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A census of seedling establishment in sugar-beet crops

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SUMMARY

Analysis of seedling establishment in 254 experiments from 1970 to 1977 showed that the target of 70%, needed for an adequate plant population and maximum yield, was achieved in only 19% of fields. However, because the plants were only counted once, when they had about six leaves, the cause and timing of the losses could not be identified. This, therefore, gave no sound basis for seeking improvements. Eight studies of all phases of establishment, from sowing to the 6-leaf stage, were then made at Broom's Barn from 1978 to 1981. The studies were on sandy loam or clay loam soils with seedbeds prepared by standard, recommended methods and sown either early or late in spring. These standard treatments were supplemented by plots which tested irrigation or protection from rain, fine or coarse tilths, and the use of a soil applied insecticide or a sterilant. Despite the widely differing weather experienced by these crops, 70% establishment was achieved in seven studies; in the eighth, seedlings emerged at 75% of seed stations, but 31% were then killed, mainly by birds.

On average, the drill failed to place seeds at 2·8% of target positions, dead seed was sown at 6%, seedlings died after germination but before emergence at 12·4% and plants died thereafter at 6·5%. Almost every viable seed sown in the field germinated eventually; waterlogging seemed to be the cause of failure in a few small areas where this was not so. In most studies the first 50% of seeds germinated as expected on the basis of the thermal time required in the laboratory test. The remainder sometimes took longer, mainly because they experienced periods when the water supply was inadequate.

Seedlings failed to emerge for several reasons; of which the principal ones were dehydration, restriction under a soil crust or stone, and pest damage. It seemed that waterlogging and herbicide damage were important causes in a few cases. After emergence bird grazing was the major cause of death, preferentially of the seedlings which emerged first and had the greatest yield potential.

Because losses occurred at every stage and from many causes the solution to the problem of poor establishment requires a multidisciplinary approach.

INTRODUCTION

In England, the trend which started in the mid-1960's to establish the sugar-beet crop by sowing monogerm seed 15 – 20 cm apart to avoid subsequent hand-thinning of seedlings, i.e. 'drilling to a stand' (Hull & Jaggard, 1971), has continued and now nearly 90% of the crop is grown in this way. Jaggard (1979) has shown that with the usual row width of about 50 cm, yield will be lost when the distance between adjacent plants exceeds 40 cm. To minimise these gaps when drilling to a stand, there must be plants at over 70% of the target seed positions. It is impractical to reduce the likelihood of such gaps simply by sowing seeds closer together because crowding in densely populated parts of the row increases the variation in plant size and decreases harvester efficiency (Harris, 1969).

During the 1970's evidence accumulated that drilling to a stand often resulted in gaps in the plant stand. One source of the information came from four series of experiments. Fig. 1 shows plant establishment in the treatments closest to currently recommended practices from experiments sown with monogerm seed in 254 fields between 1970 and 1977 (Draycott, Durrant, Davis & Vaidyanathan, 1976; Draycott, Farley & Turner, 1976; Draycott & Bugg, 1982; R. A. Dunning and G. H. Winder, unpublished). In each year establishment at different sites ranged from less than 20% to nearly 90%. In 1974 and 1976 establishment averaged only 50%, significantly lower than the 59% found in 1971, 1972, 1975 and 1977. Establishment was greater than 70% in only 19% of fields. The proportion of commercial crops with unacceptable establishment was almost certainly greater than this because the experiments were sown with well-maintained drills, did not include headlands and did not involve extreme husbandry practices.

The possible associations between establishment percentage and information recorded routinely in the experiments – surface soil texture, amount and date of application of nitrogen fertiliser, sowing date, seed depth and rainfall were examined. Classification of the experiments by soil texture into 11 categories indicated that establishment was least on the

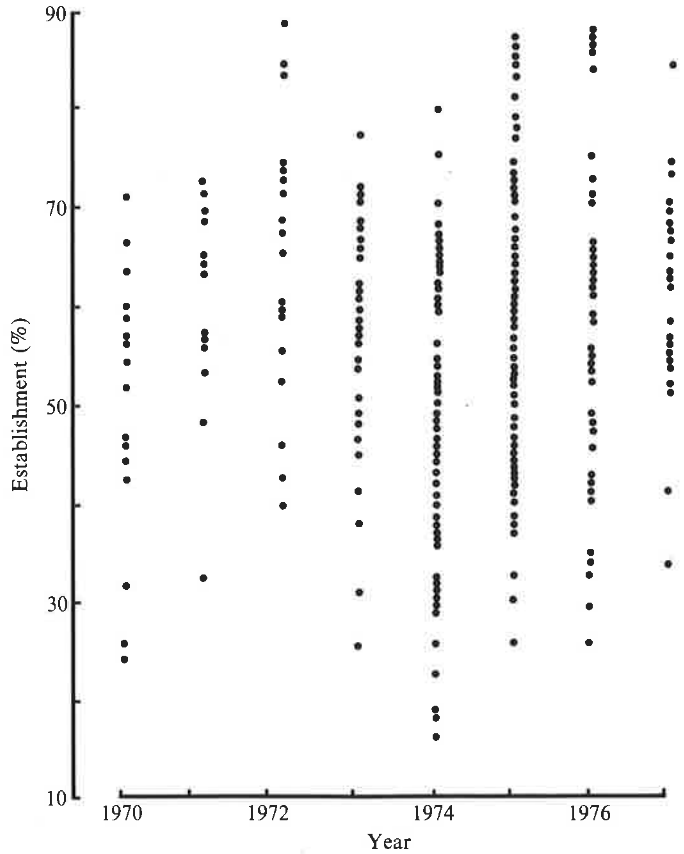

Fig. 1. Proportion of seed positions with established plants. 254 Experiments, 1970–77.

silts, but only the extremes (46% establishment on the silty loams and 66% on the loamy sands) were significantly different. Although date of sowing, the time between sowing and applying nitrogen fertiliser and the amount of fertiliser can all have a marked effect at a site, these factors hardly accounted for any of the site-to-site variation in these series of experiments. There was much variation in establishment at each nominal sowing depth and only an indication, based on few fields, that establishment was worse where sowing was shallower than 1·5 cm or deeper than 4·5 cm. Rainfall in the month after sowing was also poorly related to establishment, probably because it was the moisture supply immediately after sowing or just as the seed germinated which was critical (Durrant, 1979; Simmonds, 1983; see later).

As the analysis of data from experiments failed to identify the principal causes of variation, a systematic study was made of the placement, growth and health of seeds and seedlings at every stage from sowing to establishment. This paper reports the results of detailed studies made at Broom's Barn between 1978 and 1981, which were supplemented by less intensive monitoring of the emergence and establishment phases in commercial beet fields throughout England in 1980 and 1981 (Durrant, 1988).

MATERIALS AND METHODS

The analysis of data from the 254 experiments indicated that establishment could be influenced by soil texture; growers and advisers firmly believe that poor establishment is often associated with heavier soils. Therefore, in 1978 and 1981 the fate of seeds and seedlings was compared on the most contrasting soils (clay loam and sandy loam) at Broom's Barn. Establishment is often poor after early sowings and the failures are seldom explained satisfactorily (Hull & Webb, 1970; Jaggard *et al.*, 1983); therefore the performance of seeds sown on two occasions in 1979 and 1980 was also studied. Thus, as shown in Table 1, although some aspects of the studies differed each year at least part was always on clay loam soil of the Stretham series; these four sites were within 400 m of each other. Most sowings were made as soon in spring as soil conditions allowed, aiming for as short an interval as possible between sowing on the contrasting soils. The late sowings in 1979 and 1980 were made when most seedlings had emerged from the first sowing.

Experiment design and treatments

The central part of each study was simply a uniformly treated area of approximately 15 m × 40 m. This was divided into three blocks of four 'plots'. Each 'plot' was 10 rows wide by 9·1 m long; the rows were 51 cm apart. Within blocks, plots were allocated at random to

Table 1. *Main treatments and aggregate size distribution and bulk densities at sowing in eight studies at Broom's Barn, 1978–81*

Year	Soil type	Sowing date	Aggregate size (mm) <2·5 g/100 g dry soil	Aggregate size (mm) 2·5–5·0 g/100 g dry soil	Bulk density 2-4 cm g/ml of dry soil	Bulk density 6-8 cm g/ml of dry soil	Bulk density 10-12 cm g/ml of dry soil
1978	Clay loam	13 April	37·0	16·6	1·24	1·47	1·44
	Sandy loam	19 April	38·4	15·1	–	–	–
1979	Clay loam	17 April	37·9	12·9	1·30	1·43	1·43
	Clay loam	16 May	36·5	11·8	1·36	1·43	1·60
1980	Clay loam	26 March	37·9	18·9	1·09	1·30	1·23
	Clay loam	29 April	39·7	16·4	1·06	1·23	1·29
1981	Clay loam	9 April	33·9	19·9	1·23	1·39	1·56
	Sandy loam	9 April	36·4	12·3	1·21	1·42	1·40

each of the following: soil measurements, pest and disease observations, destructive excavation of seeds and seedlings or counts of seedling emergence.

In 1979 – 81, further information about the seedbed environment was deduced from a series of additional treatments, each of which was allocated at random to two plots in the area adjacent to the 'core-area'. In one treatment, the pesticide carbofuran (Yaltox) at 6 kg a.i./ha was raked into the surface soil just before sowing. In the second the soil was sterilised by injection with methyl bromide. In 1979 this was done on 11 April and 20 April for the first and second sowings respectively; in subsequent years, it was applied during the autumn before beet.

To examine the effect of water status, 'plots' were covered to exclude rain for either 0 – 5, 6 – 10 or 11 – 15 days after sowing whilst other areas were given water (5 mm) immediately after sowing or after 5 and 10 days or on all three occasions. In 1979 and 1980 after the standard cultivations (see below), coarse tilths were produced by digging two 'plots' just before sowing and fine seedbeds were prepared by careful raking two other areas by hand.

Soil management and the seed

Crop husbandry was similar each year to allow between-season comparisons. A blend of P K Na Mg fertiliser was applied to all experimental areas in October, before the land was ploughed to a depth of 25 cm in November. The seedbed was prepared no more than 24 h before sowing by one, or occasionally two, passes of a powered and rotary harrow working in tandem.

A single batch of seed (cv. Bush Mono G), treated with diethyl mercuric phosphate and methiocarb before pelleting was used in all studies. This was stored at low temperature and relative humidity, and throughout storage its germination remained at 94% when measured in the standard test (Hibbert & Woodwark, 1969). Tests at four constant temperatures between 5 and 25 °C (Gummerson, 1986) showed that the base tempereature for germination was 3·5 °C. The drill (Stanhay Mark 1) was set to sow seeds at a depth of 3·2 cm and 8·0 cm apart, except for the late sowings in 1979 and 1980, when, in common with recommended practice, depth was increased to 3·8 cm. At drilling, prilled ammonium nitrate fertiliser (125 kg N/ha) was applied to the soil surface but banded away from the seed. At the same time chloridazon herbicide was sprayed in a band over the row at a rate determined on the basis of soil texture.

The seedbed environment immediately after sowing

Measurements were made and soil samples were taken from within the row i.e. in the seedbed environment which was created by the drill. Aggregate size distribution of the top 5 cm was determined by sieving air-dried soil; bulk density was determined in the 2 – 4 cm, 6 – 8 cm and 10 – 12 cm horizons from cores of 42 mm diameter. As Table 1 shows, on each occasion the seedbed contained similar proportions of aggregates of pellet size or less but bulk densities of dry soil ranged from 1·06 to 1·36 g/ml. Extensive pitfall trapping, formalin application and extraction from soil cores (Raw, 1959; Brown, 1981) showed there were few *Onychiurus*, Symphylids, pygmy mangold beetles, Collembola, leatherjackets or millipedes. Plant parasitic nematodes were extracted from samples of the top 0 -20 cm of soil (Seinhorst, 1955) and potentially damaging populations of *Trichodorus* ($\simeq$ 1000/litre) and *Pratylenchoides* ($\simeq$ 200/litre) (Maughan, Cooke & Gnanasakthy, 1984), were found in studies in 1981 (sandy loam) and 1980 (first sowing) respectively.

Measurements in the 'core-area'

Soil moisture content in the 2 – 4 cm horizon was measured on alternate days by drying samples for 48 h at 105 °C. Twice each week from sowing to establishment 60 seed stations were excavated to determine the proportion without seeds and the percentage germination

(root tip visible). The germinated seeds and seedlings were examined microscopically for pest damage or disease infection; viability of the intact seeds was checked in the standard germination test.

Each day, seedling emergence was recorded on 100 seed stations on each of four rows per plot. Fresh seedlings were marked with a colour-coded cocktail stick so that subsequent observations (e.g. seedlings that died and plant weight) could be related to emergence date. Dead or dying seedlings were excavated and examined to determine the cause of death. A count of established plants was made when the seedling population stabilised (4 – 6 true leaf stage) and at this stage the distance between plants was measured. A sample of plants was cut off at soil level and the hypocotyls were excavated to expose the pellet position and its depth below the soil surface was recorded. The above-ground parts of individual plants were weighed after drying in a forced-draught oven for 24 h at 85 °C.

The germination and emergence time courses were based on frequent, often daily, cumulative measurements. However, for clarity individual data points are omitted from Figs 3, 4 and 5.

RESULTS

In the 1970 – 77 experiments the target of 70% establishment was seldom achieved, but in the studies presented here this target was exceeded in seven of the eight studies. An account sheet of the losses at each stage, germination, emergence and establishment is given in Table 2. Comparisons are made of the effects of season on a common soil type (clay loam), of sowing date within a season (1979 or 1980) and of soil type at a similar sowing date (1978 or 1981).

The weather

At each site, soil temperature was measured at seed depth (3 cm), but at some sites breakdowns prevented hourly recording throughout the germination and emergence period. Therefore the reliable observation of daily maxima and minima were compared with soil temperatures (5 cm) measured at the meteorological site 400 m away. The agreement was always close (± 1 °C) with a correlation coefficient which exceeded 0·95. Therefore, results from this site were used to provide a complete record, and together with rainfall, these data are shown in Fig. 2. In 1978, it was wet and cold immediately after sowing seeds into the clay loam soil, but warmer and drier during the next week when the seed was drilled on the sandy loam. Later, as seedlings emerged, there were periods of heavy rain followed by rapid drying and a cap formed on both soils. In 1979, there was again frequent rainfall but no capping; a

Table 2. *Summary of events per 100 seed stations*

Study	A	B	C	D	D-C	E	E-D
1978 Clay loam	4	3	93 (97)	74	−19	72	−2
Sandy loam	4	4	92 (96)	74	−18	72	−2
1979 First sowing	5	6	89 (94)	81	−8	79	−2
Second sowing	3	3	94 (97)	83	−11	80	−3
1980 First sowing	1	11	88 (89)	75	−15	44	−31
Second sowing	2	9	89 (91)	78	−10	74	−4
1981 Clay loam	1	6	93 (94)	81	−12	78	−3
Sandy loam	2	6	92 (94)	86	−6	81	−5

A, no seeds sown. B, seeds which did not germinate; C, seeds which germinated ( ) as a % of seeds sown. D, seedlings which emerged. E, seedlings which established.

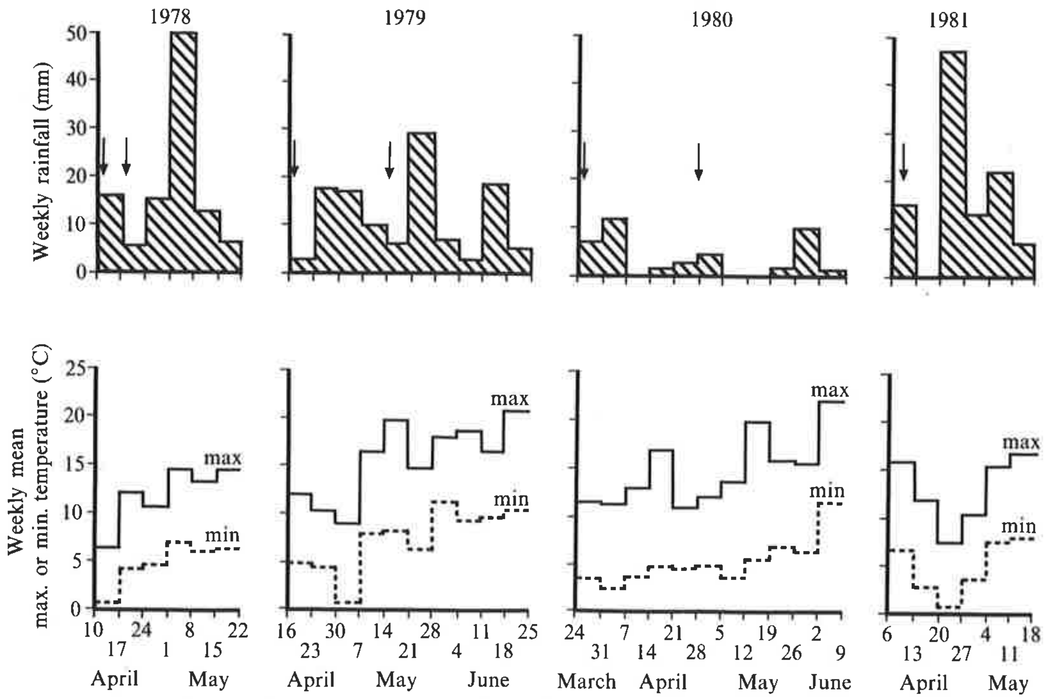

Fig. 2. Rainfall and temperatures during the study periods, 1978–81. (↓ denotes sowing date).

prolonged warm period followed the second sowing. In 1980, there was 20 mm rain in the 2 wk after the first sowing, but thereafter there was little rain and the soil dried rapidly; high temperatures and low rainfall caused the soil to dry even more quickly after the second sowing. In 1981, the week after sowing was wet and warm; a week of dry and cold weather was then followed by continuously wet conditions. Thus, within the eight studies the seeds and seedlings experienced widely differing temperatures and soil moisture conditions; for example, rainfall varied between 7 and 85 mm and average maximum temperature was between 11 and 18 °C in the 4 wk after sowing.

Seed placement

As shown in Table 2, the drill failed to sow a seed at between 1% and 5% of seed stations. In all studies only a trivial number of seeds were excavated and eaten by mice, probably because mice were trapped for at least 2 wk before sowing. Measurement of pellet depth at 'establishment' and, therefore, after considerable settlement showed that, on average, seeds were about 1 cm shallower than the target sowing depth. The standard deviation of pellet depth was commonly 5 mm but was nearly 10 mm in 1979. The mean distance between seed stations was assessed as the smallest mode of the multi-modal distribution of inter-plant distances; in all experiments this was identical to the target spacing of 8 cm.

Germination

The patterns of germination with time in the eight studies are shown as comparisons of years, sowing dates and soil types in Fig. 3.

Years. Despite sowing at the first opportunity in each year, germination in the four years occurred at widely differing times throughout April – in 1980 many seedlings had emerged on a date when few seeds had even germinated in 1978 and 1979 (Fig. 3*a*), but in all studies the

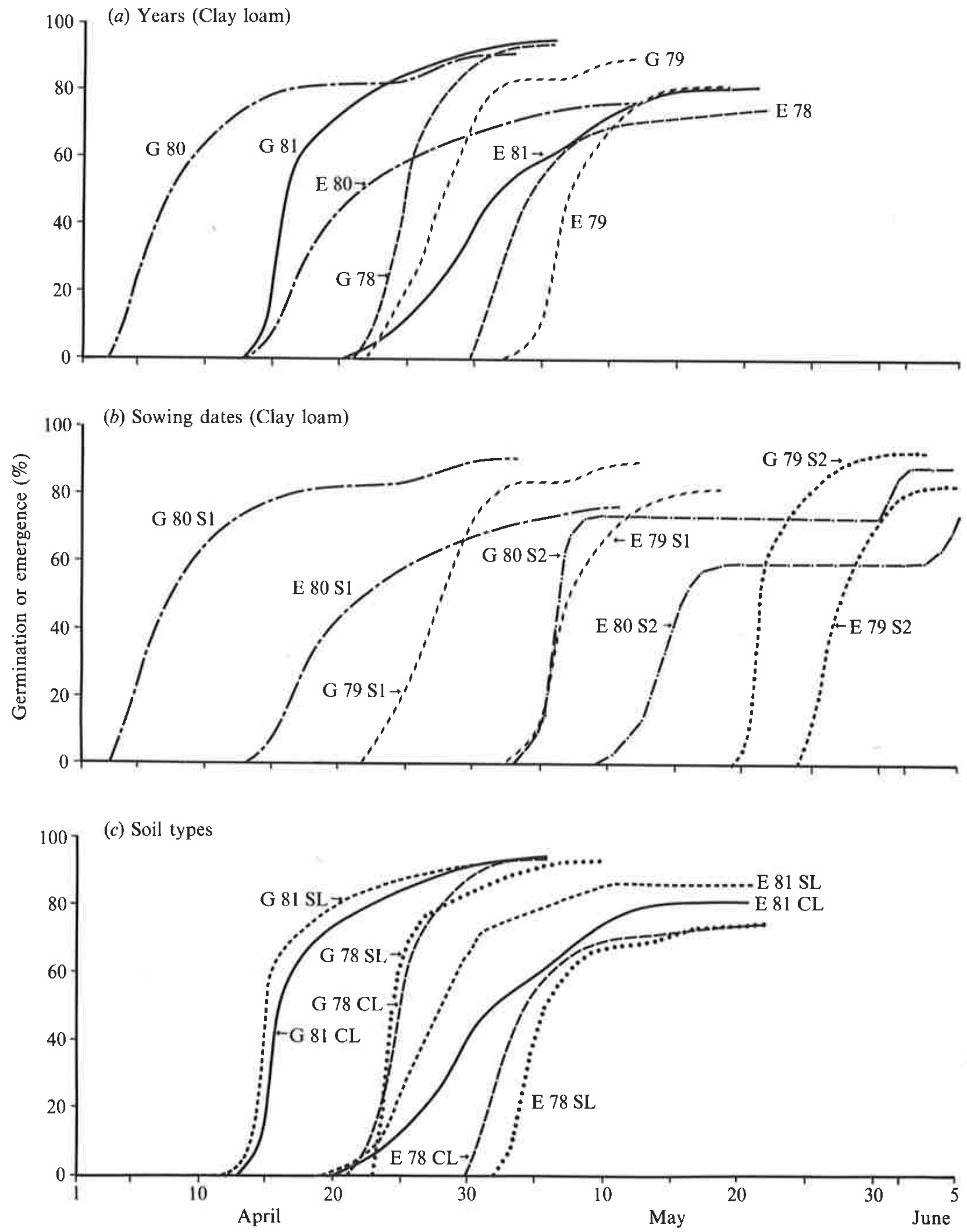

Fig. 3. Time courses of germination (G) and emergence (E) during 1978-81. Number following G or E refers to year. CL, clay loam; SL, sandy loam; S1, first sowing, S2, second sowing.

first seed germinated between 3 and 8 days after sowing. In each year the dates when germination for the first 25% or even 50% of seeds germinated were as predicted from the response to temperature in the laboratory test (Table 3), but the remainder usually required more day degrees to germinate than seeds in the laboratory test. In 1978 the delay (Table 3*a*)

Table 3. *Accumulated day degrees (> 3·5°C) experienced at different growth stages (using max. and min. temperatures, 5 cm deep in soil)*

	(Day degrees)					
	Germination (%)			Emergence (%)		
	25	50	75	25	50	75
(*a*) Years (all CL[3])						
1978	41	50	64	96	107	#
1979	42	52	75	94	104	136
1980	41	55	87	111	150	356
1981	47	62	94	115	129	189
(*b*) Sowing date (all CL)						
1979 (1st)	42	52	75	94	104	136
1979 (2nd)	41	62	86	109	121	154
1980 (1st)	41	55	87	111	150	356
1980 (2nd)	39	46	121	114	137	391
(*c*) Soil type						
1978 CL	41	50	64	96	107	#
1978 SL	38	42	50	101	111	#
1981 CL	47	62	94	115	129	189
1981 SL	43	54	80	109	117	139
Values from lab. germination test.	42[1] (±0·62)	46[1] (±0·51)	54[1] (±1·11)	98[2]	108[2]	126[2]

Notes: # 75% emergence not achieved in 1978: 1, root tip visible; 2, for hypocotyls taller than 3 cm; 3, CL = clay loam; SL = sandy loam.

was not significant; observations of germination percentage were at 3 or 4-day intervals and could only be based on 60 seeds per occasion. Therefore estimation errors of 10 or even 20 day degrees were possible when the daytime temperatures were 10 to 15 °C (Fig. 2). In other years the delay was larger, and there was no obvious reason for it in 1979 and 1981. However, Gummerson (1986) has shown that variation in thermal time to germinate is caused by variation in the base water potential, and that late germinators have a high base potential. In 1979 and 1981 there were periods of 1 or 2 days when soil water content was only about 12%, and this corresponds to a water potential close to the base value for late-germinating seeds. Also, there were occasions when rainfall was intense; waterlogging may have occurred and this could cause a delay.

It is clear that in 1980 dry conditions delayed, on a thermal time basis, the germination of the second half of the seedling population. Germination percentage from both sowings reached constant values and the remaining seeds only germinated after it had rained (Fig. 3*b*). During the period 7 to 12 April, when germination increased from 50 to 75%, the soil moisture content declined to 8·7%; the last 10% of seeds to germinate only did so after rain on 20 and 26 April.

Sowing date. The last half of the seed population to germinate in the late-sown studies was always slow to do so on a thermal time basis. The delay was not great in 1979, and what there was probably resulted from dry conditions soon after sowing. In 1980, dry conditions certainly caused the delay. Immediately after sowing on 29 April there was 3·8 mm of rain, but thereafter it was dry for a month. The moisture was sufficient for 50% of seeds to germinate (Table 3), but soon afterwards the soil became too dry (about 5·5% water) and germination stopped until rewetting occurred at the end of May (Fig. 2). Germination stopped when soil water content (% dry weight) at seed depth was less than about 10%. At this

water content the potential is approximately -1·5 MPa (C. A. H. Hodge, personal communication) which Gummerson (1986) has shown to be close to the base potential for germination in constant conditions.

Soils. Generally, germination was slightly earlier on the sandy loam than on the clay loam soil (Fig. 3*c*). There is no good explanation for this difference, it even persisted when expressed as estimated thermal time to germinate (Table 3). However, these estimates were based on temperatures at the meteorological site, not in the seedbeds themselves. It is possible that the sandy soil was warmer than the clay loam, and that this is the explanation for the different germination times. Another possibility, at least for the wet germination period in 1978, is that the clay loam was slightly waterlogged, and this delayed germination.

General. At each sampling, seeds which had not germinated in the field were tested for germination in the laboratory. On average of all excavations, 94% of seeds were viable after being sown in the field (Table 2) – the same as the viability before sowing. This was not true in 1980; a χ^2 test indicated significant loss of viability in some samples of 60 excavated seeds in both sowings (Table 4). The nine instances of low viability were not distributed uniformly, but occurred in four groups – one soon after sowing and three at least a month later. Sampling positions were not random; seeds were excavated sequentially down the row and grouping of the effect suggests that there were short lengths of row where a few seeds were killed before they germinated. In the first sowing these lethal conditions must have prevailed between sowing on 26 March and 8 April when many dead seeds were first found. One possible explanation is that the coulter of the drill smeared short lengths of the furrow, this impeded drainage and seeds became waterlogged (Swain, 1983). However, excess water was unlikely to have caused the pre-germination failures following the second sowing (Table 4). Fig. 2 shows that little rain fell before this sowing or between sowing and 27 May when the losses were first recorded. Soil moisture around the seed decreased to less than 6% and it seems possible that some seeds germinated but their root then dehydrated and shrivelled back into the fruit. If this were so then the time of death was wrongly classified; the seedlings should have been classed as post-germination losses (see later).

These results suggest that contrary to popular belief among farmers, failure of seeds to germinate in the field is not a major cause of poor establishment. Nevertheless, such losses

Table 4. *The comparison of observed germination in the 1980 field studies with the expected value from the standard test in the laboratory*

1st sowing (26 March)			2nd sowing (29 April)		
Excavation date	X^2	Observed viability (%)	Excavation date	X^2	Observed viability (%)
8 April	8·62**	85	6 May	1·63	97
11 April	16·73***	81	8 May	0·58	96
14 April	12·10**	83	12 May	0·09	95
17 April	3·60	88	15 May	0·71	97
22 April	0·08	93	19 May	0·06	93
24 April	1·82	90	22 May	2·00	98
28 April	1·70	90	27 May	16·72***	81
1 May	0·58	92	30 May	8·62**	85
6 May	0·11	95	2 June	0·05	93
8 May	0·11	98	5 June	1·82	90
13 May	5·98*	86	10 June	12·99***	83
21 May	5·98*	86	13 June	6·25**	86

*, **, *** significant at P = 0·05, 0·01 and 0·001 respectively.

occurred occasionally and were not distributed randomly in the crop, so would lead to gappiness.

Pre-emergence losses

With one exception it was more common for seedlings to die after germination but before emergence than at any other stage (Table 2). Information from the standard germination test would indicate that 2% of the losses at this stage were inevitable, since the hypocotyls of this proportion failed to grow 3 cm tall. Causes for other failures were sought by examining all excavated seedlings for damage and diseases. The root tips of large seedlings were often damaged during lifting, but usually it was possible to distinguish this fresh damage from that due to pests.

In 1978, the seedlings which failed before emergence fell into two categories. Excavations at least 10 days after the last seedling emerged revealed that normal roots and hypocotyls had grown from 12% of seeds but they could not penetrate the 1 cm thick cap which formed when the soil dried during 7 – 9 May, following 24 h of heavy rain (46 mm) on 5 May. A further 4% of seeds germinated and developed an apparently healthy root but this failed to extend beyond 5 mm. This is a characteristic legacy of very wet conditions prior to germination (Durrant, 1980; Simmonds, 1983).

In 1979, about 10% of seeds that germinated did not give plants (Table 2) but there was no obvious damage or infection by pests and diseases nor were there periods when the soil was dry enough to dehydrate the chitted seeds. For 4 or 5 days after both sowings the soil in the seed zone was quite dry, approximately 12% water content, but in both cases this soon rose to about 20%. The first sowing maintained approximately this water content for 20 days, so waterlogging was a possible cause of death.

By contrast, many seedlings from the first sowing in 1980 appeared abnormal (Table 5); a few were damaged by pests, but many had a contorted, swollen radicle and herbicide damage was suspected. At the time, this was judged sufficiently mild to reduce the rate of root growth and no more, but in the dry weather from 2 April onwards (Fig. 2, Fig. 4), it was possible that

Table 5. *An example of the systematic observations of germinated seed and seedlings excavated from the first sowing in 1980*

Sampling date†	Numbers excavated: Chitted seed	Numbers excavated: Emerged seedlings	No. deemed undamaged and healthy	Unhealthy or damaged but likely to survive: No.	Unhealthy or damaged but likely to survive: Notes	Dead or dying: No.	Dead or dying: Notes
8 April	33	0	21	12	a,b	0	–
11 April	40	0	36	4	b	0	–
14 April	44	2	8	33	b	3	c,d
17 April	25	24	4	37	e	8	c,f
22 April	17	32	12	34	e,f,h	3	i
24 April	14	35	11	32	b,e,g	6	g,i
28 April	13	39	1	35	e,g,h	16	g,i
1 May	12	42	0	43	e,g,h	11	f,g
6 May	9	48	1	46	e,g,h	10	g,i
8 May	13	44	1	39	e,g	17	g,h,j
13 May	4	47	0	38	g,l	13	b,g,j
21 May	9	41	0	34	g,h	16	g,k,m,

† 60 seed stations excavated on each occasion.
a, brown root tip. Damage due to: b, Onychumus; c, slugs; d, wireworms; e, herbicide; f, pygmy mangold beetles; g, birds; h, Pratylenchoides; i, unidentified pest; j, Pythium; k, unidentified disease; l, hare; m, flea beetle.

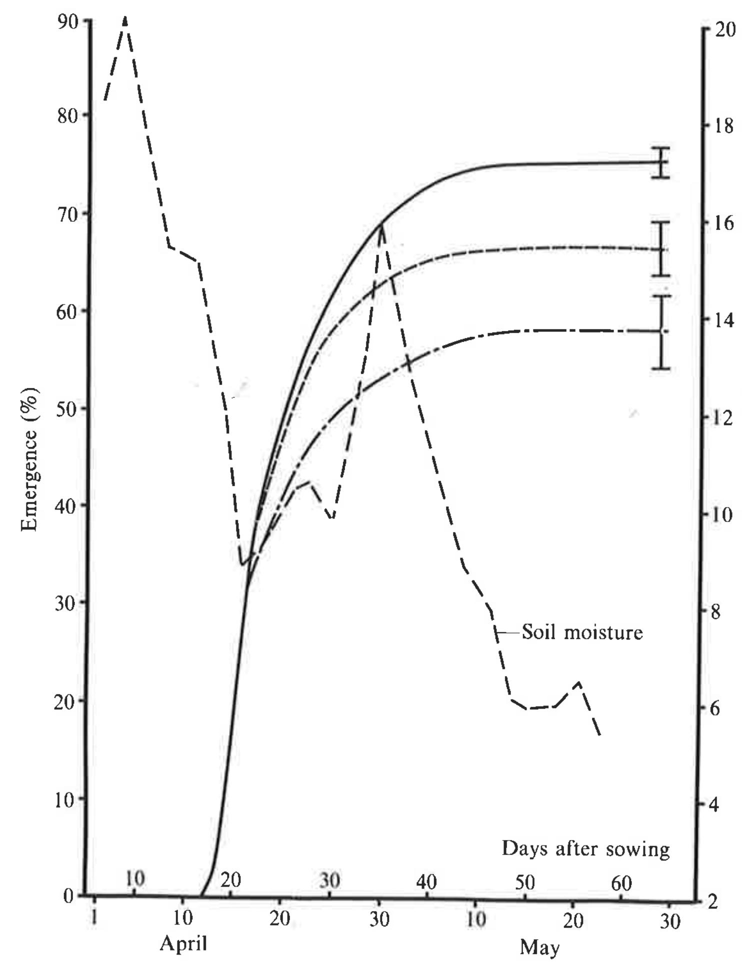

Fig. 4. Seedling emergence from three seedbeds and soil moisture 2-4 cm deep in the 'medium seedbed. First sowing, 1980. —— medium, --- fine and —·— coarse tilth.

dehydration caused their death. The soil moisture content in the 2 – 4 cm horizon was as low as 9% while most seedlings were emerging during mid-April. There were no signs of herbicide damage following the second sowing, and less than 1% of seedlings were attacked by pests. Supplementary watering 5 or 10 days after sowing increased emergence by about 10% (Table 6). This suggests that dehydration while the soil water content was down to approximately 6% (Fig. 5) was responsible for the failure between germination and emergence.

Again, in 1981 pests and diseases damaged very few seedlings prior to emergence, and yet the losses ranged from 6 to 10% (Table 2). Fig. 3 suggests that at least on the clay loam site emergence was adversely affected after 25 or 26 April, when 38 mm of rain fell. It seemed likely that emergence was impeded after the soil slumped (Hegarty & Royle, 1978).

Seedlings were particularly vulnerable during the post-germination/pre-emergence growth stage when upto 19% failures occurred and others sustained sub-lethal damage. Death due to pests and diseases accounted for about one quarter of the losses whilst extremes of water availability (waterlogging or dehydration) and deterioration in soil structure seemed to be associated with the rest.

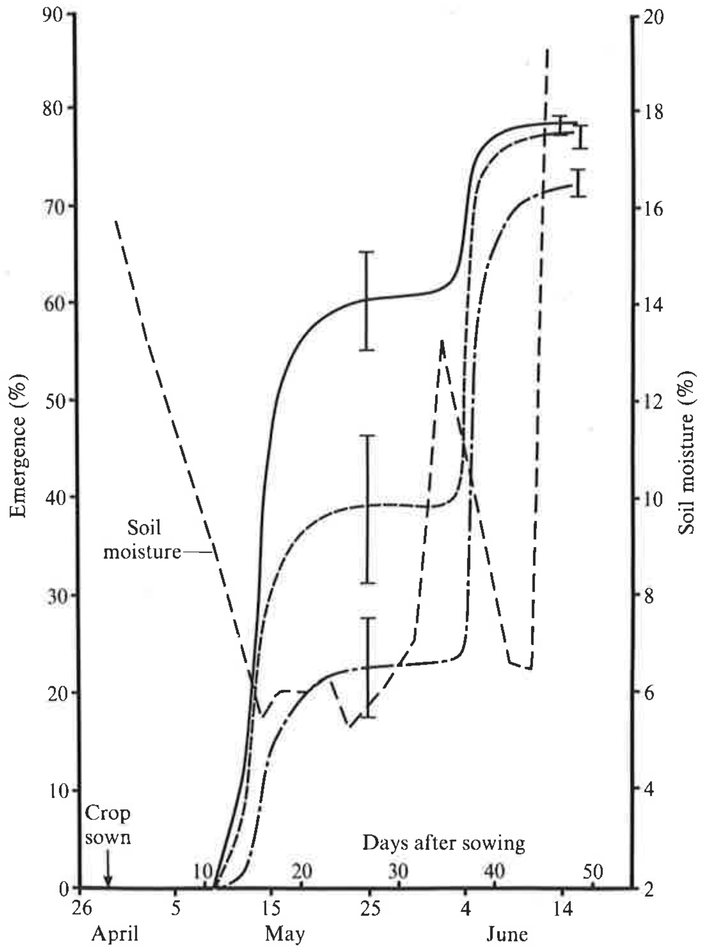

Fig. 5. Seedling emergence from three seedbeds and soil moisture 2-4 cm deep in the 'medium' seedbed. Second sowing, 1980. —— medium, --- fine and —·— coarse tilth.

Seedling emergence

The time course of emergence in each of the eight studies is also shown in Fig. 3 and, as 1200 seed stations were counted daily, data were more accurate than those for earlier phases, particularly germination. Seedlings eventually emerged at between 74 and 86% of seed stations (Table 2) but there was great variation in the time from sowing until emergence was complete. Within the eight studies the first plant emerged between 8 and 17 days after sowing. In 1978 and 1979 seedlings emerged similarly on the basis of thermal time to dates predicted from laboratory studies (Table 3). In 1980 and 1981 emergence was delayed, and the delay became progressively longer as more of the population emerged. Clearly, shortage of water affected the time of germination and hence emergence in 1980 (Figs 4 and 5). It seemed likely that impedance caused the failure of seedlings to emerge in 1981, but the rate of emergence in thermal time was already slow during the pre-germination phase (Table 3).

Seed depth. The variations in sowing depth were not extreme enough to affect the proportion of seeds which gave seedlings. However, the interval between sowing and emergence of individual seedlings was influenced by seed depth (Fig. 6). Results are shown for the major comparisons each year, except 1980, when it was not possible to get unbiased

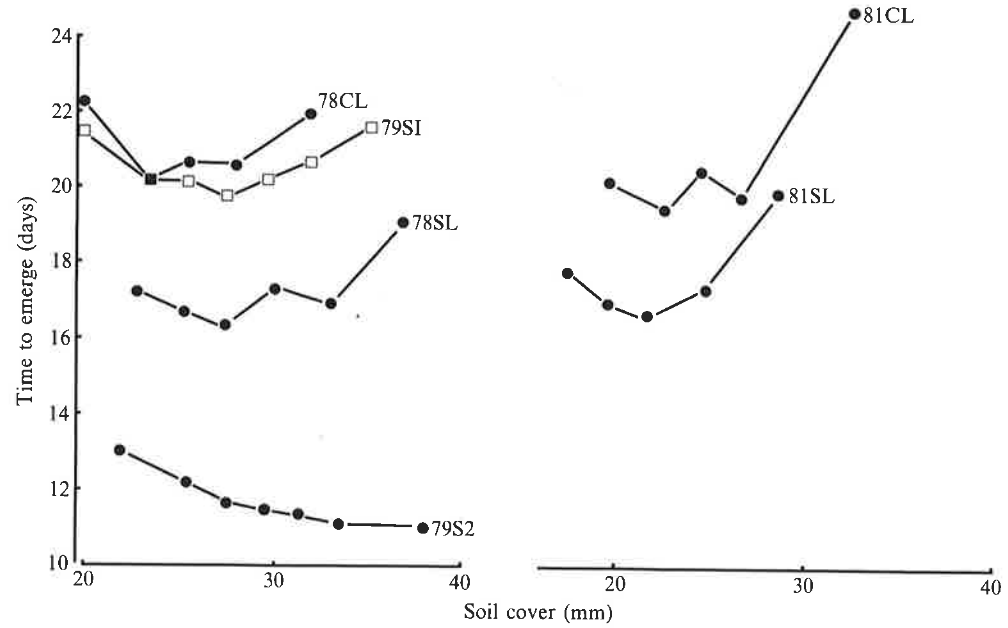

Fig. 6. Effect of depth of soil cover over seeds on the time for seedlings to emerge. CL, clay loam; SL, sandy loam. S1, first sowing; S2, second sowing.

estimates of the effects because so many seedlings were taken by birds. Seeds with little soil covering (shallower than 20 mm) emerged late, presumably because they were vulnerable to drying out. Usually emergence was also delayed where seeds were covered by more than 30 mm of soil : either they were in cooler conditions than their shallower counterparts, or the delay simply reflected the extra time required to grow to the surface. No such delay was detected following the second sowing in 1979, when the weather was warm. In these conditions the seedlings from deep seeds would rapidly cover the extra distance to the surface. In general, emergence was most rapid when seeds were covered by 25 – 30 mm of soil.

Rainfall and irrigation. An indication of the influence of rainfall and seedbed structure on emergence was given by observations on the additional treatments in the studies between 1979 and 1981. The effect of excluding rain or irrigating the soil is shown in Table 6. In general, irrigating immediately after sowing decreased emergence, and in two cases the effect was quite marked. Adding 5 mm of water to the soil immediately after the first sowing in 1979 reduced emergence from 81 to 71%. After the second sowing in 1980 this treatment reduced emergence from 78 to 66%. The causes of the reduction in 1979 were very different to those in 1980. Waterlogging and impedance were involved in 1979, whereas in 1980 the additional water delayed the drying of the seedbed and allowed more seeds to germinate, thereby increasing the proportion vulnerable to subsequent dehydration.

Extra water at later stages usually had no effect, except in 1980 when an application 10 days after sowing increased emergence. This treatment probably delayed drying of the seedbed and allowed some seedlings to establish a sufficiently large root system to escape dehydration. Covering plots to exclude rain for periods of 5 days usually had little effect on emergence, but in 1980 covering immediately after the first sowing improved emergence. The treatment excluded 4 mm within 12 h of sowing and may have prevented a few seeds being waterlogged. Another possibility is that the cover prevented the activation of the chloridazon by rain and thereby reduced the proportion of seedlings affected by herbicide (Table 5, Fig. 2).

Table 6. *Effect of covering or irrigating plots on maximum seedling emergence*

	Maximum emergence (%)					
	1979		1980		1981	
Treatment	1st sowing	2nd sowing	1st sowing	2nd sowing	Clay loam	Sandy loam
Natural rainfall	81	83	75	78	81	86
Covered for:						
5 days after sowing	78	81	88	78	–	–
6-10 days after sowing	80	86	78	77	–	–
11-15 days after sowing	82	81	75	66	–	–
Extra 5 mm water at:						
Sowing	71	83	72	66	77	79
5 days after sowing	79	84	78	85	80	86
10 days after sowing	82	83	75	90	80	89
Continuously wet:						
Three applications of 5 mm (as above)	68	77	72	79	80	85
S.E.	±2·21	±2·19	±1·07	±2·92	±2·72	±1·99

Aggregate size. Making the seedbed coarser or finer had little effect on the rate or number of seedlings which emerged in the moist conditions in both sowings in 1979. However, differences were much greater in the dry conditions in 1980 (Figs 4 and 5). For about 20 days after the first sowing, emergence from all tilths was similar but during the next 10 days, when the soil dried rapidly, few seedlings emerged from the fine and, particularly, the coarse seedbeds (Fig. 4). Rewetting occurred on 29 April, but few seedlings appeared thereafter so many must have become dehydrated and died during the dry period. Probably some seeds which germinated in the coarse tilth were covered by insufficient soil to prevent dehydration. There seems no obvious explanation for lower emergence from the fine seedbed, but it is possible that raking left the surface in an unconsolidated state, and this was prone to dehydration.

Initially, there were marked differences in emergence from the three seedbeds after the second sowing in 1980 (Fig. 5), but there was a 'flush' of emergence once rain wetted the soil and all seedbeds eventually gave a similar number of seedlings. It is likely that both raking the soil to leave a fine tilth, and leaving coarse aggregates on the surface, further decreased the moisture available to some seeds and prevented their germination until it rained.

Neither finer nor coarser seedbeds improved final emergence; the standard of emergence from the 'medium' seedbed structure indicated that it was close to providing the best that could be achieved. However, even this seedbed was not always able to buffer seeds and seedlings against small changes in the weather (simulated by irrigating or covering the soil) which were enough either to decrease emergence or to give an environment in which almost all live seeds gave a plant.

Post-emergence losses and establishment

Establishment varied between 44% and 81% (Table 2); the target of 70% was exceeded in seven of the eight studies. In these seven, post-emergence losses were small, varying between 2 and 5%, and despite careful examination it was often impossible to state the cause of death. However, as illustrated with results from 1979 (Table 7), there was always clear evidence for more than one cause. Exceptional losses followed the first sowing in 1980, when emerged plants were killed at 31% of seed positions. The first losses occurred 25 days after sowing when about 50% of seedlings had emerged (Fig. 7); small birds grazed plants which had yet to

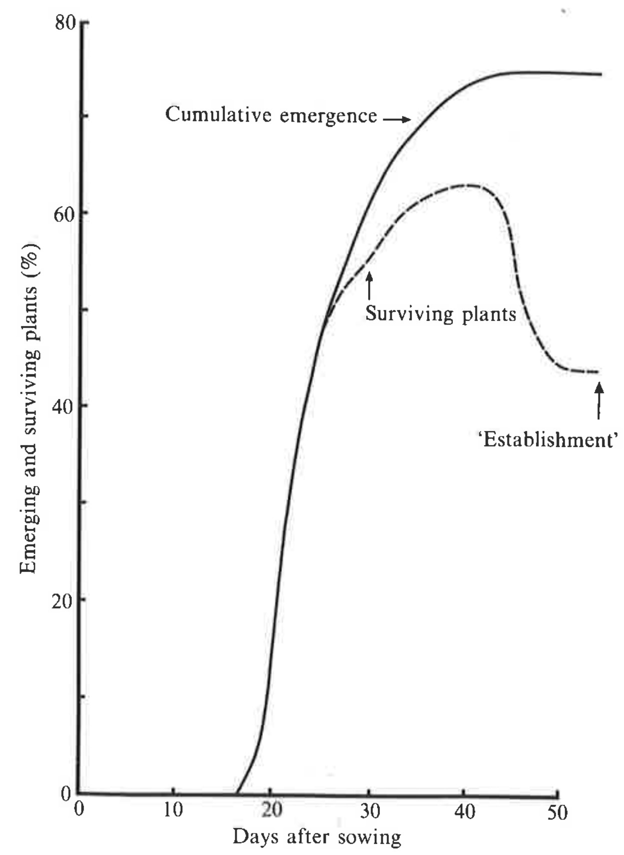

Fig. 7. Emergence and survival. First sowing, 1980.

Table 7. *Post-emergence losses in 1979*

	(No. of plants lost per 1000 seed stations)	
Cause of loss	First sowing	Second sowing
Fungal disease	8·5	6·7
Millepede, slug or wireworms	5·0	5·0
Birds	2·5	0·8
Springtails	1·7	0·8
Pygmy beetle	0	1·7
Unidentified	5·0	9·2
Total	22·5	24·2

produce true leaves (Table 5). During the next 17 days the losses rose steadily to 10% of seed stations. However, between 42 and 47 days after sowing (7 to 12 May) there was a spectacular increase in grazing and seedlings were killed at a further 18% of stations with many of the survivors damaged. Game birds, particularly partridges were responsible. Finally, hares ate a few plants when they reached about the 4-leaf stage. Birds did much of the grazing during the exceptional drought and they were probably foraging for moisture as much as for food.

The observations of post-emergence losses were sufficiently detailed to associate the date on which a seedling emerged with the day when it was grazed. Plants were not grazed

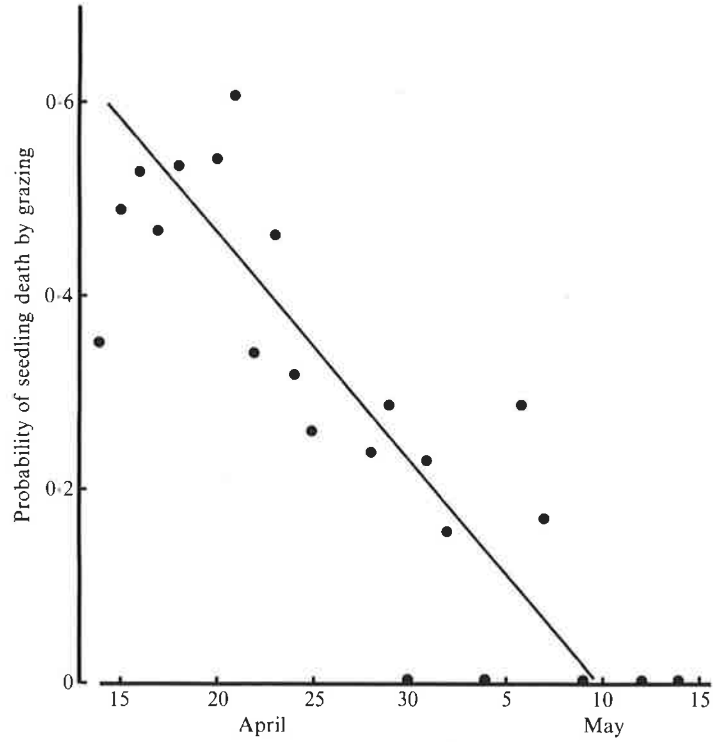

Fig. 8. The relationship between the probability of death by grazing and date of seedling emergence. First sowing, 1980.

immediately they emerged; usually damage occurred a few days later, when the cotyledons had expanded. Seedlings which emerged early were most likely to be grazed (Fig. 8). About half the plants which emerged between 15 and 20 April were killed compared to about 25% of plants which came between 25 and 30 April. Many of the survivors were also grazed. On 4 June, plants were harvested and classified according to their emergence date and the presence or absence of damaged leaves. As expected, seedling dry weight was greatly affected by emergence date (Fig. 9), but grazing caused a 3-fold reduction in the weight of foliage, even 3 – 4 wk after the damage occurred. In addition to the serious effects on the number of plants established, grazing of this severity is likely to reduce sugar yield at harvest (Green, 1978).

Soil treatment with methyl bromide or carbofuran only improved seedling establishment in one study, indicating that in most cases pests and diseases were responsible for the deaths of only a few seedlings on Broom's Barn soils. However, on the first sowing in 1980 these treatments improved establishment from 44 to 55 and 51% (S.E. ± 2·51) respectively; this was probably the result of the observed slight reduction in foliar grazing. Usually, sterilisation had no large effects on seedling numbers nor on seedling size. However, in 1981 methyl bromide fumigation stimulated seedling growth, particularly on the sandy loam soil where seedling weight was almost doubled (Table 8).

DISCUSSION

Data from 254 experiments throughout the beet growing area in the 1970's suggested that seedling establishment was inadequate for maximum sugar yield in over 75% of 'drilled to a stand' crops. The experiments were not on fields with severe pest or disease problems or extreme husbandry and many were drilled by specialists. The information raised questions about whether drilling to a stand should be the generally-used method for establishing the beet crop in the longer term. However, a major limitation of the experiments was that plants were counted only once, several weeks after sowing. Thus, there was no indication of the cause or timing of the losses and, in consequence, no sound basis for seeking improvements.

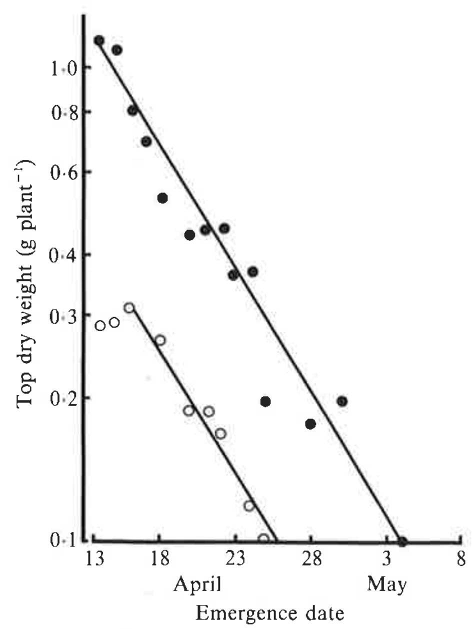

Fig. 9. Mean dry weight of tops and date of emergence. First sowing 1980, sampled on 4 June. ●, undamaged plants. ○, grazed plants.

Table 8. *The effect of soil sterilisation with methyl bromide on seedling weight. Crops sown 9 April 1981 and harvested on 9 June*

Soil type	Soil sterilisation	Top dry weight kg/ha	Root dry weight kg/ha	Total dry weight kg/ha
Clay loam	–	152	19	171
	+	209	28	237
Sandy loam	–	164	20	184
	+	296	42	338
S.E.		±25·5	±3·88	±29·1

By contrast, over 70% emergence was achieved in all eight studies at Broom's Barn and the target of 70% establishment was exceeded in seven of these despite a wide range of weather conditions, including some extremes caused by delayed sowing. In general, the results suggest that acceptable establishment should be achieved regularly but nevertheless losses did occur at most stages in every study. The average losses in the eight studies were (Table 2): dead seed was sown at 6% and no seed was sown at 2·8% of target seed stations. Between germination and emergence 12·4% of seedlings died, but thereafter the losses varied greatly, from 2 to 31%.

Commonly, growers believe that many seeds fail to germinate in the field; our observations refute this since almost all viable seeds germinated, but were sometimes slow to do so. Some losses between germination and emergence were probably the legacy of too wet conditions soon after sowing, suggesting that better drainage or more tolerant seeds would sometimes be beneficial. More recent studies have shown that a change from the clay pellet used in these studies, to a more porous structure helps to reduce the tendency for seed to become waterlogged (Durrant & Loads, 1986). In some seedbeds chitted seeds were vulnerable to dehydration, but once a seedling emerged it seemed able to survive these drying conditions. In these experiments modifying the tilth did not improve establishment; further studies of the effects of seedbed structure are in progress (Gummerson, 1985).

In the studies about 4% of chitted seeds were killed by pests or diseases but many plants had damaged or diseased root systems which seemed too mild to cause death. The small increases in establishment as a result of applying carbofuran or methyl bromide confirm this assessment. Any damage at this stage is undesirable but, in the case of pests, it is difficult to see how to eliminate it because several species are involved (Table 5) and the use of pesticides is often not justified (Dewar & Cooper, 1985). In these studies *Pythium* killed a few seedlings; improved protection against fungal diseases may be possible now that hymexazol can be incorporated into the seed coating (Byford & Payne, 1983).

Some plants died after emergence and, once again, there were several causes. Grazing by birds killed 31% of plants in 1980 and many of the survivors were badly damaged. The plants with the greatest yield potential, those which emerged first, were most vulnerable. Although chemicals such as aldicarb can decrease grazing by repelling birds (Dunning & Green, 1975) there is, as yet, insufficient data to predict if, where and when their use in this role would be justified.

There was much variation in the weight of individual plants and this was closely related to emergence date. This variation is undesirable because it increases the risk that some seedlings will be susceptible to damage by herbicides when most of the population is ready to be sprayed. Fig. 9 shows, 70 days after sowing, a 10-fold change in plant weight when emergence occurred over 20 days. This emergence period is not atypically long (Fig. 3), and even the most synchronous pattern, the second sowing in 1979, had a 3-fold weight range when sampled 43 days after sowing. A possible way to increase the synchrony of emergence is to reduce the variation in sowing depth (Sperlingsson, 1981). The depth of cover over the seed commonly had a standard deviation of 5 mm or more, and the emergence of both shallow and deep seeds tended to be delayed (Fig. 6).

These studies at Broom's Barn showed clearly that the failure to achieve a plant at every seed station was due to many factors, and therefore no single remedy seems likely. Compared with the earlier estimates, establishment at Broom's Barn was atypically good so the losses at each growth stage were monitored in nationwide surveys in 1980 and 1981 (Durrant, 1988).

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REFERENCES

BROWN, R. A. (1981). Soil pest damage studies. *Report of Rothamsted Experimental Station for 1980* Part 1, pp. 69–70.

BYFORD, W. J. & PAYNE, P. A. (1983). Experiments with hymexazol treatment of sugar-beet seed and observations on sugar-beet plants infected at the seedling stage by *Aphanomyces cochlioides*. *Aspects of Applied Biology* **2**, 99–101.

DEWAR, A. M. & COOPER, J. M. (1985). To treat or not to treat – prospects for forecasting soil pest damage. *British Sugar Beet Review* **53** (4), 39–40.

DRAYCOTT, A. P. & BUGG, S. M. (1982). Response by sugar beet to various amounts and times of application of sodium chloride fertilizer in relation to soil type. *Journal of Agricultural Science, Cambridge* **98**, 579–592.

DRAYCOTT, A. P., DURRANT, M. J., DAVIES, D. B. & VAIDYANATHAN, L. V. (1976). Sodium and potassium fertilizer in relation to soil physical properties and sugar beet yield. *Journal of Agricultural Science, Cambridge* **87**, 633–642.

DRAYCOTT, A. P., FARLEY, R. F. & TURNER, N. V. (1976). Sugar beet and nitrogen. *British Sugar Beet Review* **44** (4), 30–31.

DUNNING, R. A. & GREEN, R. E. (1975). Bird damage to sugar beet and approaches to its control. *Proceedings 8th Insecticides and Fungicides Conference*, pp. 237–244.

DURRANT, M. J. (1979). Sugar beet seedling establishment with particular reference to fertilizers. Ph.D. Thesis. University of Nottingham.

DURRANT, M. J. (1980). Plant establishment in 1980. *British Sugar Beet Review* **48**(4), 7–10.

DURRANT, M. J. (1988). Seedling establishment in sugar beet crops in 1980 and 1981. *Annals of Applied Biology* **113**, 347–355.

DURRANT, M. J. & LOADS, A. H. (1986). The effect of pellet structure on the germination and emergence of sugar beet seed. *Seed Science and Technology* **14**, 343–353.

GREEN, R. E. (1978). The ecology of bird and mammal pests of sugar beet. Ph.D. Thesis. University of Cambridge.

GUMMERSON, R. J. (1985). Effect of cultivation technique on plant establishment. *Report of Rothamsted Experimental Station for 1984*, pp. 46–47.

GUMMERSON, R. J. (1986). The effect of constant temperature and osmotic potentials on the germination of sugar beet. *Journal of Experimental Botany* **37**, 729–741.

HARRIS, P. M. (1969). A study of the interaction between method of establishment and method of harvesting the sugar beet crop. *Journal Institut International de Recherches Betteravieres* **4**, 84–103.

HEGARTY, T. W. & ROYLE, S. M. (1978). Soil impedance as a factor reducing crop seedling emergence and its relation to soil conditions at sowing and to applied water. *Journal of Applied Ecology* **15**, 903–910.

HIBBERT, D. & WOODWARK, W. (1969). Germination testing of sugar beet seed on different types of paper substrate. *Journal Institut International de Recherches Betteravieres* **4**, 169–174.

HULL, R. & JAGGARD, K. W. (1971). Recent developments in the establishment of sugar-beet stands. *Field Crop Abstracts* **24**, 381–390.

HULL, R. & WEBB, D. J. (1970). Effect of sowing and harvesting date on sugar beet. *Journal of Agricultural Science, Cambridge* **75**, 223–229.

JAGGARD, K. W. (1979). The effect of plant distribution on yield of sugar beet. Ph.D. Thesis. University of Nottingham.

JAGGARD, K. W., WICKENS, R., WEBB, D. J. & SCOTT, R. K. (1983). Effects of sowing date on plant establishment and bolting and the influence of these factors on yields of sugar beet. *Journal of Agricultural Science, Cambridge* **101**, 147–161.

MAUGHAN, G. L., COOKE, D. A. & GNANASAKTHY, A. (1984). The effects of soil-applied granular pesticides on the establishment and yield of sugar beet in commercial fields. *Crop Protection* **3**, 439–450.

RAW, F. (1959). Estimating earth worm populations by using formalin. *Nature, London* **184**, 1661.

SEINHORST, J. W. (1955). Een eenvoudige methode vor het afscheidei van aaltjes uit grond. *Tijdschrift over Plantenziekten* **61**, 188–190.

SIMMONDS, L. P. (1983). Soil aeration and seedling establishment. Ph.D. Thesis. University of Nottingham.

SPERLINGSSON, C. (1981). The influence of the seedbed soil physical environment on seedling growth and establishment. *Proceedings 44th Winter Congress. Institut International de Recherches Betteravieres*, pp. 59–77.

SWAIN, R. (1983). Soil management and cultivation. *British Sugar Beet Review* **51** (2), 49.

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