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Effects of field treatments on processing quality of Record and Pentland Dell potatoes during storage

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SUMMARY

Previous research has suggested that fry colour of processed potatoes is inversely correlated with tuber reducing sugar content, and agronomic practice should therefore be tailored to minimize amounts of tuber sugars at harvest and during storage as a means of maximizing processing quality. A total of 30 experiments from three sites in England from 1985 to 1988 examined this hypothesis for two cultivars using a wider range of husbandry than that used in practice and long periods of storage. No tuber sugar value was sufficiently well correlated with fry colour for the relationship to be interpreted as causal and of use predictively, irrespective of whether it was measured early in growth, at harvest or at the time of processing. Fry colour at harvest was not correlated with fry colour after storage. No agronomic practice (variables used were physiological age, date of planting, irrigation or date of harvest) consistently caused fry colours to be darker than the acceptable colour limit, whether at harvest or after long term storage. Crops producing unacceptable fry colours early in storage generally improved to produce acceptable fry colours after long term storage. Agronomic practices within the range normally found in commercial production are therefore considered to have little effect on long-term processing quality, although harvesting, handling and transport operations were not investigated.

INTRODUCTION

One of the major criteria for measuring quality in the potato processing industry is fry colour of the processed product. A continuous supply of suitable tubers has to be available throughout the year and it is advantageous to identify as soon as possible those crops which are most likely to process with desirable fry colours after storage. In practice this usually involves sampling the crop during growth and at entry to storage in order to measure tuber reducing sugars and sucrose. This approach is based on the implicit belief that, for each cultivar, a single causal relationship between fry colour and amount of tuber reducing sugar (or its precursor sucrose; see Sowokinos 1978) exists which allows discrimination between samples as to current and future processing quality.

Early workers (Sweetman 1930; Denny & Thornton 1940) identified reducing sugars as important reagents in the Maillard reaction (Danehy & Pigman 1951; Hodge 1953) which causes non-enzymic browning when potato slices are fried to produce chips or crisps. Many subsequent authors have attempted to assess the potential of crops for processing by measuring tuber reducing sugars or their precursor, sucrose (Clegg & Chapman 1962; Sowokinos 1978; Chase *et al.* 1982; Nelson & Sowokinos 1983). For all sugars, amounts decrease from tuber initiation onwards and may reach a stable minimal amount if the growing season is sufficiently long unless soil temperatures fall below 4·5 °C, when reducing sugars may increase (Smith 1959). A general improvement (lightening) in fry colour usually occurs during growth (e.g. Miller *et al.* 1975), and it has been reported that harvesting before tuber sugars have reached their minimal values results in unacceptably dark fry colours (Hope *et al.* 1960; Sowokinos 1973; Nelson & Shaw 1976). While there is general agreement on the changes in sugars during growth and storage, a wide range of absolute amounts of all sugars has been reported for comparable harvest or sampling dates. For example, Iritani & Weller (1977) reported total sugars to be 1·50% of tuber fresh weight for a mid-September harvest of Kennebec, while Miller *et al.* (1975) reported a value of 0·21 % for the same cultivar under similar conditions. In Russet Burbank, tuber reducing sugars ranged from 0·10% (Santerre *et al.* 1986) to 0·92% (Mazza 1983) of fresh weight for similar periods of growth. Pisarczyk (1982) and Siecza & Maatta (1986) observed that tuber sugar contents were extremely variable, and large differences between treatment means of both sucrose and reducing sugar contents in tubers were not statistically significant. The variation over cultivars is even greater. Yamaguchi *et al.* (1966) reported a tuber sucrose content in Kennebec of 3% of tuber fresh weight after storage at 10 °C, but Sowokinos *et al.* (1987) found only 0·2% sucrose after 8 months storage of Norchip. For Majestic, Burton (1965) reported only 0·03% sucrose after 8 months storage at 10 °C. Billington (1984) found that reducing sugars in Pentland Dell after 6 months in store at *c.* 10 °C ranged from 0·37 to 0·70% of tuber fresh weight. Such variation is not matched by changes in fry colour (e.g 6·3–6·6 on the USDA colour scale; Billington 1984) and is therefore irreconcilable with any direct causal relationship between fry colour and amount of tuber sugar. Some lack of consistency in the relationship is inevitably caused by the discrepancy in the accuracy with which sugars and fry colour are measured. The former can be measured with great accuracy, while fry colour is frequently estimated by comparison with standard charts using an arithmetic scale, one to five or one to nine. However, the wide range in tuber sugar contents which correspond to narrow ranges of fry colour suggest that there exists no sufficiently close relationship to have practical utility. Roe *et al.* (1990) showed that changes in tuber amino acid content caused variation in colour per unit of tuber sugar. Nonetheless, there are many statements in the literature that fry colours are closely and inversely related to amounts of reducing sugars (e.g. Kirkpatrick *et al.* 1956; Smith & Treadway 1960; Burton 1966; Carlsson 1970; Ludwig 1987; Brown *et al.* 1990). When regression analyses were carried out, the relationship between fry colour and amount of tuber reducing sugar was often found to be significant for individual treatments, but when data were combined for a range of treatments, correlation coefficients were not sufficiently high to suggest a causal relationship, and decreased markedly where a range of data was combined. Even when data cannot be analysed together, it is apparent that regression parameters vary considerably between treatments and between experiments. For example, Carlsson (1970), who varied sugar contents by delaying harvest date, found for different experiments that the relationship between fry colour and tuber reducing sugar content was most closely fitted by positive linear, negative linear and negative quadratic functions. For the nine experiments with Bintje giving negative linear relationships, only one was statistically significant, and the correlation coefficients ranged from −0·55 to −0·96, the slopes from −0·063 to −0·360 and the intercepts from 38·3 to 142·7. Hughes & Fuller (1984) found that the relationship between fry colour and amount of tuber reducing sugar changed considerably with both soil nitrogen status and time in store. Even Ludwig (1987), who reported a high positive correlation coefficient of 0·74 for an exponential relationship between fry colour and amount of tuber reducing sugar in a sample of Bintje crops, seemed unconvinced of its biological validity, for he wrote 'there is evidently a (reasonably) good relation between the calculated colour index and the reducing sugar content'.

In order to resolve this apparent conflict between practice and the published evidence, a series of experiments was carried out with the two major processing cultivars, Record (crisps) and Pentland Dell (chips), in which a wide range of agronomic variables was used to produce tubers for processing (immediately or after storage) with a diverse range of sugar contents. From the data, a rigorous test of the validity and practical utility of the relationship between fry colour and tuber sugar contents has been made.

MATERIALS AND METHODS

Field treatments

In each year from 1985 to 1988, a common seed tuber stock of each of the major processing cultivars, Pentland Dell and Record, was grown at three sites in the UK: Cambridge University Farm (CUF, gravelly loam of the Milton Series in all years), Gleadthorpe EHF (sandy soils of the Cuckney Series in all years) and Terrington EHF (silt loam of the Newchurch Series in 1985 and 1988 and the Agney Series in 1986 and 1987). The experimental treatments and basic agronomic details are given in Tables 1–3. In all experiments there were four replicates. In order to vary the growing season available to crops, a wide range of dates of planting and harvesting was used and extreme treatments such as planting in June and harvesting in early September were deliberately used to stretch the range of crops well beyond that normally found in practice.

The two irrigation regimes applied in Expts 20a and 23a using Record at Gleadthorpe, were (i) early irrigation: 15 mm at 20 mm soil moisture deficit (SMD) for 4 weeks after tuber initiation, then 25 mm at 35 mm SMD, and (ii) late irrigation: 25 mm at 35 mm SMD after tubers attained *c.* 12 mm. In Expt 22a for Record at CUF, the two irrigation regimes were (i) zero and (ii) late irrigation: 30 mm at 40 mm SMD.

For all experiments, rates of fertilizer and water applications (when not used as treatments) and crop protection measures were chosen in relation to site characteristics and weed, pest and disease incidence, and are detailed by Hogge (1989), Colenso (1989) and Stalham (1989). After 50% plant emergence, percentage ground cover was measured twice weekly using ground cover grids (Burstall & Harris 1983). Full growth analyses were conducted fortnightly, and leaf area indices, number of tubers, branches and

Table 1. *Physiological age and dates of planting, defoliation and harvest of Pentland Dell in experiments at Cambridge, Gleadthorpe and Terrington from 1985 to 1988 (Expts 1–15)*

		Field treatments (all combinations of)			
Experiment	Year	Date of planting	Phys. age (Day° > 4 °C)	Date of harvest	Date of defoliation
1–3	1985	29 April	*c.* 300	4 September 18 September	—
4, 6	1986	6 May 23 May 9 June	*c.* 300	3 September 18 September	—
5	1986	5 May	*c.* 300	3 September 18 September	—
7–9	1987	5 May 27 May	0 300	3 September 18 September	—
10–12	1988	5 May 25 May	0	1 September 15 September	—
13*	1986	13 May	300	0 and 14 days after defoliation	15 September 14 October
14*	1987	5 May	55	0 and 14 days after defoliation	4 September 12 October
15*	1988	26 April	10	0 and 14 days after defoliation	7 September 10 October

* Field treatments include two levels of air drying at harvest (0 and 1 hour).

above and below ground nodes, tuber fresh and dry weights and haulm dry weight were recorded. In 1988 on 27 July, 10 August and 17 August, Pentland Dell tubers from Terrington and Cambridge in the size range 20–40 mm were harvested and analysed for tuber sucrose and reducing sugar content as detailed below.

Defoliation was mechanical (by flail mower or hand sickle) and occurred 2 weeks before harvest, except where used as a treatment in Expts 13–15 and 28–30 (Tables 1 and 2). At harvest, tubers were lifted by tractor-drawn elevator digger and immediately hand picked off the soil surface, except when air drying treatments were imposed. Tubers were mechanically graded, counted and weighed to determine yield and number of tubers, then sufficient tubers of 50–70 mm in Pentland Dell and 40–65 mm in Record for storage and processing requirements were transported to the PMB Experimental Station at Sutton Bridge, Lincolnshire.

Storage and processing

All stored samples, after an initial 'curing' phase of 2 weeks at 15 °C, were held in 6 kg boxes in a sealed store set at 10 °C with relative humidity of 95%. Periods of storage are given in Table 4. Two weeks after the completion of 'curing', an application of 0·5 kg/t of CIPC granules was made to each box, which successfully inhibited sprout growth.

At intake to store and at processing, tubers were rumble peeled and chipped to a cross-sectional area of 15·9 × 15·9 mm (Pentland Dell) or sliced to a thickness of 1·25 mm (Record) and a randomly selected subsample was fried at 185 °C for 3 minutes or until the oil had ceased to bubble. Chip and crisp colours were measured using an Agtron M35 Color Quality Meter (Magnusson Corporation, Reno, Nevada) calibrated to 0 and 100 units using black and white discs respectively. The minimum level of acceptability for both chip and crisp colour was taken to be 18 Agtron units. There is rarely commercial benefit, bonus or premium gained by achieving Agtron ratings greater than 18. Each datum point was the mean of three observations, with random reorientation of fried potato material between readings. A subsample of 200 g from the remainder of the freshly chipped or sliced material was selected at random and liquidized with 100 ml of distilled water for 60 s. After 10 min, 1·5 ml of the supernatant liquor was added to 0·3 ml 0·25 mM zinc acetate solution to prevent further sugar synthesis or denaturing. This was diluted to 10 ml with distilled water, and after centrifuging at 2000 rpm for 10 min, the clear sap was frozen at −20 °C until analysis.

Table 2. *Physiological age and dates of planting, defoliation and harvest of Record in experiments at Cambridge, Gleadthorpe and Terrington from 1985 to 1988 (Expts 16–30)*

		Field treatments (all combinations of)			
Experiment	Year	Date of planting	Phys. age (Day° > 4 °C)	Date of harvest	Date of defoliation
16–18	1985	29 April	*c.* 300	18 September 9 October	—
19–21	1986	6 May	*c.* 300	24 September 15 October	—
20a†	1986	26 March 29 April	0 300	24 September	—
22–24	1987	6 May	0 330	22 September 8 October	—
22a	1987	15 April 6 May	0 330	22 September	—
23a†	1987	6 April 5 May	0 330	22 September	—
25–27	1988	6 May	0 330	20 September 6 October	—
28*	1986	13 May	350	0 and 14 days after defoliation	19 August 8 September 29 September 24 October
29*	1987	29 April	220	0 and 14 days after defoliation	16 August 14 September 19 October
30*	1988	26 April	190	0 and 14 days after defoliation	15 August 12 September 17 October

Field treatments include (†) two irrigation regimes (see text) or (*) two levels of air drying at harvest (0 and 1 hour).

Table 3. *Seed weight and spacings in all experiments at Cambridge, Gleadthorpe and Terrington from 1985 to 1988*

Experiment	Location	Seed weight (g)	Within-row spacing (cm)	Between-row spacing (cm)
1, 4, 7 & 10	Cambridge	30–40	26	71
2, 5, 8 & 11	Gleadthorpe	30–40	22	86
3, 6, 9 & 12	Terrington	30–40	21	91
13 & 15	Cambridge	40–50	30	71
14	Cambridge	20–30	25	71
16 & 19	Cambridge	35–45	26	71
17, 20 & 20a	Gleadthorpe	35–45	22	86
18 & 21	Terrington	35–45	21	91
22, 22a & 25	Cambridge	30–40	26	71
23, 23a & 26	Gleadthorpe	30–40	22	86
24 & 27	Terrington	30–40	21	91
28	Cambridge	40–50	30	71
29 & 30	Cambridge	50–60	30	71

Sugar analysis of the sap extracts was performed on a Technicon Auto-analysis AA2 and spectrophotometer system (Boehringer Mannheim GmbH). Total reducing sugars were estimated by the loss of NADP during conversion of glucose to glucose-6-phosphate and of fructose, after isomerization with phosphoglucose isomerase (PGI), to glucose-6-phosphate. Glucose was estimated before the introduction

Table 4. *Storage period between harvesting and processing of tubers from all experiments at Cambridge, Gleadthorpe and Terrington from 1985 to 1988*

Experiment	Period of storage (weeks)
1–3	1, 2, 3, 4, 12, 20, 28, 40
4–6	1, 2, 4, 8, 12, 22
7–9	1, 4, 8, 32
10–12	2, 4, 8, 33
13	1, 3, 18, 32
14	1, 2, 18, 33
15	1, 2, 19, 33
16–18	1, 2, 4, 8, 20, 28, 36, 40
19–21	1, 2, 3, 4, 8, 12, 20, 28, 36, 40
22–24	2, 4, 8, 20
25–27	1, 2, 4, 8, 12, 16, 20, 28, 36
28	1, 3, 19, 32
29	1, 2, 18, 35
30	1, 2, 20, 34

of PGI, and fructose calculated by difference. Sucrose was cleaved into glucose and fructose with invertase at 35 °C and the concentration of glucose determined as above and corrected for the original amount of glucose in the sap sample. This allowed the tuber sucrose content to be calculated, based on the known ratio of glucose to fructose in sucrose.

RESULTS AND DISCUSSION

Total tuber yields for crops harvested for storage ranged from 16·0 to 63·3 t/ha in Record and 23·2 to 64·7 t/ha in Pentland Dell (Tables 5–7). Thus the agronomic treatments were successful in producing a much wider range of yields than usually found in commercial practice. The short season resulting from very late planting and/or early defoliation produced the lowest yields and the tubers in these crops would not be regarded as suitable for processing as they were defoliated before any loss of ground cover had occurred and before sugars were at minimal values.

In Expts 13–15 (Pentland Dell), when a wide range of harvesting practices was used, mean yields (t/ha) were 45·2 (S.E. = 0·81), 37·5 (S.E. = 1·45) and 64·7 (S.E. = 1·52) respectively, and the treatments were imposed on canopies with full ground cover through to those with advanced senescence.

Table 5. *Total tuber yields (t/ha) of Pentland Dell at Cambridge, Gleadthorpe and Terrington from 1985 to 1988 (Expt 1–12)*

		Date of harvest					
		Cambridge		Gleadthorpe		Terrington	
Year	Date of planting	Early September	Mid/late September	Early September	Mid/late September	Early September	Mid/late September
		Expt 1		Expt 2		Expt 3	
1985	29 April	40·9	50·7	38·9	48·7	51·6	53·9
	S.E.	2·92		1·27		1·26	
		Expt 4		Expt 5		Expt 6	
1986	6 May	40·7	51·4	44·6	48·7	38·0	47·8
	23 May	31·3	44·0	—	—	31·3	40·2
	9 June	24·2	36·9	—	—	23·2	32·5
	S.E.	0·67		3·60		0·64	
		Expt 7*		Expt 8*		Expt 9*	
1987	5 May	39·0	49·6	29·5	36·6	43·2	51·5
	27 May	28·7	37·8	—	—	31·7	41·2
	S.E.	1·09		0·84		0·69	
		Expt 10		Expt 11		Expt 12	
1988	5 May	39·4	48·7	47·0	54·2	36·3	42·3
	25 May	28·2	37·9	36·3	44·2	28·6	34·6
	S.E.	0·91		0·73		0·52	

* Means of two physiological ages.

Table 6. *Total tuber yields* (*t/ha*) *of Record at Cambridge, Gleadthorpe and Terrington from 1985 to 1988* (*Expts 16–27*)

		Date of harvest					
		Cambridge		Gleadthorpe		Terrington	
Year	Date of planting	Late September	Mid October	Late September	Mid October	Late September	Mid October
		Expt 16		Expt 17		Expt 18	
1985	29 April	44·8	50·6	43·9	49·8	44·2	44·6
	S.E.	1·11		1·27		1·25	
		Expt 19		Expt 20		Expt 21	
1986	4 May	40·0	46·5	47·1	51·9	38·6	50·3
	S.E.	1·31		1·09		1·03	
				Expt 20a*			
1986	26 March	—		49·3		—	
	6 May	—		43·0		—	
	S.E.			1·03			
		Expt 22		Expt 23		Expt 24	
1987	6 May	45·8	52·1	33·9	37·6	54·6	55·6
	S.E.	0·82		1·14		1·11	
		Expt 22a*		Expt 23a*			
1987	15 April	56·3		36·4		—	
	6 May	46·2		43·6		—	
	S.E.	1·03		1·38			
		Expt 25		Expt 26		Expt 27	
1988	6 May	53·8	62·5	51·1	55·7	45·7	50·4
	S.E.	1·63		1·24		0·82	

* Means of two physiological ages and two irrigation regimes.

Table 7. *Total tuber yields* (*t/ha*) *of Record in date of harvest experiments at Cambridge from 1986 to 1988* (*Expts 28–30*)

	Experiment		
Date of harvest	28	29	30
Mid August	16·0	25·5	43·2
Early September	39·1	46·4	51·3
Late September	44·6	—	—
Mid October	63·3	53·5	52·7
S.E.	1·13	1·32	1·74

All values are means of two defoliation practices and two air drying regimes.

Tuber sugar content

There were large fluctuations in amounts of sucrose and reducing sugars in both Pentland Dell and Record between dates of sampling during the growing season and storage in all years when sugars were measured (Figs 1 and 2), although standard errors for each sampling were small. There was no such large scale fluctuation in fry colour (e.g. Figs 6 and 8).

The changes in amounts of sucrose, total and individual reducing sugars with time were sometimes similar to those demonstrated by other authors. Both sucrose and reducing sugars were present in Pentland Dell tubers in relatively large amounts early in the growing season (respectively 0·45 and 0·37% of fresh weight of 20–40 mm tubers on 27 July; data are

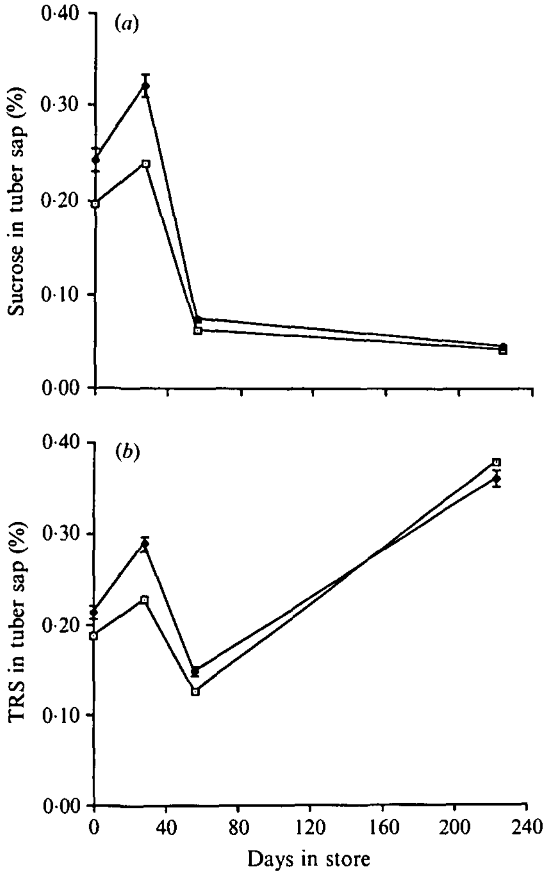

Fig. 1. Effect of date of planting on amount of (*a*) sucrose and (*b*) total reducing sugars (TRS) during storage of Pentland Dell from Cambridge in 1987 (Expt 7). Dates of planting: 5 May (□) and 27 May (◆).

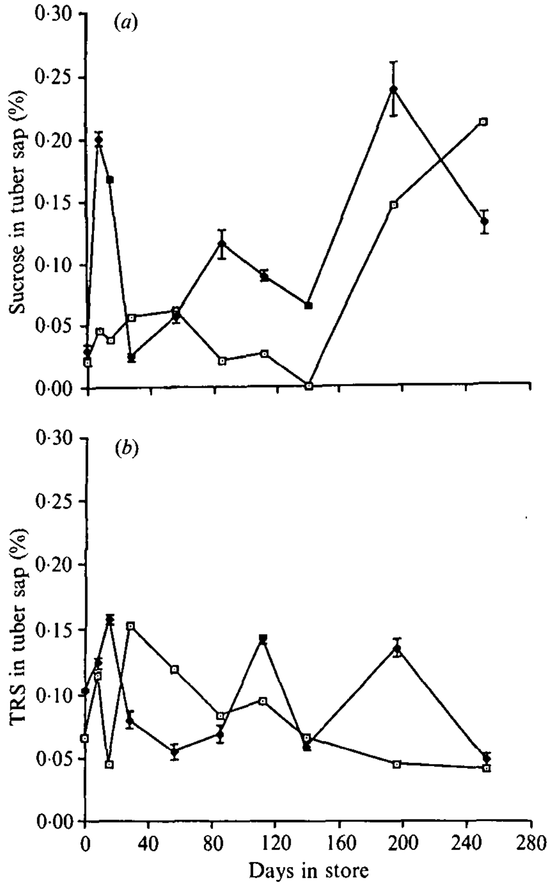

Fig. 2. Effect of date of harvest on amount of (*a*) sucrose and (*b*) total reducing sugars (TRS) during storage of Record from Cambridge in 1988 (Expt 25). Dates of harvest: Late September (□) and Mid-October (◆).

means of two dates of planting at two sites in 1988) and decreased as the growing season progressed (respectively 0·07 and 0·23% of fresh weight of 20–40 mm tubers on 17 August; data as for earlier sampling). Later planting in Expt 7, as for crops termed 'immature' by Burton (1965), caused amounts of sucrose in Pentland Dell tubers to be higher soon after intake to store than earlier planting, with tuber sucrose content from both dates of planting decreasing during prolonged storage (Fig. 1). Similarly, the behaviour of tuber reducing sugar content in some experiments followed the time courses detailed by Burton for different dates of planting, with amounts of tuber reducing sugar in Expt 7 generally decreasing after harvest before increasing after an extended period of storage (Fig. 1). In other experiments, there was no clear trend in amount of tuber reducing sugar with time in store.

In many instances for Record, there were deviations from the time courses demonstrated by Burton, with amount of tuber sucrose in Expt 25 generally remaining relatively low early in storage, but rising dramatically after 21 weeks in store (Fig. 2), well before the anticipated onset of senescent sweetening. Amount of total reducing sugar followed no clear trend with time in store (Fig. 2). In Expt 30, the earliest harvest had a higher tuber total reducing sugar content than other dates of harvest, although this effect was not common to all experiments, and delayed harvest in some (e.g. in Expts 25 and 29) caused more tuber total reducing sugars than earlier harvesting.

At intake to store in Expt 30, a delay of 2 weeks between defoliation and harvesting for late harvested crops resulted in more tuber total reducing sugars than harvesting immediately without defoliation (Table 8). The delay allowed mean daily soil temperatures at 10 cm depth for 3 days before harvesting to

Table 8. *Effects of date of defoliation, period between defoliation and harvest and period of air drying on amount of tuber total reducing sugars (% fresh weight) in Record at Cambridge in 1988 (Expt 30)*

	Period between defoliation and harvesting (days)			
	0	0	14	14
	Period of air drying (hours)			
Time of Defoliation	0	1	0	1
15 August	0·390	0·325	0·168	0·084
12 September	0·105	0·083	0·019	0·028
17 October	0·036	0·016	0·110	0·120

S.E. for comparison between dates of harvest 0·0149.
S.E. for all other comparisons 0·0163.

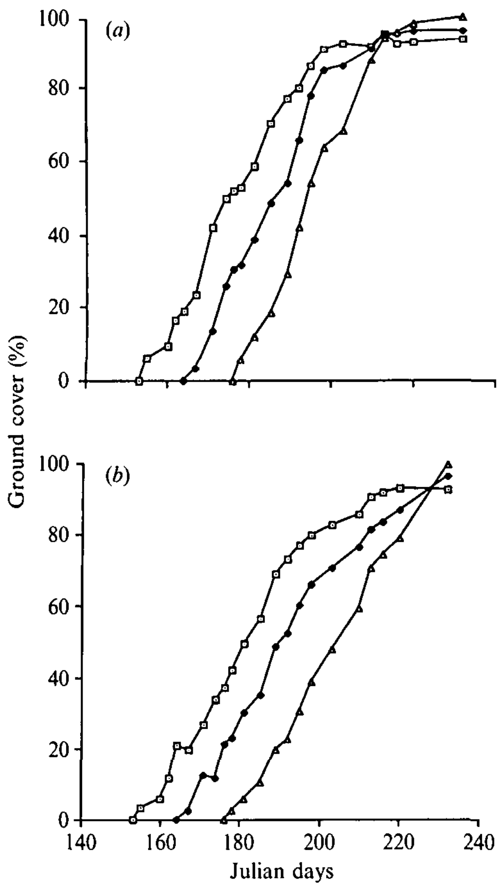

Fig. 3. Effect of date of planting on ground cover percentage of Pentland Dell in 1986 at (*a*) Cambridge (Expt 4) and (*b*) Terrington (Expt 6). Dates of planting: 6 May (□), 23 May (◆) and 9 June (△).

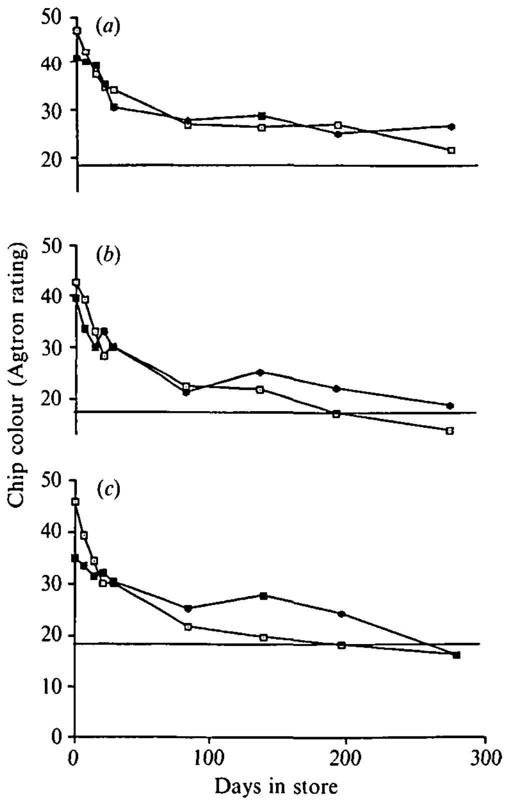

Fig. 4. Effect of date of harvest on chip colour during storage of Pentland Dell in 1985 at (*a*) Cambridge (Expt 1), (*b*) Terrington (Expt 3) and (*c*) Gleadthorpe (Expt 2). Dates of harvest: Early September (□) and Mid/late September (◆). Horizontal line represents acceptable limit.

decrease from 11·5 to 5·8 °C. Effects of date of harvest and period of defoliation were confounded in this instance, but increase in tuber total reducing sugar content from exposure of tubers to cold end-of-season temperatures has been reported by a number of workers (e.g. Kissmeyer-Nielsen & Weckel 1967).

Although in some years there was agreement between the changes in amounts of sugars with time

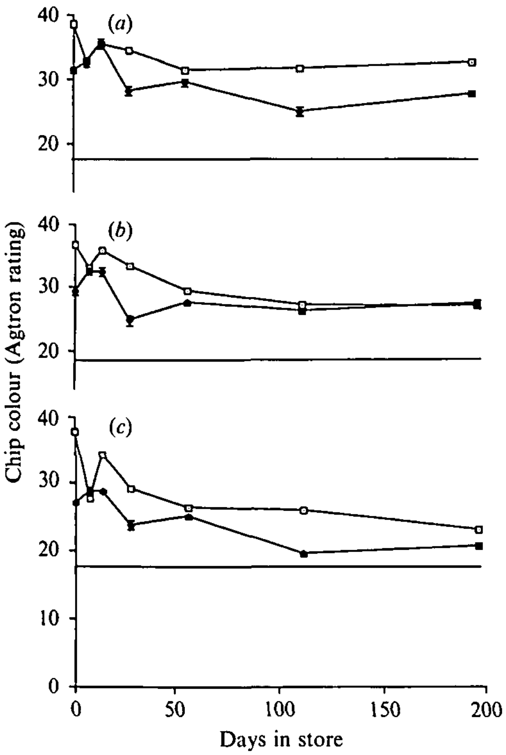

Fig. 5. Effect of date of harvest on chip colour during storage of Pentland Dell in 1986 at (*a*) Cambridge (Expt 4), (*b*) Terrington (Expt 6) and (*c*) Gleadthorpe (Expt 5). Dates of harvest: Early September (□) and Mid/late September (◆). Horizontal line represents acceptable limit.

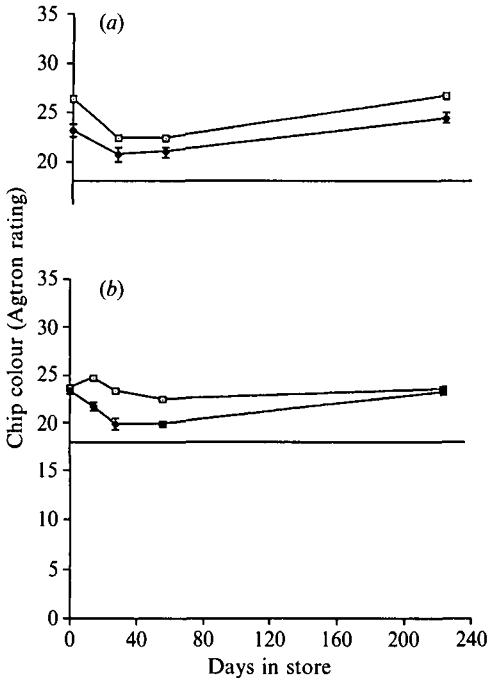

Fig. 6. Effect of date of planting on chip colour during storage of Pentland Dell in 1987 at (*a*) Cambridge (Expt 7) and (*b*) Terrington (Expt 9). Dates of planting: 5 May (□) and 27 May (◆). Horizontal line represents acceptable limit.

and previously published results, there was wide variation between years in amounts of tuber sugars in store, even for similar agronomic treatments. In 1987 (for both cultivars), tuber total reducing sugar content increased to *c.* 0·30% of tuber fresh weight while similar treatments in 1988 produced reducing sugar contents less than half this value (Figs 1 and 2). There was no correlation between decrease in amounts of sucrose with time and concurrent increase in amounts of tuber total reducing sugars in either year, in contrast to the observations of other authors (e.g. Richardson *et al.* 1990).

Effects of agronomy and time in store on fry colour

In Pentland Dell, dates of planting and harvest were manipulated to produce a range of growing periods in order to test the hypothesis that the physiological state of tubers (primarily influenced by the duration of growth between tuber initiation and date of defoliation) was crucial in determining immediate and post-storage processing quality. Some treatments produced very young tubers from crops with canopies retaining almost complete ground cover up to defoliation (Fig. 3). Generally, within a year, a similar trend in processing quality of Pentland Dell with time in store was observed, irrespective of site and husbandry. Between years, however, there was substantial variation in the change in fry colour with time in store, with colours improving in some years but slowly deteriorating in others. When effects of husbandry did occur, as in 1986, they were generally early in the storage period, and, after long term storage, colours from different treatments tended to converge (Fig. 5).

There was no effect of physiological age on processing quality of Pentland Dell at any time in store. In 1985, earlier harvesting at all sites caused slightly darker chips through much of the storage period than later harvesting, but differences were not commercially important except after prolonged storage when early harvesting at Terrington produced unacceptable chip colour (Fig. 4). Date of planting had no consistent effect on processing quality of Pentland Dell. Early planting produced lighter coloured chips during the first 50 days in store than the later planting at Terrington in 1987, while from CUF in 1987, early planting produced slightly lighter chips than later planting after 30 weeks in store (Fig. 6). However, no differences from date of planting or date

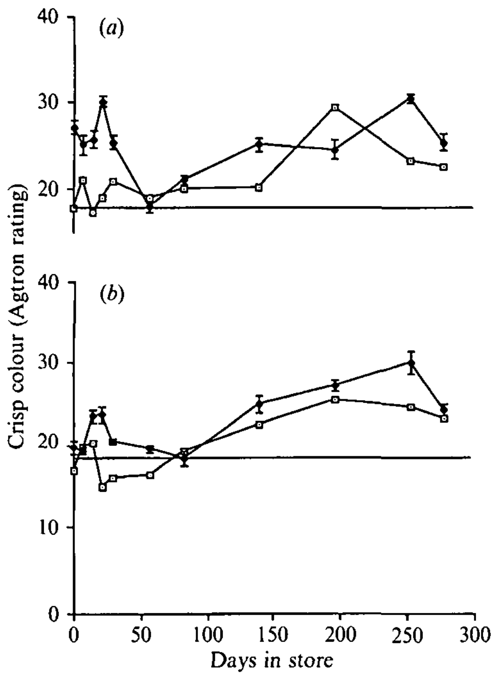

Fig. 7. Effect of date of harvest on crisp colour during storage of Record in 1986 at (*a*) Cambridge (Expt 19) and (*b*) Gleadthorpe (Expt 20). Dates of harvest: Late September (□) and Mid-October (◆). Horizontal line represents acceptable limit.

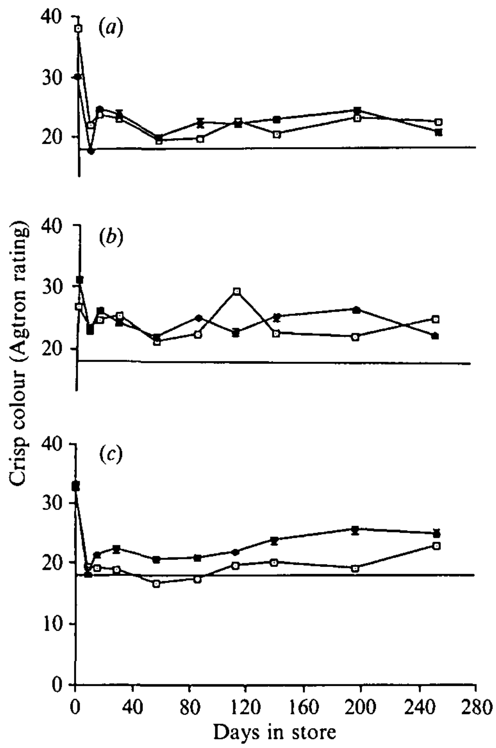

Fig. 8. Effect of date of harvest on crisp colour during storage of Record in 1988 at (*a*) Cambridge (Expt 25), (*b*) Terrington (Expt 27) and (*c*) Gleadthorpe (Expt 26). Dates of harvest: Late September (□) and Mid-October (◆). Horizontal line represents acceptable limit.

of harvest (except from Terrington in 1985) were of commercial importance.

Unacceptable fry colour in Record occurred more frequently than in Pentland Dell. In 1986 and 1988 the incidence of unacceptable crisp colour was short lived (Figs 7 and 8), but in 1987 tubers from Expts 22–24 produced unacceptable crisp colours for all treatments throughout storage. Storage in these three experiments was of limited length (20 weeks), while that for a similar crop of Record from Cambridge in 1987 (Expt 29) was for 35 weeks. In Expt 29, crisp colours became acceptable by 35 weeks in store, having been unacceptable in the early period of storage (Fig. 9).

In all experiments with Record in 1985, date of harvest had no consistent effect on crisp colour during storage. In 1986, early harvesting of Record at Terrington consistently produced darker crisps than later harvesting, but Agtron rating did not fall below 18 after an initial unacceptable value at intake. At other sites, there was no consistent effect of date of harvest on crisp colour at intake or after storage. In 1987 (Fig. 7), effects of date of harvest were small, and all crisps were of unacceptable colour early in storage. Only for the intake sample from Gleadthorpe did later harvest produce crisps of acceptable colour, while earlier harvesting produced unacceptable crisp colour at intake. In 1988 (Fig. 8), early harvest of Record at Gleadthorpe produced darker crisps than

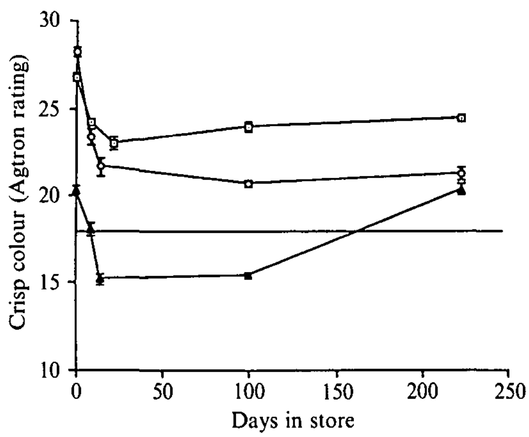

Fig. 9. Crisp colour during storage of Record from Cambridge in Expts 28–30. 1986 (□), 1987 (▲) and 1988 (○). Horizontal line represents acceptable limit.

Table 9. *Regression parameters for the relationship between both amount of tuber total reducing sugars (TRS) (% fresh weight) and fry colour (Agtron) after storage and amount of tuber sucrose (% fresh weight) at intake to store for Pentland Dell*

Year	Site	Treatments	Period in store (weeks)	Variable	Regression coefficient	S.E.
1987	Terrington	Early harvest	4	TRS	0·25	0·103
			8	TRS	0·20	0·097
			37	TRS	−0·04	0·201
			8	Colour	−16·1	5·44
			37	Colour	−9.6	5·02
1988	Cambridge	All treatments	32	Colour	90·4	33·11
	Gleadthorpe	All treatments	32	Colour	84·9	28·11
	Terrington	All treatments	32	Colour	82·3	22·13

later harvest after more than 2 weeks in store, while at other sites there was no consistent effect of date of harvest on fry colour.

Effects of defoliation in Expts 28–30 were intermittent and confounded with date of harvest. Some interesting observations, however, were made. Defoliation before early harvest (when ground cover was 98% in 1986 and 96% in 1987) generally caused lighter colours than undefoliated crops, although effects were small and not maintained throughout storage. In 1988, defoliation of early harvest (when ground cover was 88%) had the reverse effect and caused darker colours than undefoliated crops after long term storage. In 1986, defoliation of late harvested crisps (when ground cover was close to zero, so that the defoliation treatment was effectively a delay in harvest of 2 weeks) caused darker crisps after long term storage than no defoliation. Mean soil temperature in the intervening period between defoliation and harvesting was 7·7 °C at 10 cm depth, while in the 10 days before harvesting without defoliation, mean soil temperature at 10 cm depth was 8·9 °C. It is questionable whether such a difference in soil temperature is sufficient to account for the effect of defoliation on fry colour. Defoliation had no consistent effect on crisp colours of late harvested crops in other years.

Relationship between sugars during growth or at intake and sugars and colours after storage

In Pentland Dell in 1988 (when it was possible to measure early season tuber sugar contents), regression analyses were carried out to determine the relationship between amounts of tuber sugars at sampling dates early in the growing season and those after mid-term and prolonged storage. A range of sugar contents was generated early in growth on each sampling occasion through the use of date of planting as a treatment. No significant relationships could be found between amounts of sucrose shortly after tuber initiation and at 2 week intervals in the growing season and sucrose and total and individual reducing sugars at any time in store. This was contrary to the observations of some workers (e.g. Nelson & Sowokinos 1983) who have suggested that tuber sucrose contents early in the growing season can be related to and used to predict fry colours after long term storage.

Other workers have suggested that amounts of sucrose at commercial harvest time (the 'Sucrose Rating') can be used as a measure of post-storage processing potential (e.g. Sowokinos 1978; Chase *et al.* 1982; Santerre *et al.* 1986). In the 3 years when tuber sugar content was measured (1985, 1987 and 1988), in both Record and Pentland Dell, amounts of sucrose at harvest were only rarely significantly correlated with total or individual reducing sugars after both short and long-term storage. When regressions of post-storage chip colour were made against amount of sucrose at harvest, there were few significant relationships, and these only accounted for a small percentage of the variance. The closest relationships between amount of sucrose at intake to store and fry colour after long term storage occurred in 1988 for Pentland Dell and had positive slopes when all treatments were combined over sites (Table 9). However, this was in contrast to 1987, where the few significant relationships were negative and accounted for even less of the variance.

Relationship between fry colours and amount of tuber sugars at the time of processing

If amount of tuber reducing sugar is to be immediately useful as a means of identifying potential fry colour, a single unifying relationship between fry colour and amount of tuber reducing sugar at the time of processing is required for each cultivar, irrespective of agronomic treatment or period in store. No close linear relationships could be found in any experiment

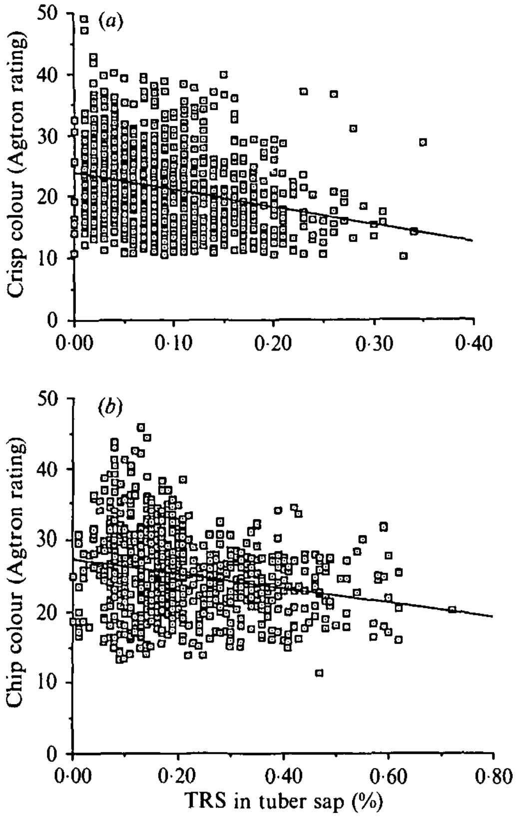

Fig. 10 (*a*). Relationship between crisp colour (Agtron rating) and amount of tuber total reducing sugars (TRS) in Record in 1985, 1987 and 1988. Line equation: Agtron rating = 23·8 − 28·54(TRS). (*b*). Relationship between chip colour (Agtron rating) and amount of tuber total reducing sugars (TRS) in Pentland Dell in 1985, 1987 and 1988. Line equation: Agtron rating = 27·3 − 10·36(TRS).

in either cultivar (Tables 10 and 11), although in some comparisons a similar amount of the variance to that previously reported in the literature (30–40%) was accounted for. Fry colours for some field treatments (over a range of sampling occasions from store) were found to be correlated with total or individual sugars at the time of processing, but variation about the fitted line was large in every case, and the regression never accounted for more than 50% of the variance. However, in the majority of instances, there was no significant relationship between fry colours and amounts of sugars at the time of processing. The slopes and intercepts of the relationship varied greatly and inevitably when the data for all years were combined in each cultivar, a very weak relationship was found. The relationships between fry colours and amounts of both TRS and sucrose for all experiments in 1985, 1987 and 1988 combined (excluding date of harvest experiments at CUF) are presented graphically for each cultivar in Fig. 10.

Table 10. *Regression parameters for the relationship between fry colour (Agtron) and amount of tuber total reducing sugars (% fresh weight) in Pentland Dell*

Year	Site	Date of harvest	Regression coefficient	S.E.
1985*	Cambridge	4 September	−13·8	15·40
		18 September	10·1	24·60
	Terrington	4 September	−6·0	12·90
		18 September	22·0	17·73
	Gleadthorpe	4 September	16·3	25·00
		18 September	14·3	15·62
1987*	Cambridge	3 September	−15·5	4·91
		18 September	20·1	5·35
	Terrington	3 September	3·5	2·60
		18 September	3·0	2·32
	Gleadthorpe	3 September	13·4	4·37
		18 September	9·5	5·91
1988†	Cambridge	—	−29·4	9·99
	Terrington	—	−8.8	19·21
	Gleadthorpe	—	−28·4	8·17

* Data are combined for all sampling dates from store.
† At harvest. Data are combined for 2 harvest dates: 1 and 15 September.

Table 11. *Regression parameters for the relationship between fry colour (Agtron) and amount of tuber total reducing sugars (% fresh weight) in Record*

Year	Site	Regression coefficient	S.E.
1985	Cambridge	1·5	13·91
	Gleadthorpe	36·6	19·20
	Terrington	33·5	15·02
1987	Cambridge (Expt 22)	3·0	4·52
	Cambridge (Expt 22a)	3·4	4·39
	Gleadthorpe (Expt 23)	14·2	4·68
	Gleadthorpe (Expt 23a)	6·1	4·14
	Terrington	2·4	4·92
1988	Cambridge	7·7	8·29
	Gleadthorpe	8·1	6·85
	Terrington	0·1	5·37

Data are combined for all treatments and sampling dates from store.

For fry colour against TRS in Record, the relationship was found to be significant:

$$\text{Agtron} = 23{\cdot}8 - 28{\cdot}54(\text{TRS})$$

but this was because the number of observations was large, and the variance accounted for was only 7·6%. In Pentland Dell, the equation for the relationship between fry colour and TRS was:

$$\text{Agtron} = 27{\cdot}3 - 10{\cdot}36(\text{TRS})$$

and this accounted for 5·3% of the variance. The wide range of colours observed at a single TRS content (especially at TRS contents close to zero) in both cultivars suggests that the Maillard reaction may simply depend on amino acids to a greater extent than previously considered and the amount and types of amino acids may influence the effect of any sugar content on fry colour. Here, browning has occurred to some degree and has varied widely with minimal quantities of reducing sugars.

From these results, it is apparent that the utility of sugars in determining or explaining processing quality is limited. Such relationships between fry colours and amounts of tuber total reducing sugars which were significant were generally similar to those observed in the literature, with increasing tuber reducing sugar content causing darker fry colour. Although this supports conclusions in the literature, such relationships are of little practical value as there was no consistency in regression parameters between different treatments, whether field or storage. Consequently, measurement of amounts of sugars cannot discriminate amongst samples of tubers as to their potential processing quality and will not be able to do so unless a greater understanding of the browning reaction and the role of other constituent reagents is obtained. Reducing sugars may then be of use as one component or group of components among a number of factors combining to determine colour. Ultimately, quality is measured by colour, and tuber sugar content alone is an intermediary factor of exaggerated value.

Relationship between fry colours at harvest and after storage

It is important for processors, when managing storage and processing facilities, to maintain a strategy of allocating loads to be stored or processed immediately. At present, those loads whose subsamples process at close to the minimum level of acceptability are generally sent for processing immediately, while those with lighter colours at intake are placed in long term storage. The results presented here suggest that this approach is unjustified. Figs 4–9 demonstrate that the ranking of samples by colour at intake was changed after periods in store for both Record and Pentland Dell. A series of regressions between fry colours after long term storage and those at intake produced poor correlations in all instances for both cultivars. The closest fitting relationship occurred for Pentland Dell at CUF in 1988, when 35·3% of variance was accounted for by a positive linear regression. However, in many instances the residual variance from each regression analysis exceeded the variance of chip or crisp colour after long term storage. Colours at intake were clearly inadequate for predicting colour after long term storage. In some instances, as much as 50% of the variance was accounted for by the regression of fry colours after long term storage against colours after the initial 2-week 'curing' phase. However, this was again inconsistent and no clear trends were apparent, whether data were combined or individual sites and years were treated separately.

In 1987 for Pentland Dell, tubers processed poorly at intake (Fig. 6) but in most cases processed acceptably after long term storage. This contrasts with observations for Pentland Dell in 1985, when samples processed with very light fry colours at intake, but darkened rapidly with short term storage before the decrease in Agtron rating was reduced or arrested as storage continued (Fig. 4). One can understand that in practice in the first case, store managers would be unwilling to commit to storage tubers of poor fry colours, as the general belief is that they could not improve. The data suggest that this is at least as likely as tubers of light fry colours deteriorating during long-term storage.

CONCLUSIONS

The only basis on which amounts of sugars could be of importance to processors as a means of predicting processing potential of potatoes would be a close relationship between fry colours and amounts of tuber reducing sugars at the time of processing. All other observations (whether on tuber sugar contents in the field and in store or on relationships between post-storage fry colour and sugars in growth or at harvest) are of little value unless a close fitting, causal relationship can be found between fry colour and simultaneous tuber reducing sugar content. Such a relationship is not to be found in the literature. Data in these experiments were wide-ranging both in amounts of tuber sugars and in fry colour, each distributed widely around the values previously reported to be critical in determining processing acceptability. Despite this, the relationship between fry colour and tuber reducing sugar content was poor and patently not causal. Even when curves were fitted for individual treatments, there were rarely significant relationships between fry colours and tuber reducing sugar contents. While sugars may on occasion be the limiting factor influencing the degree of non-enzymic browning, this does not occur with sufficient regularity or with any degree of predictability to be of use as a measure of immediate or post-storage processing potential. Although such conclusions are contrary to much that has been stated in the literature, in reality there is agreement between data presented in the literature and in these experiments. It is therefore irrelevant to the improvement of fry colours whether the response in tuber sugar behaviour to some storage and, to a lesser extent field conditions is known, and continued attention to refining techniques for measurement of sugars will not help. The priority must be to increase overall understanding of the

Maillard reaction and hence allow the determination of the relative importance of the components in determining colour. Reducing sugars clearly influence fry colours (e.g. low temperature sweetening in storage or after delay to harvest), but the effect of sugar is too variable to be useful and attention must be directed to those factors which alter the colour at any amount of sugar.

After initial disparity in fry colour between treatments in the period covering harvest, curing and early storage, long-term storage caused a convergence of fry colour. Such developments would be expected, since crops were accumulated from diverse sites with a range in husbandry and environmental conditions, and, at intake, tuber characteristics determining fry colour inevitably depended upon the scope of such variation. Subsequently, during long-term storage, tubers experienced constant and similar environmental conditions for an extended period of time and achieved a common and stable degree of processing quality. Ultimately, if harvesting, transport, handling and storage conditions can be adequately controlled, these results show that agronomic parameters within the range found in commercial practice have little effect on long-term processing quality. This suggests that store managers, when relating agronomy to storage procedure, should concentrate on damage and tuber weight loss considerations, since there is likely to be more impact of these on profit margins than deterioration in processing performance.

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