In practice the interval from defoliation to harvesting is frequently longer than this. Of course, these effects also apply in the seed crop where minimal disease infection of the seed tubers is of paramount importance.

The definition of maturity

At present, maturity is commonly used to describe the condition of potatoes at harvest and supposed to be indicative of the suitability of a stock of tubers for storage. Until now, the use of the term has been deliberately avoided in this paper because whilst it is often used to explain differences in storage performance, it is a concept which is little understood. There are various definitions: when the tuber skins are set; when total sugars in the tuber are at a minimum; when the crop's foliage is completely dead (Braue *et al.* 1984). As early as 1926, Appleman & Miller (1926) recognized the deficiencies of the term and stated that 'the term immature expresses a rather vague idea on account of our lack of a definite and scientific conception of what constitutes maturity'. It is doubtful if we are much further forward 50 years later as Moorby (1978) suggests that 'a precise definition of an immature tuber is impossible at present, but in general terms it is one without a fully developed periderm and in which the starch-synthesizing enzymes are fully active'. Tubers from 10 to 80 mm diameter meet this definition. However, Burton (1978*a*) has attempted to make a fuller and more objective definition. 'A mature tuber can be defined as one which prior to haulm destruction either chemically or mechanically is no longer growing and in which the total sugar is no longer decreasing i.e. it has reached a minimum value. This implies that carbohydrate is no longer being received from the senescent foliage and that sufficient time has elapsed since the arrival of the last supply for the carbohydrate composition of the tuber to reach a state of apparent equilibrium, albeit temporarily'. He points out that this stage is reached when the haulm is senescent and dying down and the tuber periderm no longer slides off at the phellogen when subjected to a tangential force and the skin is described as set. Few crops in practice reach this condition because they are defoliated. Thus, the term is a subjective and largely unusable description. The current work also suggests that it contains an incorrect assumption regarding the relationship between tuber growth and storage losses.

Maturity is undoubtedly a complex physiological and morphological condition with several facets, respiration and carbohydrate changes, dry-matter content, skin thickness and suberization, dormancy and sprouting, which are inextricably linked. Moreover, the picture is further complicated because a tuber may be mature in certain respects but not in others. For example, if crop growth is stopped by deliberate haulm destruction, suberization occurs in otherwise immature tubers. Mechanically, the tubers could then behave as if mature, but their biochemical composition and physiological activity would be quite different. Furthermore, there seems to be overwhelming evidence from the literature which suggests that samples of tubers which differ greatly in their characteristics and hence maturity at harvest time very quickly, perhaps within 2 or 3 weeks, assume the behaviour of fully mature tubers in store, at least as regards rates of respiration and moisture loss. Thus, whilst the effects of contrasting growth environments and husbandry treatments on maturity may be initially very marked, they are generally short-lived and may not re-appear until dormancy breaks and sprout growth commences. In commercial stores the use of sprout suppressants prevents this occurrence.

For these reasons, there are no prospects for providing a quantitative scale of maturity which could be used predictively as a guide to the performance in storage of different lots of potatoes. The variables used in these experiments generated crops for storage which must have covered the whole range from very immature to completely mature according to the usual definitions of maturity. Yet, it proved impossible to formulate a quantitative measurement of the condition. As the experiments showed that crops which would be regarded as immature stored just as well if not better than mature ones the conventional view of maturity improving during growth and leading to lower storage losses is neither accurate nor particularly helpful. Complete avoidance of the term maturity would probably help all future discussion of factors influencing the suitability of tubers for storage.

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