Predicting the emergence of potato sprouts

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SUMMARY

Sprout emergence in the potato variety Estima was investigated in controlled environment and field experiments. The effects of temperature, physiological age, planting date and soil moisture were examined in controlled environments and the results were compared with the emergence of physiologically young and old seed in field experiments with different soil types, planting dates and planting depths.

Elongation of sprouts could be described by a lag period of slow growth followed by a period of rapid linear growth. The lag period was shorter with increase in temperature up to 20 °C and sprout length at planting up to *c*. 10 mm. The lag period was slightly reduced by warming seed at 10 °C before planting, compared with planting seed directly from cold storage. The rate of linear growth increased with temperature up to 20 °C but was similar for young and old seed at different planting dates. The rate of growth was lower in dry soil than in soil near to field capacity, particularly at high temperatures.

The observed date of emergence in the field was usually later than predicted, particularly with shallow planting, but prediction was improved by accounting for soil moisture. The use of this model should give more accurate estimation of emergence for farm operations and crop growth models than existing equations.

INTRODUCTION

A number of efforts have been made to predict the rate of emergence of potato sprouts on the basis of temperature after planting (e.g. Sale 1979; MacKerron 1984; Thomas 1988; Sands 1989). As these authors have not used the same varieties, differences would be expected, but whilst all authors suggest that rates of growth increase with temperature between a base and an optimum, the equations used for sprout growth are quite different.

Sale (1979) suggested that there was a requirement of *c*. 450 day degrees above 2 °C for emergence of varieties Sebago and Sequoia planted at a depth of 75 mm. MacKerron (1984) found that the apparent rate of sprout growth at constant temperatures for Maris Piper was higher with increasing planting depth and suggested that this could be explained by a temperature-dependent lag period after planting, when sprout growth was slow. MacKerron (1984) estimated that a longer lag period was needed for unsprouted seed (270 °C days > 0 °C) than for sprouted seed (153 °C days), but in a later model Marshall *et al*. (1984) and MacKerron (1985) assumed a requirement of 125 °C days > 5 °C for unsprouted seed and no lag for sprouted seed and that the rate of extension growth was 1 mm/°C > 2 °C. Sands (1989) used a non-linear function of temperature to model the data of Sale (1979) and included a factor which increased the rate of growth as the period of storage of the seed tubers was extended, in order to explain the increase in the rate of sprout growth with delay in planting date found by Sale.

Sadler (1961), Sale (1979) and Thomas (1988) all found that the optimum temperature for sprout growth was *c*. 20–25 °C. Sale reported that rate of growth was reduced with temperatures > 22 °C and that at > 30 °C rotting of tubers may occur. The base temperature for sprout elongation is suggested to be in the range 2–6 °C (Krijthe 1962; MacKerron 1984; Sands 1989). Thomas (1988) compared rates of sprout growth in Estima obtained from a constant temperature experiment with emergence data from field experiments and suggested that the data could be combined in a single regression line of rate of sprout growth against mean temperature to emergence. Thomas (1988) found that the rate of sprout growth in Estima was much faster than the rates for Sebago and Sequoia indicated by the data of Sale (1979) but slower than the rates reported by MacKerron (1984) for Maris Piper.

Although the effects of factors such as soil moisture and physiological age have been reported to affect emergence (e.g. Letnes 1958; Headford 1961; Sadler

Table 1. *Treatments in controlled-temperature experiments in 1988 and 1989*

Expt	Planting date	Temperatures (°C)	Other treatments
1	11 Feb 1988	10	
2	8 Mar 1988	8,10,13,20	
3	13 May 1988	8,13,20	Wet or dry soil
4	21 Jun 1988	8,10,13,20	Wet or dry soil
5	7 Sep 1988	13,16·5,20,23,25,28	
6	29 Mar 1989, 26 May 1989, 15 Aug 1989	10,20	Young or old seed, warm or cold at planting

1961), little attempt has been made to quantify these effects. This investigation was conducted to provide a better understanding of the factors affecting pre-emergence sprout growth.

MATERIALS AND METHODS

A series of experiments was carried out in controlled-temperature rooms during 1988 (Expts 1–5) and 1989 (Expt 6) using certified potato seed tubers of the variety Estima. The same seed stock was used for all controlled-temperature experiments in each year and seed was held at < 4 °C in chitting trays, with constant illumination (*c.* 25 Wm^2) from fluorescent strip lights, between planting dates. For these experiments, seed tubers were planted with sprouts uppermost in pots 147 mm high with *c.* 20 mm of a loam-based compost below and *c.* 120 mm above the seed tuber. Pots were moved to rooms at different temperatures immediately after planting and kept in the dark. Samples of at least four pots from each treatment were removed at intervals between planting and emergence and the length of the longest sprout in each pot was measured. In Expt 5, a single sample of ten pots per treatment was taken 5 days after planting (DAP). Measurements of the length of the longest sprout from ten tubers were made before each planting date.

Treatments for the experiments comprised combinations of different constant temperature, planting date, soil moisture, seed age and pre-planting seed temperature as shown in Table 1. For Expts 3 and 4, the moisture of the soil was manipulated by adding water to air dry soil until near field capacity in the wet soil treatment (19·0% water by weight) and adding half as much water for the dry soil treatment. The moisture content of soil for all other experiments was near to field capacity. In Expt 6, seed which had just broken dormancy (sprouts of *c.* 3 mm) was either aged for 50 days at 13 °C (illuminated as for cold stored seed) then held at 2 °C or kept physiologically young by cold storage throughout. In addition, seed was planted either cold, directly from cold storage, or warmed, by placing seed at 10 °C for 4 days before planting.

Net sprout growth (sprout length less mean length at planting) was plotted against time after planting. Multiple regression was used to fit parallel lines to net growth > 10 mm for different treatments. Regression was done separately for different temperatures and moisture regimes, having different growth rates, and for the 1988 and 1989 experiments with different treatment factors. The slopes of these lines were used to estimate the relationship between temperature and the rate of linear growth (mm/day) by combining the estimates from both years and using a weighted mean for 10 and 20 °C to account for the different number of observations in each year. The non-linear function of temperature (T) used by Sands (1989), (Eqn 1), was fitted using a modified Gauss–Newton technique (Ross 1987) to estimate the cardinal temperatures (T_a, the base and T_b, the optimum temperature) and the maximum rate of sprout growth (R_o) for wet and dry soil:

$$R(T) = R_o[1-(T-T_b)^2/(T_a-T_b)^2] \quad \text{where} \quad (T_a < T \leqslant T_b) \qquad (1)$$

For each treatment combination, a lag period (days) was calculated from the fitted lines as the apparent time after planting at which linear growth began. The lag period (day degrees) above different base temperatures was plotted against sprout length at planting (of cold seed) and the residual variance compared for fitted curves. Parallel curves were fitted for cold and warmed seed planted in wet soil and three instances with large residuals were omitted from the analysis.

Data from hand-planted field experiments carried out with the variety Estima were compared with the results from the pot experiments. Treatments consisting of different planting dates, sites (in East Anglia), physiological age of seed, planting depth and seed size were as shown in Table 2. Seed was held at < 4 °C between plantings but sprout length (mean of longest sprout per tuber) increased from *c.* 3 to 19 mm in Expt 7 and *c.* 3 to 14 mm in Expts 8 and 9.

In Expts 7–12, the date of 50% plant emergence

Table 2. *Details of the field experiments in East Anglia*

Expt	Planting dates No.	Planting dates Range	Sites No.	Sites Soil types	Other treatments	Sprout length at first planting (mm)	Replicates
7	6	14 May–31 Aug 1987	1	Light gravel	—	3	3
8	3	13 Mar–21 May 1987	4	Light gravel, light silt, sand loam (2 sites)	2 seed ages; 0 and 300 day degrees > 4 °C	3 (0 day degrees) 14 (300 day degrees)	1
9	3	22 Mar–1 Jul 1988	4	Light gravel, light silt, sandy loam, peaty loam	2 seed ages; 0 and 300 day degrees > 4 °C	3 (0 day degrees) 14 (300 day degrees)	1
10	1	22 Mar 1990	1	Light gravel	4 planting depths; 63,93,124,167 ± 4 mm	9·6	3
11	4	14 Mar–6 Jun 1990	1	Light gravel	2 seed ages; 0 and 300 day degrees > 4 °C; 3 seed sizes; 30–35, 35–55,45–50 mm	0·5 (0 day degrees) 8·9 (300 day degrees)	3
12	1	18 May 1990	1	Black peat	2 planting depths; 106,196 ± 5 mm	10·4	4

and mean soil temperature (calculated from hourly measurements at planting depth at each site) were recorded. Sprout length was either measured at planting, or was estimated from measurements made at intervals during storage. The planting depth was measured as the underground stem length and it was assumed that the distance to the soil surface was, on average, not affected by sprout length at planting, due to the random orientation of the seed tuber. In cases where underground stem lengths were not measured, the planting depth was estimated as the mean for that site.

Samples of two plants per plot were harvested 8 and 18 DAP in Expt 10 and samples of *c*. 1 kg of soil were taken from the upper three planting depths and oven dried (24 h at 105 °C) to determine the moisture content. Samples of eight plants per plot were harvested every 2 weeks after planting until emergence in Expt 11 and four plants per plot harvested 5 and 9 DAP in Expt 12.

RESULTS

In all the controlled temperature experiments, elongation of sprouts was characterized by a period of slow growth until sprouts had grown *c*. 10 mm, the lag period, after which sprout elongation was approximately linear with time (Fig. 1). Measurable sprout growth was always preceded by root extension, which was observed as early as 1 DAP in old seed at 20 °C.

Delay in planting date was associated with a gradual increase in sprout length at planting despite seed being held at < 4 °C. The lag period decreased with increasing temperature and with delay in planting with young seed, but with old seed, there was little difference in the lag with delay in planting (Fig. 1).

The relationship between lag period and sprout length (at different planting dates) could be repre-

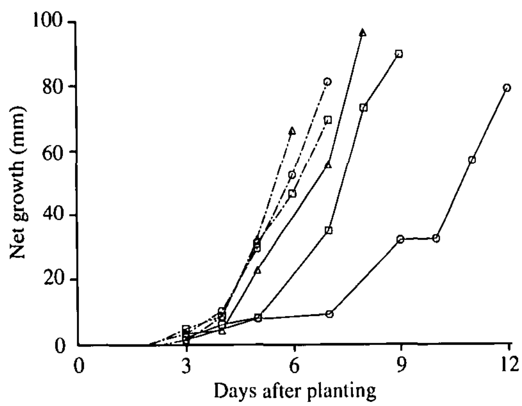

Fig. 1. Effect of planting date and seed age on net growth of sprouts (mm) at 20 °C in Expt 6 (seed warmed before planting). Planted 29 Mar, ○; planted 26 May, □; planted 15 Aug, △. Young seed, solid line; old seed, broken line.

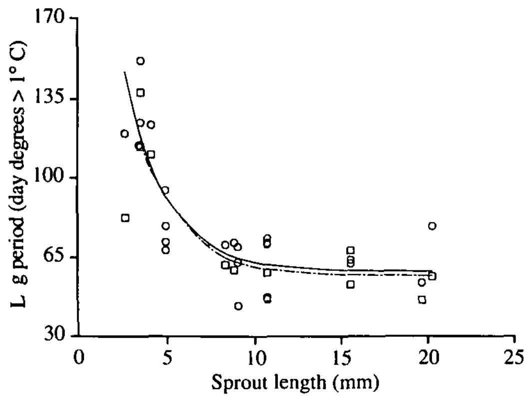

Fig. 2. Relationship between lag period and sprout length for controlled-temperature experiments (Expts 1–6). Seed planted from cold, ○ and solid line ($y = 60+276 \times 0{\cdot}652^x$); seed warmed before planting, □ and broken line ($y = 58+276 \times 0{\cdot}652^x$).

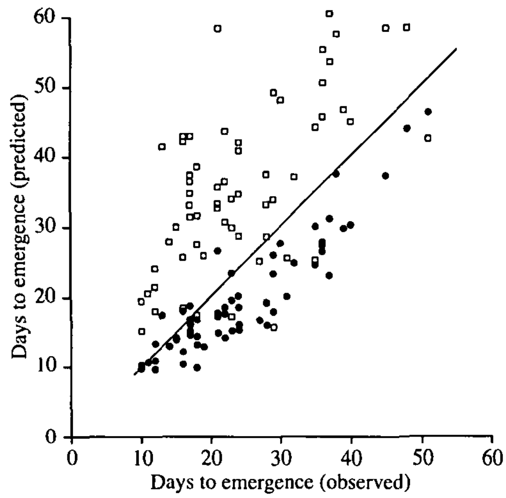

Fig. 4. Plot of observed and predicted time from planting to emergence for field experiments. Prediction using Eqn 3, ●; prediction of Thomas (1988), □; solid line indicates $y = x$.

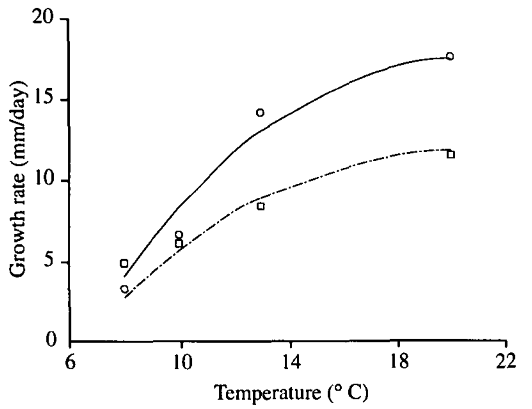

Fig. 3. Relationship between rate of sprout elongation and temperature from controlled-temperature experiments (Expts 1–6). Wet soil, ○ and solid line [$y = 17{\cdot}7(1-(x-19{\cdot}8)^2/(6{\cdot}3-19{\cdot}8)^2)$]; dry soil, □ and broken line [$y = 12{\cdot}1(1-(x-19{\cdot}8)^2/(6{\cdot}3-19{\cdot}8)^2)$].

sented by an exponential curve (Eqn 2, Fig. 2) with the residual variance minimized using a base temperature of 1 °C:

$$L = L_0 + b \times c^S \tag{2}$$

where L is the lag period (day degrees > 1 °C), L_0 is the lag period for well sprouted seed, b and c are constants and S is the sprout length of cold seed (mm).

The estimates of the parameters of Eqn 2 for cold seed were $L_0 = 60$, $b = 276$ and $c = 0{\cdot}652 \pm 0{\cdot}0445$. For well-sprouted, cold seed, Eqn 2 reduces to a thermal requirement of 60 day degrees > 1 °C. Warming the seed before planting in Expt 6 reduced the lag period by 0·8 days at 20 °C and 1·4 days at 10 °C (mean of all other treatments), or *c.* 15 day degrees > 1 °C, although the estimated reduction from the curve fitted to data from all pot experiments was 2 day degrees > 1 °C (i.e. $L_0 = 58$; Fig. 2).

Sprout growth after 5 days in Expt 5 increased with temperature up to 23 °C and decreased at higher temperatures. Net growth was fitted as a quadratic function of temperature (T) (net growth = $10{\cdot}6T - 0{\cdot}22T^2 - 95{\cdot}3$; $r^2 = 0{\cdot}92$). The effects of temperature on the lag period and on linear growth are confounded in this observation but the rate of linear growth calculated from the other experiments could be represented by Eqn 1 (Fig. 3) with cardinal temperatures; $T_a = 6{\cdot}3 \pm 0{\cdot}8$ °C and $T_b = 19{\cdot}8 \pm 2{\cdot}6$ °C. Maximum sprout growth rate (R_0) was higher for wet ($17{\cdot}7 \pm 1{\cdot}4$) than for dry soil ($12{\cdot}1 \pm 1{\cdot}3$ mm/day) and the effect of dry soil was greater at high than at low temperatures.

Combining Eqns 1 and 2, the time from planting to emergence (t_{EM}) could be predicted (Eqn 3) using the planting depth (D), the sprout length at planting (S) and the soil temperature (T). For temperatures > 19·8 °C, the relationship of Sands (1989) could be assumed and the cardinal temperature $T_c = 37$ substituted for T_a in Eqn 3:

$$t_{EM} = [(L_0 + b \times c^S)/(T-1)] + D/[R_0(1-(T-T_b)^2/(T_a-T_b)^2)] \tag{3}$$

The time from planting to emergence in the field Expts (7–12) tended to decrease with delay in planting date as soil temperatures increased and ranged from 10 to 51 days. The difference in time to emergence between young and old seed was nearly 2 weeks from early planting, but decreased with delay in planting and there was no difference at some of the later plantings in Expts 8 and 9. Application of Eqn 3 to the field data gave predicted times to emergence which were usually earlier (on average 4 days) than observed (Fig. 4).

In Expt 10, there was little sprout growth by 8 DAP for all depths, but by 18 DAP, sprouts from the two shallow depths had grown less (29·0 and 29·3 ± 4·2 mm) than the deeper plantings (41·3 and 43·2 mm) despite small differences in soil temperature (< 1 °C) at different depths. The predicted dates of emergence assuming wet soil for Expt 10 were earlier than observed, particularly with the shallow plantings (Table 3). The soil was very dry at the surface and use of the growth rate for dry soil improved the accuracy of the predicted date of emergence for the shallow plantings. In Expt 11, there was no difference in the time of emergence between seed sizes, but there were large differences between young and old seed, particularly at the first planting date (Table 4). Samples dug before emergence showed that this was due to differences in the lag period as predicted by Eqn 3, with a lag period of *c* 15 days for old seed but *c*. 30 days for young seed. As with Expt 11, use of the rate for dry soil usually improved the prediction where planting depth was shallow (Table 4). Observed and predicted sprout lengths from Expt 12 were very close for both depths (Table 5).

Table 3. *Effect of planting depth on the observed and predicted number of days from planting to emergence and soil moisture content in Expt 10*

	Planting depth (mm)	Observed	Predicted		Soil moisture (% by wt)
			Wet	Dry	
	63	31	20	25	5·5
	93	32	25	32	14·8
	124	35	24	32	16·4
	167	37	31	42	—
S.E.	4·3	0·65			

Table 4. *Effect of seed age and planting date on the observed and predicted number of days from planting to emergence in Expt 11*

	Planting date	Planting depth (mm)	Observed	Predicted	
				Wet	Dry
Young seed					
	14 Mar	128	51	46	53
	11 Apr	107	35	30	34
	9 May	80	29	23	26
	6 Jun	88	23	23	26
Old seed					
	14 Mar	136	38	37	51
	11 Apr	113	23	15	20
	9 May	89	18	10	12
	6 Jun	86	16	10	13
S.E.		4·1	0·25		

DISCUSSION

The results show that the rate of growth of potato sprouts after planting at a given temperature is not constant, but is initially slow and may be described by a lag period after which extension growth is approximately linear, as suggested by MacKerron (1984). The duration of the lag period was shorter with increasing sprout length (up to *c*. 10 mm) which may reflect a gradual release from dormancy. A similar effect was reported by Sale (1979), and Sands (1989) suggested that the rate of growth increased with duration of seed storage at 2–3 °C.

Seed stored at < 4 °C is usually assumed to remain at a constant physiological age, but sprout growth can occur at < 4 °C (Sadler 1961; Krijthe 1962; Firman *et al.* 1991) so that sprout length and age may increase with storage duration even at cold temperatures. The reduction in the lag period with increasing sprout length may be equated with an effect of age because, under conditions of similar illumination, there is a relationship between sprout length and age (Firman *et al.* 1991). The reduction in lag period by warming seed before planting may be partly explained by an increase in sprout length but pre-warming also

Table 5. *Observed and predicted sprout length (mm) of two planting depths in Expt 12*

Planting depth (mm)...	100		200		
Days after planting	Observed	Predicted	Observed	Predicted	S.E. (observed)
5	23	13	20	14	3·4
9	70	79	70	80	5·1
11	106	111	—	—	5·4
17	—	—	196	212	5·4

raises tissue temperature and increases cell activity so that growth can begin sooner, and is a useful treatment for promoting more rapid emergence. In commercial practice, pre-warming could be achieved if stores are allowed to warm or if seed is moved outside prior to planting.

The pot experiments indicated that, for sprouts grown with constant illumination, there is little reduction in the lag period once sprouts reach 10 mm in length. Sprouts may grow to 10 mm during long periods of cold storage or after rapid ageing at high temperature, but it is unknown if etiolated sprouts from dark conditions, which frequently occur in commercial practice, would show similar effects; it is likely that the response would be quantitatively different but length might still be a useful predictor of the lag period for such seed. With extreme sprout age, rate of sprout emergence is often slightly reduced (Sadler 1961; Jones & Allen 1983). By measuring sprout length at intervals after planting, these experiments have shown that even with old seed planted at optimum temperatures for growth, rapid extension is preceded by a period of slow growth. The lag period is longer at low temperatures and in young seed but ignoring the lag period may lead to significant inaccuracy even with old seed as MacKerron & Waister (1985) found.

Application of Eqn 3 to the field data indicated that emergence was usually slower in the field than in pots, as found by Sale (1979). In some cases, however, field rates were similar. Very close agreement was obtained for peat soils, with conditions similar to the pots, but a lower rate may be appropriate for types of soils which impede sprout extension. Delayed emergence may reflect poor soil conditions for emergence due to dryness or compaction. Dry soil was found to delay emergence in the pot experiments and predictions of field emergence were improved in many cases by using the growth rate for dry rather than wet soil. In Expt 11, the soil near the surface was drier than that used for the pot experiments so that even slower rates may be appropriate and extreme dryness may completely inhibit emergence (Letnes 1958). Potato growers who use very shallow planting for earlier emergence may find this to be counterproductive, due to dry surface soil. Inhibition of sprout elongation by sunlight as the sprout approaches the soil surface and the method of recording emergence in the field are likely to delay the apparent time of field emergence compared with emergence in pot experiments. Nitrogen fertilizer may also delay emergence in the field (Firman 1987) and there may also be effects of soil compaction, clods and capping and of diseases such as skin spot (*Polyscytalum pustulans*).

Although predictions of time of emergence for the field experiments taking account of sprout length and a lag period using Eqn 3 (for wet soil) were too early, they were closer than predictions based on the equation of Thomas (1988), which were often much later (11 days on average) than observed (Fig. 4). Applying the model for the variety Maris Piper used by MacKerron (1985) predicted even earlier emergence than Eqn 3 (11 days on average). The model of Sands (1989) predicts maximum overall growth rates of *c*. 3 mm/day in the varieties Sebago and Sequoia, much slower than observed in Estima (> 10 mm/day). Small differences between varieties are to be expected, but these relatively slow overall rates probably result from the lag period being ignored and thereby substantially reducing the overall rate for the shallow planting used (75 mm). At these plantings, the lag period was a greater proportion of the time to emerge than for the deeper plantings (> 100 mm) in these experiments. The shallow planting may also have meant that the soil at seed tuber depth was dry. Equation 3 could be improved by calculating growth on a daily basis and taking account of diurnal temperature changes, but this would only alter predictions significantly where large temperature changes occur. Using the mean soil temperature from planting to emergence will tend to underestimate the lag period when temperatures are increasing but is simpler than accounting for daily changes.

The difference in the time of emergence of young and old seed in the field experiments indicates the requirement of a predictive equation to account for this, and the controlled temperature experiments suggest that the degree of sprouting may usefully be used rather than simply recording whether tubers are sprouted or unsprouted. Emergence of sprouts from dormant seed requires estimation of the time of dormancy break but usually seed tubers have broken dormancy by planting and results from Expt 11 indicate that reasonable predictions can be made for seed with sprouts < 1 mm.

Use of Eqn 3 should enable the earliest likely time of emergence in the field to be estimated for Estima, which may be useful for timing pre-emergence farm operations and for the development of models of potato crop growth. The latter require accurate predictions of emergence and further investigation would be useful to determine how lag periods and extension rates differ between varieties and for seed sprouted in the dark. Separate predictive equations could be derived if necessary. The range of temperatures used in the pot experiments (8–20 °C) is applicable for many crops but potato sprouts can grow at < 6 °C and experiments at lower and higher temperatures would be useful for accurate determination of the cardinal temperatures.

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