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Determination of optimum tuber planting density in the potato varieties Pentland Squire, Cara, Estima, Maris Piper and King Edward

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SUMMARY

Thirty-two experiments examining the effects of the weight and within-row spacing of potato seed tubers on graded tuber yields of five varieties were conducted on eight sites from 1980 to 1985. A complex analysis technique was used to combine these data and estimate the optimum tuber planting densities for different ratios of seed cost to small (40–60 mm) and large (60–80 mm) ware value. The same technique could be applied to any other combination of seed cost, ware size and ware value.

The optimum tuber planting density decreased with increasing seed-tuber weight. Differences in optimum planting density between varieties were much greater with small (35 g) than with large (105 g) seed tubers and decreased as the cost of seed increased relative to the value of ware. As large ware became worth more than small ware the influence of increasing seed cost on the optimum density was reduced. As the value of large ware increased, net returns increased and the effect of seed cost on net returns was reduced. Mean tuber size decreased with increasing stem density at harvest and at the same stem density was lower in varieties producing more daughter tubers/stem. Changes of mean tuber size (μ) and the spread of yield across size grades (σ) with time were well described by parallel curves in different varieties.

It is suggested that in future it may not be necessary to determine optimum tuber planting densities by complex experiments involving several seed-tuber weights and spacings. Instead μ and σ could be estimated from simple experiments and tuber spacings determined by comparison with control varieties.

INTRODUCTION

Recommendations for the optimum tuber planting densities of the major maincrop potato varieties have been available from the Agricultural Development and Advisory Service (ADAS) for several years (MAFF 1985). However, the analysis techniques used to produce these figures have not been described or justified in published form nor has the basis for the differences between varieties ever been fully explained. In recent years the size specifications for ware potatoes have become much more specific with, for example, a price premium for larger tubers suitable for sale as 'bakers'. Thus growers now need information on the most economic tuber planting densities to enable them to grow crops which produce an increasingly wide range of target tuber sizes.

In this paper, we describe a series of experiments designed to study the effect of seed-tuber weight and within-row spacing on the yield of tubers in various size grades. We calculate the optimum tuber planting density for a range of economic circumstances and attempt to provide an understanding of the differences in optimum density and therefore ultimately the underlying principles controlling tuber size distribution between crops.

THE EXPERIMENTS

Thirty-two experiments, examining the effects of seed-tuber weight and within-row spacing, were conducted with five maincrop potato varieties from 1980 to 1985 on commercial sites in Cambridgeshire, Norfolk, Lincolnshire, Yorkshire and Scotland. There were eight experiments with Pentland Squire and six with each of Cara, Estima, Maris Piper and King Edward. All the experiments used two seed-tuber weights: a mean of $35 \pm 3{\cdot}5$ g (tuber count 1430/50 kg) and a mean of 105 ± 10 g (tuber count 480/50 kg). The seed was all Scottish in origin and was held in wooden

Table 1. *Experimental details*

Year	Site	Potato variety	Number of densities at each tuber weight	Range of tuber densities ('000/ha) 35 g seed tubers	105 g seed tubers	Between-row spacing (m)	Total yield (t/ha) (Mean of all treatments)
1980	Feltwell Fen	Pentland Squire	5	39–154	26–77	0·86	63·8
		Maris Piper	5				60·7
1981	Feltwell Fen	Maris Piper	5	39–154	26–77	0·86	63·5
	Montrose	Maris Piper	5	44–175	29–88	0·76	58·3
1983	Bassingbourn	Pentland Squire	6	22–88	15–55	0·76	29·4
		Estima	6				34·2
	Soham	Pentland Squire	6	19–78	13–49	0·86	29·3
		Estima	6				39·4
	Stretham	Cara	6	21–82	14–51	0·81	54·0
		King Edward	6				68·3
	Holbeach	Cara	6	19–77	13–48	0·86	58·8
		Maris Piper	6				52·0
		King Edward	6				49·2
1984	Bassingbourn	Pentland Squire	6	22–88	15–55	0·76	45·6
		Estima	6				62·2
		Maris Piper	6				45·2
	Cambridge	Pentland Squire	6	24–94	16–59	0·71	58·0
		Estima	6				49·9
	Stretham	Cara	6	21–82	14–51	0·81	78·3
		Maris Piper	6				77·3
		King Edward	6				64·6
	Holbeach	Cara	6	19–77	13–48	0·86	57·4
		King Edward	6				57·9
	Melbourne	Pentland Squire	6	22–88	15–55	0·76	87·9
	(Yorks)	Pentland Squire	6				73·0
1985	Bassingbourn	Pentland Squire	5	21–62	14–41	0·81	52·3
		Estima	5				54·9
	Cambridge	Estima	5	24–70	16–47	0·71	46·0
	Stretham	Cara	6	21–82	14–51	0·81	38·7
		King Edward	6				45·4
	Holbeach	Cara	6	19–77	13–48	0·86	63·6
		King Edward	6				60·7

trays at ambient temperature with fluorescent lighting until just before planting. Further details of the experiments and the range of tuber planting densities used are shown in Table 1. The within-row spacings for many of these experiments were the same; different tuber planting densities were due to the row width varying from site to site. In all experiments, the treatments were arranged in a randomized-block design with three replicates. Rates of application of fertilizer and crop culture were those normally used by the grower. The number of above-ground stems on each site was counted just before the crop was harvested. The tubers were hand-graded over square mesh riddles and the number and weight of tubers were recorded in several grades; the number of these varied from five to eight depending on the experiment.

The riddles used were both Imperial and metric and it was necessary to use the technique developed by Travis (1987) to estimate the yields in comparable size grades. This involved describing the size distribution of potatoes, measured as the weight in discrete grades, by two parameters, the grade size at which there is most yield (μ) and a measure of the spread of yield across size grades (σ). In order to calculate μ and σ, it was first necessary to carry out a weighting procedure to stabilize the variance in different size grades. Once μ and σ had been calculated, it was possible, by using the normal distribution function, to calculate the proportion of yield in any size grade and then from the total yield to estimate the actual yield in those grades. Here the yields in the ware grades 40–60 and 60–80 mm were estimated.

In addition to the experiments described above, four other experiments, which provided information on the changes in μ and σ during crop growth, were conducted. These were in 1984 and 1985 at Cambridge and Soham, Cambridgeshire each year. They used all combinations of the three varieties, Pentland Squire,

Table 2. *The changes in residual mean squares fitting models where x is planting density ('000/ha) and subscripts indicate that coefficients in the models are affected by variety (i), trial (j), or variety-trial combination (ij)*

		Tuber weight (g)					
		35	35	35	105	105	105
Return ...		1:1	1:2	1:3	1:1	1:2	1:3
Changes due to including successively	D.F.	MS	MS	MS	MS	MS	MS
$bx+c_{ij}$	31	688·17	2066·43	4786·60	818·99	2306·20	5243·60
$ax^{0.5}$	1	805·61	518·95	295·00	1251·71	1605·90	2003·90
$b_i x$	4	324·72	1011·64	2102·80	241·08	904·37	2021·80
$b_j x$	15	65·27	239·16	570·12	107·55	399·85	932·70
$b_{ij} x$	11	26·97	56·80	110·40	24·32	71·68	159·80
$a_{ij} x^{0.5}$	30	15·08	42·19	94·38	17·23	56·98	126·30
Residual fitting $a_{ij}x^{0.5}+b_{ij}x+c_{ij}$	92	11·76	32·86	72·07	24·33	53·49	101·10

Estima and Maris Piper and three within-row spacings of 80, 40 and 20 cm using tubers weighing 75 ± 5 g (tuber count 667/50 kg). The treatments were arranged on main plots of a split-plot design with three replicates. Sub-plots of each treatment were harvested on nine occasions in 1984 and six occasions in 1985. Fertilizer application, crop culture, harvesting and grading were as previously described.

Determination of optimum tuber planting densities

In order to make an economic interpretation of the data, the value of the ware was calculated in small ware equivalents. Fitting models to the data ignored the cost of seed and the optima for non-zero seed cost were subsequently calculated by adjustment of the fitted parameter values, as described below.

For both seed tuber weights, and for ratios of small ware (40–60 mm) to large ware (60–80 mm) of 1:1, 1:2 and 1:3, the value of the crop (y) was calculated for each combination of trial, variety and planting density. Models incorporating a square root response to planting density (x),

$$y = ax^{0.5}+bx+c$$

were then fitted to the data. This model gave a better fit than linear and quadratic responses (data not shown). The parameters a, b and c were successively held constant and then allowed to vary over trials, varieties and trial-variety combinations, using the scheme of model fitting shown in Table 2. Inspection of the mean squares due to adding successive terms allowed the best model to be chosen.

The optimum tuber planting density, defined as that at which the value of the crop was maximized, was estimated for each seed-tuber weight using the square root curves from the chosen model. For each variety, the optimum was taken to be the mean value of the fitted optima calculated for those trials in which it was grown. Standard errors were calculated, using a Taylor series expansion, from the variance-covariance matrix of the fitted parameters, after adjustment to include a term for site to site variation in parameter values. Optima for different seed costs were then calculated using the same formulae as before, but substituting $(b-s)$ for b where s is the relative cost of the seed.

RESULTS

Optimum tuber planting densities

Table 2 shows the mean squares from fitting successive models to the data. On the basis of these results the model

$$y = ax^{0.5}+(b_i+b_j)x+c_{ij}$$

was used in subsequent calculations, the b value depending, additively, on the variety (i) and trial (j), and the c value depending on the individual variety-trial combination (ij).

The mean optimum tuber planting densities for both seed-tuber weights of each variety are shown in Table 3 for the nine economic situations described. Limited data are presented for 35 g seed tubers of Pentland Squire and Cara because many of the calculated optima were beyond the range of plant densities tested, as shown in Fig. 1 for Pentland Squire, and the standard errors were unacceptably high. Table 3 shows that the optimum density was higher for 35 g tubers than for 105 g tubers and varied more between varieties when using 35 g tubers than when using 105 g tubers. When using 35 g tubers (tuber count 1430/50 kg) the optima for the varieties were in the order Maris Piper > Estima > King Edward for all ratios. With 105 g tubers (tuber count 480/50 kg) the optima were in the order Pentland Squire > Cara > Maris Piper > Estima > King Edward. The data show that as seed became more

Table 3. *The optimum seed tuber planting density ('000/ha) for different ratios of seed cost: small ware value: large ware value. For 35 g seed tubers of varieties Pentland Squire and Cara only those optima within the treatment range are presented* (D.F. = 133, *residual from model fit*)

	Potato variety									
Ratio of seed: small ware: large ware	Pentland Squire	S.E.	Cara	S.E.	Estima	S.E.	Maris Piper	S.E.	King Edward	S.E.
35 g Seed tubers										
1:1:1	140·1	104·34	—	—	63·3	16·63	75·2	8·48	44·3	5·31
2:1:1	101·9	68·71	75·3	15·50	51·9	13·98	61·0	7·03	37·6	4·81
3:1:1	69·3	39·07	55·3	9·65	39·9	10·40	46·2	5·63	30·1	4·09
1:1:2	—	—	—	—	51·3	18·87	57·3	16·32	31·7	6·37
2:1:2	—	—	—	—	43·8	17·09	48·7	15·42	28·1	6·36
3:1:2	95·4	172·24	63·2	25·45	35·4	13·69	39·0	12·84	23·7	5·80
1:1:3	—	—	—	—	45·3	21·59	49·3	21·77	25·9	7·61
2:1:3	—	—	—	—	39·7	20·41	43·0	21·28	23·5	7·82
3:1:3	—	—	75·1	59·55	33·0	17·09	35·7	18·33	20·5	7·35
105 g Seed tubers										
1:1:1	57·4	19·13	46·9	8·49	38·7	7·81	44·0	4·71	32·1	4·15
2:1:1	43·0	13·25	36·5	6·03	30·6	6·22	34·5	3·72	26·0	3·52
3:1:1	29·9	8·15	26·3	4·02	22·6	4·49	25·1	2·98	19·7	2·80
1:1:2	58·5	31·24	42·7	9·79	33·2	7·01	36·9	7·52	26·2	4·27
2:1:2	46·8	24·06	35·9	8·40	28·4	6·43	31·3	7·07	22·9	4·18
3:1:2	35·2	16·08	28·3	6·49	23·0	5·29	25·1	5·90	18·9	3·70
1:1:3	60·6	43·45	41·0	11·21	31·0	7·31	34·1	9·28	23·8	4·55
2:1:3	50·3	35·76	35·3	10·43	27·5	7·17	30·1	9·25	21·5	4·70
3:1:3	39·5	25·46	29·7	8·71	23·3	6·30	25·4	8·17	18·6	4·39

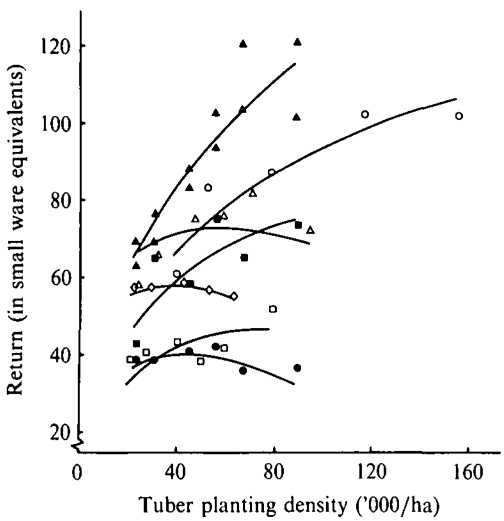

Fig. 1. The relationships between return (small: large ware value ratio of 1:2) and tuber planting density for small seed tubers of Pentland Squire. Different symbols and fitted lines represent individual variety–trial combinations.

expensive relative to the value of the ware produced, so the optimum tuber planting density decreased. However, as large ware (60–80 mm) became worth more than small ware, the influence of increasing seed cost on optimum tuber planting density was reduced. Increasing value of large ware also reduced the optimum tuber planting density except with 105 g seed tubers of Pentland Squire.

Table 4 shows the net return for each monetary ratio at the optimum tuber planting density. It shows that the net return from using 105 g seed tubers exceeded that from 35 g seed tubers in Estima, Maris Piper and King Edward. Net returns increased and were affected less by the cost of seed as the value of large ware (60–80 mm) increased.

Table 5 shows mean varietal values of numbers of stems/seed tuber, tubers/stem harvested, total number of tubers, stems, μ, σ and total yield. Since the varieties were not planted at the same mean tuber planting density, the values of these variables were adjusted to a common tuber planting density of 40000/ha using the slope parameter of the fitted linear relationship with tuber planting density. The total number of tubers above the bottom riddle size was used, since this varied according to experiment and in some experiments there were no tubers recorded below the minimum riddle size. Except in Estima, the total yield of varieties was high, being greater than 50 t/ha.

The most obvious characteristic trends were with the total number of tubers produced/ha and μ. The

Table 4. *Net return at the optimum seed tuber planting density in small ware equivalents for different ratios of seed cost : small ware value : large ware value. For 35 g seed tubers of varieties Pentland Squire and Cara, data are presented, only where the optimum densities are within the treatment range (D.F. = 133, residual from model fit)*

Ratio of seed : small ware : large ware	Pentland Squire	S.E.	Cara	S.E.	Estima	S.E.	Maris Piper	S.E.	King Edward	S.E.
35 g Seed tubers										
1:1:1	48·8	5·92	—	—	43·6	1·97	54·1	2·04	50·9	1·55
2:1:1	49·2	3·49	53·9	2·26	43·1	1·66	53·2	1·88	50·5	1·61
3:1:1	46·4	1·98	51·0	1·62	41·6	1·66	51·0	1·99	49·3	1·76
1:1:2	—	—	—	—	58·1	2·70	68·9	3·08	66·2	2·81
2:1:2	—	—	—	—	58·0	2·65	68·7	3·20	66·0	2·97
3:1:2	68·4	5·13	77·4	2·96	57·2	2·88	67·5	3·53	65·4	3·22
1:1:3	—	—	—	—	73·7	3·90	85·8	4·69	83·3	4·55
2:1:3	—	—	—	—	73·9	4·02	85·9	4·96	83·3	4·77
3:1:3	—	—	104·3	5·43	73·5	4·42	85·4	5·44	82·9	5·08
105 g Seed tubers										
1:1:1	53·2	3·81	61·8	2·90	47·0	2·55	57·6	2·56	56·2	2·07
2:1:1	51·5	2·57	59·9	2·22	45·7	2·13	55·7	2·59	55·1	2·01
3:1:1	46·5	2·19	55·4	2·01	42·2	2·17	51·5	3·06	52·3	2·15
1:1:2	77·3	6·15	88·2	4·03	63·0	3·48	73·0	3·98	72·7	3·15
2:1:2	77·6	4·43	87·2	3·43	62·3	3·28	72·3	4·24	72·2	3·22
3:1:2	74·5	3·51	84·1	3·15	60·2	3·38	69·8	4·79	70·5	3·42
1:1:3	100·7	9·22	115·1	5·45	79·8	4·75	90·0	5·77	90·5	4·51
2:1:3	102·8	6·91	114·6	4·85	79·6	4·63	89·7	6·12	90·2	4·63
3:1:3	101·7	5·29	112·4	4·49	78·1	4·75	88·2	6·73	89·1	4·86

Table 5. *Varietal mean data adjusted to a common seed-tuber density of 40000/ha*

Potato variety	Stems/seed tuber planted	Tubers/ stem harvested	Total number of tubers ('000/ha)	Stems ('000/ha)	μ* (mm)	σ* (mm)	Total yield (t/ha)
Pentland Squire	3·9	3·6	450	138	63·8	11·7	54·1
S.E.	0·12	0·14	18·9	4·2	0·76	0·23	2·16
D.F.	90	90	90	90	90	90	90
Cara	6·0	2·8	526	212	61·4	11·2	58·9
S.E.	0·33	0·08	25·4	11·3	0·86	0·25	1·73
D.F.	70	70	70	70	70	70	70
Estima	3·9	4·4	580	139	55·4	11·1	47·8
S.E.	0·12	0·09	16·2	4·4	0·60	0·27	1·31
D.F.	66	66	66	66	66	66	66
Maris Piper	5·2	3·2	612	200	56·2	9·8	58·3
S.E.	0·18	0·08	25·8	9·4	0·64	0·17	1·55
D.F.	54	54	64	54	64	64	64
King Edward	4·7	5·4	788	169	53·2	10·1	57·8
S.E.	0·23	0·28	32·0	6·8	0·43	0·14	1·20
D.F.	70	70	70	70	70	70	70

* See text.

total number of tubers/ha increased from Pentland Squire to King Edward, while values of μ for Pentland Squire > Cara > Maris Piper > Estima > King Edward. The number of stems/seed tuber, daughter tubers/stem and stems/ha did not follow any obvious pattern. Indeed, Cara stands out as an unusual variety with the most stems/seed tuber, yet the fewest daughter tubers/stem. In contrast, Estima (with

Table 6. *Correlation coefficients between characters and parameters using data from individual experiments of each variety*

		Potato variety				
		Pentland Squire	Cara	Estima	Maris Piper	King Edward
Total yield	Tubers/ stem harvested	0·115	0·842	−0·328	0·842	−0·115
μ*	Total number of tubers/ha	−0·117	−0·561	−0·516	−0·854	−0·645
	σ	0·723	0·946	0·446	0·791	0·778
	Total yield	0·756	0·649	0·523	0·318	0·408
σ*	Total number of tubers/ha	0·132	−0·557	0·429	−0·959	−0·161
	D.F.	10	9	5	4	5

* See text.

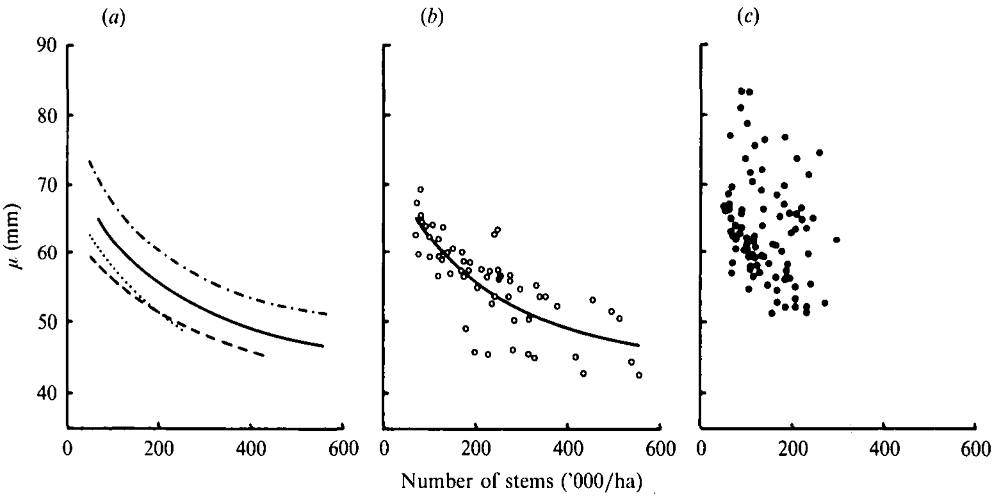

Fig. 2. The relationships between μ and stem density showing (*a*) fitted curves for all varieties except Pentland Squire; Cara (—·—·), Maris Piper (——), Estima (·····) and King Edward (– – –) (*b*) data and the fitted curve for Maris Piper (○——○) and (*c*) data for Pentland Squire (●).

Pentland Squire) produced the least stems/seed tuber and the second highest number (4·4) of daughter tubers/stem. Maris Piper also had few daughter tubers/stem but more than five stems/seed tuber. The values of both μ and σ were lower in varieties producing more tubers, except in Maris Piper, which had a higher value of μ than Estima yet the lowest value of σ.

Correlations within a variety

In order to determine how plant characters and parameters were related within each variety and provide some understanding of the mechanism of tuber size control, data from both seed-tuber weights of individual experiments were combined (Table 6). The correlations show that the yields of both Cara and Maris Piper were strongly associated with the number of tubers/stem, which were low in these varieties. Mu (μ) was significantly negatively correlated with the total number of tubers/ha in Maris Piper, significantly positively correlated with σ in Pentland Squire, Cara and King Edward and significantly positively correlated with yield in Pentland Squire and Cara. There was no significant correlation between μ and σ in Estima or Maris Piper, suggesting that mean tuber size and uniformity are controlled

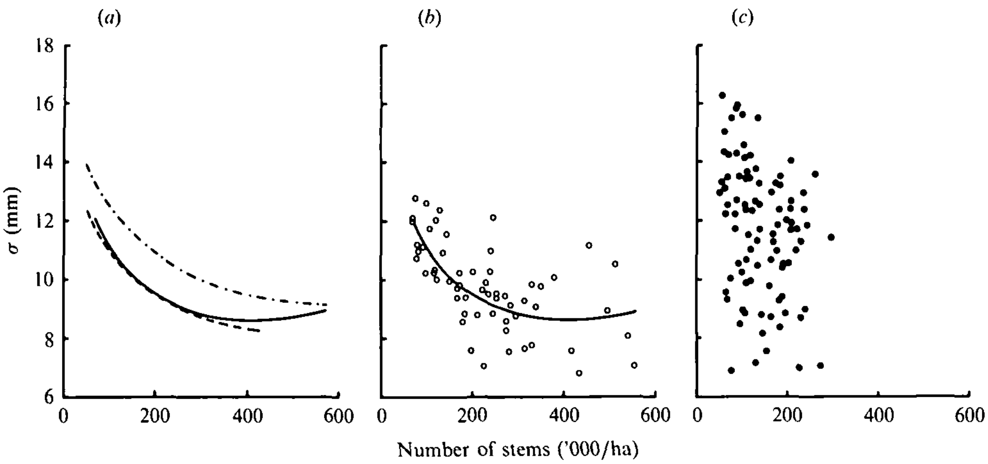

Fig. 3. The relationships between σ and stem density showing (*a*) fitted curves for Cara (—·—·), Maris Piper (——) and King Edward (– – –) (*b*) data and the fitted curve for Maris Piper (○——○) and (*c*) data for Pentland Squire (●).

independently in these varieties. Thus the relationships between μ and other characters differed according to variety. Sigma (σ) was significantly negatively correlated with the total number of tubers/ha in Maris Piper only, showing that the spread of yield across size grades in Maris Piper was particularly affected by the total number of tubers produced.

Relationships between μ and σ and plant density

Using data from all the experiments, linear, quadratic and square root relationships were fitted to relate μ and σ to the number of seed tubers planted/ha and also to the number of above ground stems/ha. A comparison of the percentage variance accounted for, using a model fitting parallel curves for each experiment within a variety, showed that the square root curves accounted for a higher proportion of the variance than the quadratic curves in 80% of the comparisons. For μ, a single square root curve for each variety fitted against the number of stems/ha, accounted for a higher proportion of the variance than when fitted against the number of seed tubers, in every variety except Pentland Squire. With σ, the number of stems/ha gave a better fit than the number of seed tubers/ha in all varieties except King Edward. Figure 2(*a*) shows the independent fitted lines for μ against stem density for each variety except Pentland Squire. The fitted line for Pentland Squire only accounted for 4% of the variance and is not presented, but for Cara, Maris Piper, King Edward and Estima the variance accounted for was 52, 66, 50 and 40%, respectively. For any stem density, the value of μ decreased in the order Cara > Maris Piper > King Edward, as would be expected on the basis of the number of tubers/stem and the total number of tubers. The odd variety was Estima, which produced a response most similar to King Edward, although over a limited range of stem densities. Figure 2(*b*) shows the data and the fitted line for Maris Piper which showed a close fit, while Fig. 2(*c*) simply presents the data for Pentland Squire. With σ, the variance accounted for was 9, 30, 10, 51 and 46% for Pentland Squire, Cara, Estima, Maris Piper and King Edward, respectively. Figure 3(*a*) shows the fitted curves for Cara, Maris Piper and King Edward, with σ declining with increasing stem density. Figures 3(*b*) and (*c*) respectively show the data and fitted line for Maris Piper and the data for Pentland Squire. Maris Piper and King Edward produced very similar responses, while Pentland Squire again behaved very differently.

Changes of μ and σ with time

Using the data from experiments in 1984 and 1985 with Pentland Squire, Estima and Maris Piper, which were harvested over time; linear, quadratic and square root relationships were fitted to relate μ and σ to time. A model fitting parallel quadratic curves for each variety gave the best fit and accounted for 64% of the variance of μ (Fig. 4) and 70% of the variance of σ (Fig. 5). With both parameters, values decreased in the order: Pentland Squire > Estima > Maris Piper.

DISCUSSION

Experiments studying the effects of seed tuber weight and spacing on yield have been conducted in the UK for more than a century with Maw (1867) being perhaps the first to report his work. Since then Bates (1935) and Boyd & Lessells (1954) have produced notable contributions, and more recently Jarvis & Shotton (1971), Jarvis (1971) and Jarvis & Rogers-

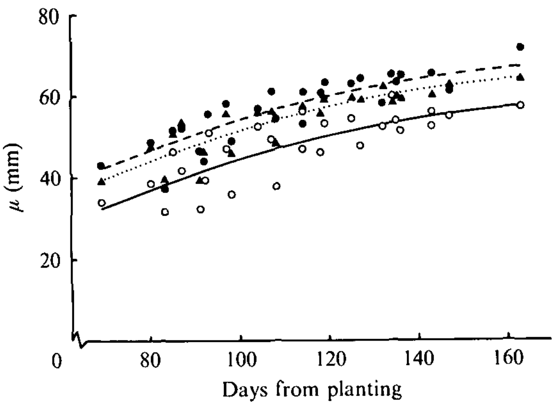

Fig. 4. The change in μ with time for Pentland Squire (●--●), Estima (▲·····▲) and Maris Piper (○——○).

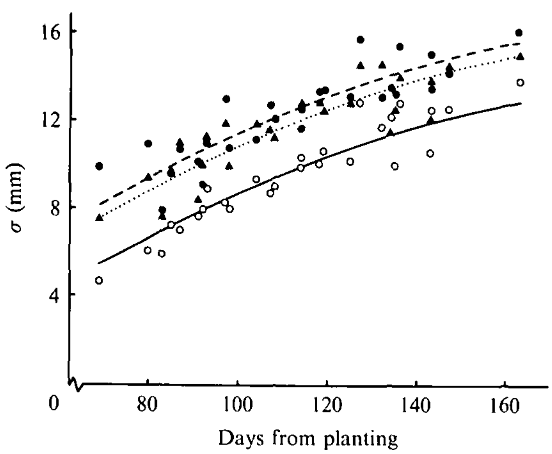

Fig. 5. The change in σ with time for Pentland Squire (●--●), Estima (▲·····▲) and Maris Piper (○——○).

Lewis (1974, 1976) have reported the effects of seed tuber weight and spacing on a range of varieties and these data have provided the basis of the current recommendations (MAFF 1985). Since then Travis (1987) has shown how to model the size distribution of tubers in potato crops. This has proved to be a valuable breakthrough in attempts to adjust plant densities according to the precise size requirements of the market, which have become much more specific in recent years. We have used Travis's technique here for two purposes: first to combine data from experiments graded over different riddle sizes and second to predict the yields in the size grades 40–60 mm and 60–80 mm. This model would equally well have predicted the yields in any other size grades as shown by Wurr *et al.* (1990) with the variety Record. In fact, we have used a different technique from that of Wurr *et al.* (1990) and have fitted models to determine the optima in relative ware units and subsequently calculated optima for different relative seed costs. These optima were then combined to provide recommended optimum tuber planting densities which are derived from data collected in different years and from different locations and soil types and therefore represent a considerable range of conditions.

Some of the optima (Table 3) are similar to those produced by ADAS (MAFF 1985), but others differ from the ADAS figures, suggesting that a systematic trend due to the analysis technique was not responsible. For example with the 2:1:1 seed:small ware:large ware ratio, in Pentland Squire the optimum is about the same as the ADAS figure when using 105 g seed tubers. In Estima the optima given here are lower than those of ADAS, by about 18000 and 14000 seed tubers/ha for 35g and 105g seed tubers respectively, while in Maris Piper the optima obtained here are respectively *c.* 14000 and 10000 seed tubers/ha higher than those of ADAS. For Estima, Maris Piper and King Edward, when using batches of seed tubers of different tuber count from those used here, the optimum tuber planting density can be estimated using linear interpolation. It is difficult to make further comment about comparisons between the optima obtained by us and by ADAS because the technique used by ADAS to produce their recommendations has not been described.

Differences between varieties in optimum tuber planting density are much greater with 35 g seed tubers than with 105 g seed tubers. This is because the stem is the fundamental plant unit (Bleasdale 1965) and, since 35 g seed tubers produce fewer stems/tuber than 105 g seed tubers, more of them are needed to produce any required stem density. Thus the optimum density needs particular attention when small seed tubers are used. However, the differences between varieties decline as the cost of seed increases relative to the value of ware produced. Indeed, with 105g seed tubers costing three times the value of the ware that they produced (3:1:1) the maximum difference between the varieties was only 10200 tubers/ha. One other important feature of practical value is where 'bakers' are sold at high value, the cost of seed had a smaller effect on the optimum planting density than where all ware had the same value.

Comparisons of net returns suggest that, in general, these were greatest from Cara and least from Estima. However, comparisons between varieties may be slightly misleading because they are strongly dependent on the level of yield, which could have been affected by environmental and site conditions. Greater reliance can be placed on comparisons within a variety which show that net returns were greatly affected by cost:value ratios. The cost of seed had only a small effect on net returns at the optimum, though this was greater when small and large ware had the same value than when high value 'bakers' were sold.

Having analysed so many experiments, it is important to develop some appreciation of the principles involved in determining the correct plant density for a specific use. However, understanding the factors influencing the control of tuber size is not simple because the importance of plant characters changes from one variety to another. Indeed effects on tuber size can be considered in two ways: those explaining differences between varieties and those explaining differences within a variety. When comparing varieties, the values of μ and σ in general decreased with an increasing number of daughter tubers (Table 5). Within varieties it is notable that relationships between μ and σ and between μ and yield were strongest in Pentland Squire and Cara, the varieties with the fewest tubers. This is perhaps in contrast to Struik (1987) who found that as a result of changing environmental conditions there was no strict relation between the number of daughter tubers and their size distribution. It suggests that Struik may have used a variety producing a reasonable number of tubers, which was therefore buffered against the effect of short term environmental change. Correlations within varieties also suggest sensitivity of yield to factors controlling numbers of tubers/stem in varieties like Cara and Maris Piper, which tend to produce low numbers of daughter tubers/stem (Table 5). This accords well with commercial observations (W. Kerkham, personal communication) that the performance of Cara in particular is sensitive to tuber set. Indeed it is an unusual variety (Table 5) in that it produces many stems and few daughter tubers/stem. In contrast, Estima shows no significant correlations between plant characters (Table 6) which again agrees with the practical observation that Estima is a 'stable' variety whose performance is not easily altered from crop to crop (Firman *et al.* 1991).

One fundamental feature of this work has been that it demonstrates the close relationships across varieties between μ and the total number of tubers/ha. This suggests that in future it may not be necessary to carry out large-scale experiments over several years involving a range of seed-tuber weights and spacings in order to determine the optimum tuber planting densities. Instead it should be possible to calculate μ and σ from much simpler experiments and, by comparison with the μ and σ of a control variety, to determine the optimum tuber planting density by interpolation of existing varietal data.

Another important use for the data on μ and σ collected here would be to develop a system to predict the tuber size distribution of a crop later in growth, based on a crop sample during early growth, the rate of change of μ and σ with time (Figs 4 and 5) and a simple model of tuber yield over time.

The work described in this paper is an attempt to carry out comparative analyses of varietal density data in order to develop the principles for recommending tuber planting densities for any variety, now or in the future, in order to maximize returns from ware tubers of any required size. The ware grades used here (40–60, 60–80 mm) are but one example of the use to which our analysis techniques could be put. They could equally well be used to calculate the optimum tuber planting density for any other combination of seed cost, ware tuber size and ware value.

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REFERENCES

Bates, G. H. (1935). A study of the factors influencing size of potato tubers. *Journal of Agricultural Science, Cambridge* **25**, 297–313.

Bleasdale, J. K. A. (1965). Relationships between set characters and yield in maincrop potatoes. *Journal of Agricultural Science, Cambridge* **64**, 361–366.

Boyd, D. A. & Lessells, W. J. (1954). The effect of seed rate on the yield of potatoes. *Journal of Agricultural Science, Cambridge* **44**, 465–476.

Firman, D. M., O'Brien, P. J. & Allen, E. J. (1991). Leaf and flower initiation in potato (*Solanum tuberosum*) sprouts and stems in relation to number of nodes and tuber initiation. *Journal of Agricultural Science, Cambridge* **117**, 61–74.

Jarvis, R. H. (1971). Population studies with Pentland Crown and Pentland Dell potatoes. *Experimental Husbandry* **20**, 84–92.

Jarvis, R. H. & Rogers-Lewis, D. S. (1974). Population studies with Pentland Ivory and Record potatoes. *Experimental Husbandry* **27**, 23–30.

Jarvis, R. H. & Rogers-Lewis, D. S. (1976). Population studies with Desirée, Maris Piper and Stormont Enterprise potatoes. *Experimental Husbandry* **31**, 135–144.

Jarvis, R. H. & Shotton, F. E. (1971). Population studies with King Edward potatoes. *Experimental Husbandry* **20**, 12–29.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (1985). Seed rate for potatoes grown as maincrop. *MAFF leaflet* 653.

MAW, G. (1867). Results of experiments on the potato crop with reference to the most profitable size of the sets; the influence of thick and thin planting etc. carried out in the years 1864 and 1865 at Benthall near Broseley. *Journal of the Royal Agricultural Society II* **3**, 552–570.

STRUIK, P. C. (1987). Effects of short changes in environmental conditions on the development, yield and tuber-size distribution of potatoes. In *Proceedings of the 10th Triennial Conference of the European Association of Potato Research, Aalborg*, pp. 346–347.

TRAVIS, K. Z. (1987). Use of a simple model to study factors affecting the size distribution of tubers in potato crops. *Journal of Agricultural Science, Cambridge* **109**, 563–571.

WURR, D. C. E., FELLOWS, J. R., SUTHERLAND, R. A. & ALLEN, E. J. (1990). Determination of optimum tuber planting density for production of tubers in processing ware grades in the potato variety Record. *Journal of Agricultural Science, Cambridge* **114**, 11–18.