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SOME EFFECTS OF NON-DAMAGING TEMPERATURES ON THE LIFE AND RESPIRATORY BEHAVIOUR OF BANANAS

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SUMMARY

The preclimacteric respiration rate of bananas falls for approximately 48 hr after harvest, but then increases linearly with time until the onset of the climacteric. The rate of increase is a linear function of fruit immaturity and is dependent on the temperature at which the fruit is held, the relationship with temperature probably being an exponential one. In one experiment involving very immature fruit, the respiration rates fell steadily for several weeks before beginning a steady rise.

Respiration rates at the onset of the climacteric show no relationship to immaturity but are a linear function of the temperature at which the fruit is held. Respiration rates at the climacteric peak are dependent on temperature, probably in a logarithmic manner, data being insufficient to clarify this relationship.

Green-life of fruit bears an inverse linear relationship to the temperature at which they are held. Departures from this relationship which occurred at lower temperatures are believed to indicate an earlier initiation of senescence brought on by these temperatures. Green-life temperature coefficients have been shown to be linearly related to fruit immaturity. The effect of temperature on green-life is three to four times as great as its effect on the duration of the climacteric.

With fruit of one immaturity, the amount of carbon dioxide produced up to maturity is constant, being generally independent of the temperature at which the fruit is held. The amount of carbon dioxide produced does, however, bear a linear relationship to the immaturity of the fruit, at least over a green-life range of about 5-30 days. There is evidence that this relationship may depart from linearity with more immature fruit, since such fruit are liable to be affected by temperatures of 55 and 59°F, and the amounts of carbon dioxide produced may be lower at these temperatures than those produced at higher temperatures.

I. INTRODUCTION

In post-harvest storage investigations the effects of temperature on the duration of life in store have been most extensively studied (Wardlaw 1937; Wright, Rose and Whiteman 1954).

Usually the end of storage life has been assessed in terms of either senescence characteristics, such as edibility and susceptibility to fungal attack, or the development of some physiological disorder such as scald in apples. Assessments of this nature are usually based on personal preference and commercial considerations. While such assessments produce results which are of considerable value from a commercial point of view, frequently they do not add greatly to an understanding of the nature of a disorder or to the physiological effects of factors such as temperature.

Such studies pay little heed to the fact that during storage the fruit may pass through several distinct physiological states during which a factor such as temperature may exert markedly different effects. To obtain a clearer understanding of the effects of different factors on the physiology of fruit it is necessary to give consideration to the physiological age of fruit used and to identify results with a particular physiological state. As stated by Forward (1960), "in interpreting the effects of temperature on the respiration of fruits, it is essential to compare rates at the same stage of senescence".

There have been few storage investigations where such attempts have been made. Harding (1929) and Kidd and West (1932) related the susceptibility of apples to low-temperature breakdown to a particular part of the climacteric rise in respiration. Also, Kidd and West (1930) and Tindale, Trout and Huelin (1938) examined the effects of temperature on the storage life of apples and pears respectively and related their results to the occurrence of the climateric maximum. In these cases the occurrence of the respiratory climacteric was used to define particular physiological stages.

It is considered that the use of this phenomenon in this way is very desirable, being far more definitive of a fruit's physiological age or state than other criteria usually adopted (e.g. harvest date in apples).

With bananas there is much to be gained commercially by maintaining the fruit in its preclimacteric state. This is frequently attempted by lowering its temperature. However, it appears that little work has been done to determine the quantitative advantage of such a treatment. The only work of this kind known to the authors is that published by Gane (1936) and Tsalpatouros (1956*a*). The latter's publication appears to be a theoretical enlargement of the results of Gane.

The work reported here was designed to determine, for bananas, the effects of non-damaging temperatures on the duration of the preclimacteric and climacteric phases and to examine its effects on respiration rates during these periods.

II. DEFINITIONS

Such terms as maturation, maturity and senescence are often used with a variety of meanings. Since such terms will be used in this paper, it is considered essential to detail the meanings intended. Definitions of these terms are shown below, together with two new terms which are considered useful. These definitions are intended to apply in a physiological sense to only those fruit exhibiting a respiratory climacteric.

Maturation: The physiochemical processes of development, initiated at the time of inception of the fruit, which result in maturity being reached.

Maturity: The stage of biochemical development which a fruit has reached when the climacteric rise commences.

Immaturity: The difference in physical and/or biochemical status of a fruit at any particular time during maturation on the plant and the status it will have at maturity on the plant. The difference would be reflected by the time the fruit would take to reach maturity on the plant. This time would be a measure of this difference (immaturity) if growing conditions were defined.

Green-life: The time a harvested fruit takes to reach maturity under defined conditions.

(*a*) Green-life is a measure of the difference in the biochemical status of a fruit at any time during maturation off the plant and the status it will have at maturity.

(*b*) It follows that the green-life of a fruit at harvest is a measure of its immaturity.

Senescence: The irreversible physiochemical processes which are initiated at maturity and which result in the death of the fruit.

III. MATERIALS AND METHODS

Six fruits were held continuously at each of five temperatures, viz. 55, 59, 63, 67 and 71° F. This temperature range was chosen as it was considered to be non-damaging and, once behaviour patterns were established, future work on the effects of temperature outside this range might be assessed in terms of departures from these patterns.

Each fruit was held in a container made from a section of pneumatic tubing of suitable size, closed at each end with a rubber stopper. This type of container bends to the banana's shape and thus reduces "dead space" within the container to a minimum.

Tsalpatouros (1956*b*) stated that decreasing relative humidity prolongs green-life of bananas, but some results obtained by the authors (unpublished) indicate that the reverse may be the case. An airstream saturated with water vapour was used to eliminate the variable effects of vapour pressure differences which would occur if a constant humidity other than 100% was used. The ventilating airstreams were saturated by passing the air through sintered glass bubblers immersed in heated water, then cooling the airstream to the required temperature and trapping the condensate.

The constant temperatures required in this work were obtained using thermostatically controlled heated cabinets operated in a constant-temperature room. Temperatures were maintained at $\pm$ 0·5°F of the desired value.

The bananas (cv. Giant Cavendish, Queensland synonym Mons Mari; Simmonds 1959) used in this study were obtained locally. Fruit which were expected to have a green-life of at least 14 days at 71°F were selected from two or three adjacent hands of a bunch and divided so that an equal number of fruit from each hand were held at each temperature. This experiment was replicated on four separate occasions, detailed as experiments 1–4 in the text. Prior to being placed in store, the fruit were weighed and treated to control fungal growth. The first two experimental lots were dipped in sodium salicylanilide and the last two lots were treated with thiabendazole. Fruit weights (Table 1) illustrate the variability in the size of fruit used.

TABLE 1

FRUIT WEIGHT (g) IN RELATION TO HOLDING TEMPERATURE

Temperature (°F)	Exp. 1		Exp. 2		Exp. 3		Exp. 4	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
71	98·6	8·6	73·7	1·7	161·5	14·3	155·1	13·7
67	98·7	5·2	75·1	3·7	169·3	11·1	157·5	15·5
63	99·3	5·0	75·1	2·6	168·9	9·5	143·6	11·7
59	99·6	4·3	75·1	3·7	159·8	10·6	156·4	15·7
55	98·9	10·4	73·6	4·6	159·9	10·5	149·3	13·0

Flow rates of CO_2–free air were measured with manometric-type flow-meters calibrated to an accuracy of $\pm$ 1·5% and adjusted so that carbon dioxide concentrations of the effluent airstreams, which were measured using an infrared gas analyser, were maintained approximately at 0·02%. Respiration rates were calculated from these data.

Respiration rate was plotted against number of days from harvest, and the times at which the onset of the climacteric and the peak of the climacteric occurred were estimated by inspection. The respiration rate at the peak of the climacteric was also estimated. The regressions for respiration rate on time after harvest were determined for each fruit and the rate of respiration at the onset of the climateric determined by substitution.

Using the same equipment, a further trial (experiment 5) was conducted to determine whether the immaturity of the fruit could modify the responses obtained over this temperature range.

In this experiment bunches of bananas were selected to be of approximately 12 different immaturities. In an attempt to spread the selected immaturities evenly over a range, it was assumed that the number of bracts shed from the bell of a bunch would be a measure of the chronological age and growing conditions (and hence the physiological age) of that bunch. The bunches used were therefore selected so that the number of bracts shed ranged from approximately 80 to 120, and were fairly evenly spaced over this range. Four adjacent fruits from the top hand of each bunch were then selected, two fruits being placed at 70°F and two at 60°F. The experiment thus comprised 48 fruits of 12 different immaturities, 24 of these fruits being held at 70° and 24 at 60°F. All fruits were dipped in thiabendazole before being placed in store. Data were treated as described above.

IV. RESULTS

(a) Experiments 1–4

The data show that the respiration rate falls for approximately 48 hr after harvest and then increases, apparently linearly with time, over the remainder of the preclimacteric period. Figure 1 illustrates this for some fruit from experiment 3.

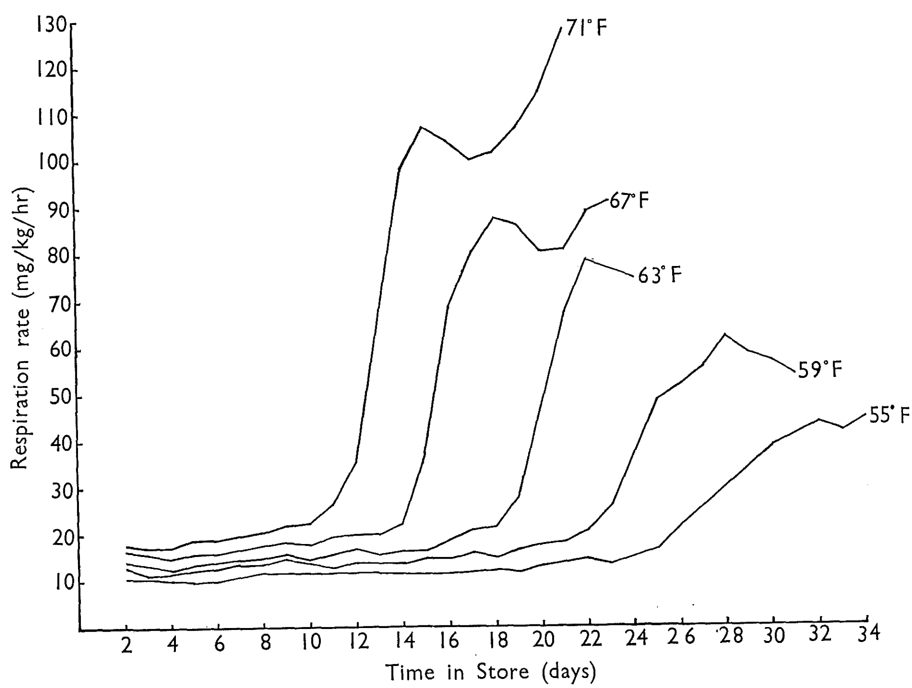

Fig. 1.—Sample of data from experiment 3, showing respiration rates of representative individual fruits held continuously at the temperatures indicated.

In experiment 2, an initial fall in respiration rate continued for 28–30 days and a steady rise then commenced. In calculating the regression of respiration rate on time from harvest, the only data used were those obtained after a steady state had been reached. The mean coefficients obtained for these regressions

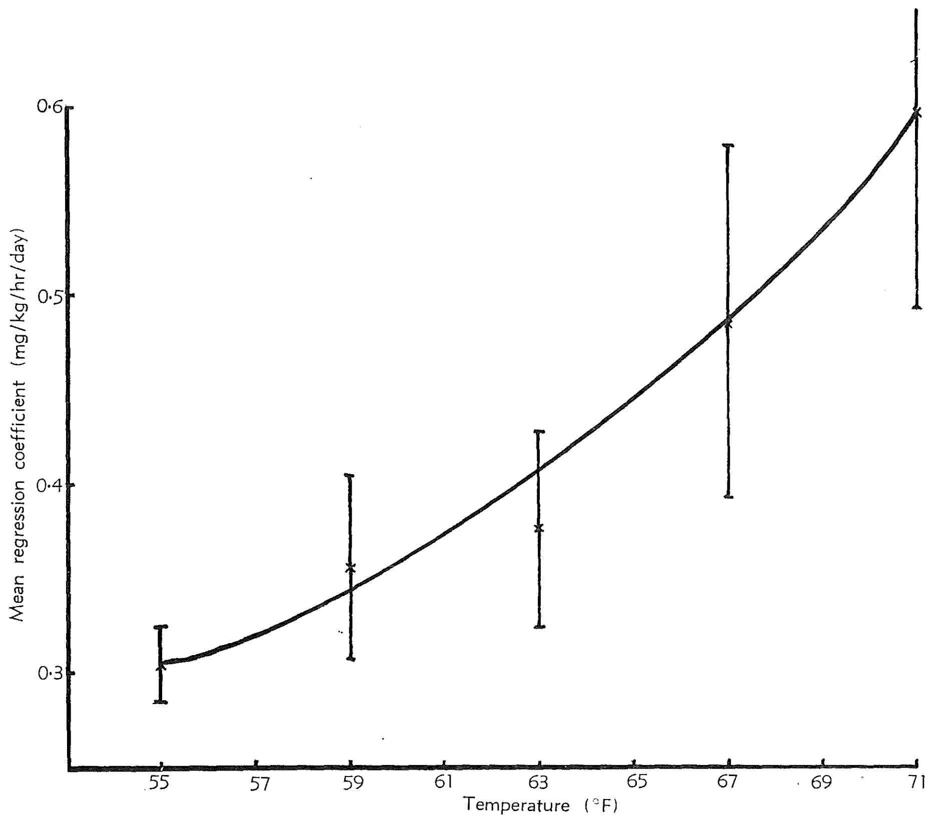

Fig. 2.—Effect of temperature on the rate of change of preclimacteric respiration rate (results of experiment 4), showing standard deviations.

(Table 2) increase with temperature (cf Figure 2, which illustrates the results of experiment 4). The mean regression constants (a, Table 2) should not be taken as the respiration rates at harvest. Due to the slight fall in respiration rate immediately after harvest, the true initial respiration rates are somewhat higher.

Mean respiration rates at maturity and mean green-lives are shown in relation to temperature in Table 3. Over the temperature range examined, respiration rate at maturity appears to be linearly related to temperature (Figure 3), while green-life appears to vary linearly but inversely with temperature (Figure 4).

TABLE 2

REGRESSION COEFFICIENTS (b) AND REGRESSION CONSTANTS (a) FOR THE REGRESSIONS OF THE PRECLIMACTERIC RESPIRATION RATE (mg/kg/hr) ON TIME FROM HARVEST (DAYS) IN RELATION TO HOLDING TEMPERATURE

Temperature (°F)	Exp. 1				Exp. 2				Exp. 3				Exp. 4			
	b		a		b		a		b		a		b		a	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
71	0·546	0·110	15·9	1·3	0·274	0·068	..	..	0·759	0·184	15·3	0·5	0·597	0·103	17·1	0·9
67	0·446	0·096	13·9	1·3	0·152	0·056	..	..	0·613	0·231	14·1	0·7	0·485	0·093	14·3	0·7
63	0·286	0·051	12·1	0·8	0·123	0·047	..	..	0·386	0·080	12·2	0·5	0·376	0·052	11·8	0·4
59	0·129	0·068	11·3	1·5	0·170	0·045	..	..	0·235	0·053	11·0	0·4	0·357	0·048	9·3	0·9
55	0·150	0·029	8·7	0·7	0·269	0·063	..	..	0·209	0·038	8·8	0·5	0·305	0·020	7·6	0·2

TABLE 3

Respiration Rate at Maturity and Green-life in Relation to Holding Temperature

Temperature (°F)	Exp. 1				Exp. 2				Exp. 3				Exp. 4			
	RR		g		RR		g		RR		g		RR		g	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
71	26·7	0·9	19·9	2·1	22·6	0·3	52·6	2·3	23·0	1·1	10·3	0·9	25·1	1·3	13·6	1·2
67	24·0	0·7	22·9	2·2	18·9	0·9	57·2	2·5	21·6	1·4	12·7	1·6	23·1	1·7	18·1	0·6
63	20·2	0·9	26·6	1·1	17·6	1·4	62·4	1·1	18·0	0·7	15·1	1·0	19·8	1·4	21·2	1·5
59	17·2	0·8	30·3	1·1	17·0	1·5	61·1	1·6	15·9	1·0	20·5	0·6	18·4	0·8	25·8	1·3
55	13·8	0·5	33·4	1·5	17·0	1·1	59·4	2·4	13·8	0·5	24·0	0·9	16·2	0·5	28·1	1·6

RR = Respiration rate (mg/kg/hr). g = Green-life (days).

The regression equations for respiration rate at maturity on temperature were as follows:

Experiment 1 $RR = 0 \cdot 813\theta - 30 \cdot 86$
Experiment 3 $RR = 0 \cdot 608\theta - 19 \cdot 84$
Experiment 4 $RR = 0 \cdot 563\theta - 14 \cdot 92$,
where RR = respiration rate (mg/kg/hr), and θ = temperature (°F).

The regression equations for green-life on temperature and average green-life at 71°F were as follows:—

		g71
Experiment 1	$g = -0 \cdot 858\theta + 80 \cdot 7$	19·9
Experiment 2	$g = -1 \cdot 230\theta + 139 \cdot 8$*	52·6
Experiment 3	$g = -0 \cdot 883\theta + 72 \cdot 1$	10·3
Experiment 4	$g = -0 \cdot 920\theta + 79 \cdot 3$	13·6

Where g = green-life (days); θ = temperature (°F); * = equation calculated from results at 71, 67 and 63°F only; and g71 = average green-life (days) at 71°F for each experiment.

These regression equations can be defined as green-life temperature coefficients in that they represent the change in green-life per degree (F) temperature change.

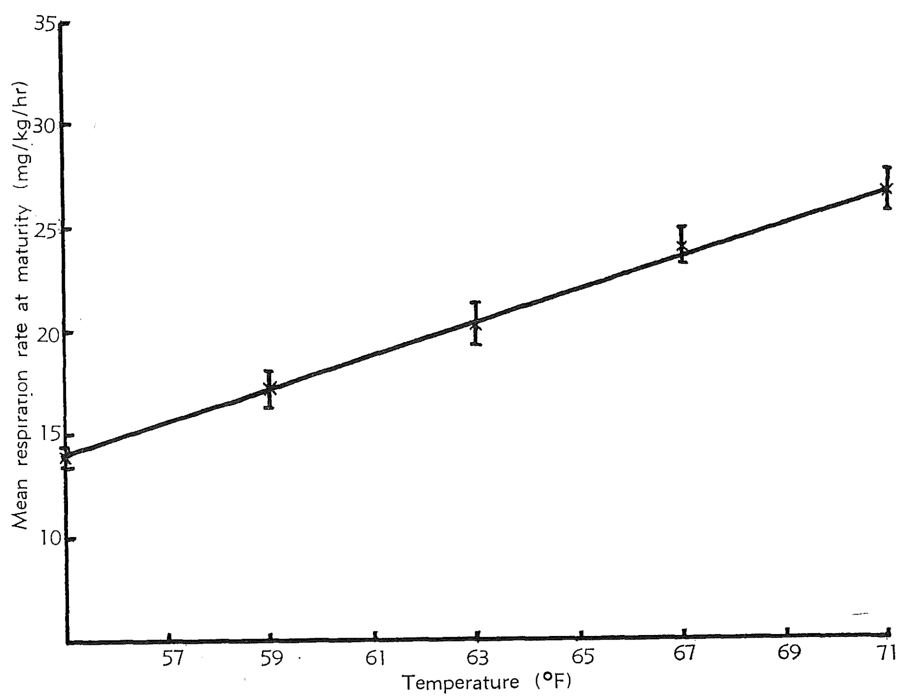

Fig. 3.—Effect of temperature on the respiration rate at maturity (results of experiment 1), showing standard deviations.

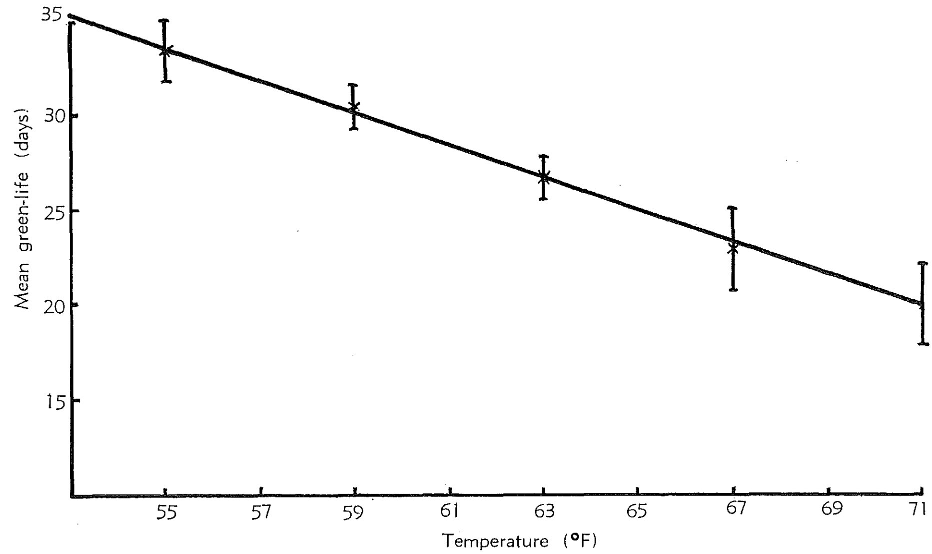

Fig. 4.—Effect of temperature on green-life (results of experiment 1), showing standard deviations.

TABLE 4

RESULTS OF EXPERIMENT 2 SHOWING ACTUAL GREEN-LIVES AT 55 AND 59°F IN RELATION TO EXPECTED GREEN-LIFE

Temperature (°F)	Expected Green-life* (days)	Actual Green-lives (days)
		62·4
		57·5
55	72·15	60·9
		59·7
		60·3
		55·8
		Mean 59·4 ± 2·4
		63·4
		61·2
		60·5
59	67·2	58·7
		62·1
		60·7
		Mean 61·1 ± 1·6

* Calculated from results obtained at 71, 67 and 63°F.

The results obtained in experiment 2 were abnormal below temperatures of 63° F and hence relationships were determined only over the temperature range 71-63° F. Using the particular equation obtained for the regression of green-life on temperature over this range (Table 5), the mean times that fruit at 59 and 55° F should have taken to ripen have been calculated. These are shown in relation to actual green-lives in Table 4. The actual green-lives are significantly different (1% level) from the calculated means.

The mean climacteric peak respiration rates, with respective standard deviations, are shown in Table 5. They obviously vary with temperature, apparently in a non-linear fashion (Figure 5).

TABLE 5

Respiration Rate (mg/kg/hr) at the Climacteric Peak in Relation to Temperature

Temperature (°F)	Exp. 1		Exp. 2		Exp. 3		Exp. 4	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
71	182	8·9	172	12·8	115	8·4	161	21·1
67	140	5·4	140	9·4	93	7·5	134	16·6
63	113	3·4	97	7·2	75	5·1	92	6·4
59	85	2·6	76	4·1	61	1·3	65	3·6
55	56	2·1	61	5·9	42	1·9	45	2·1

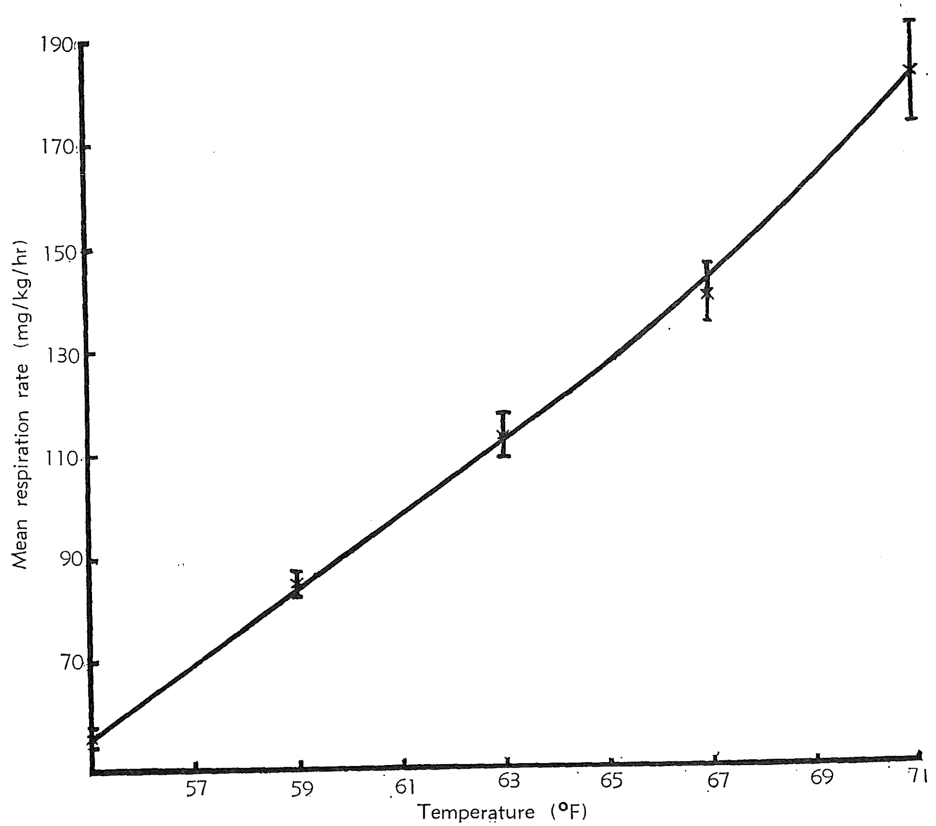

Fig. 5.—Effect of temperature on the respiration rate at the climacteric peak (results of experiment 1), showing standard deviations.

The duration of the climacteric was taken as the time from the onset of the climacteric rise to the climacteric peak, and the mean values were calculated at each temperature (Table 6). A plot of these values against temperature reveals an approximately inverse linear relationship (Figure 6).

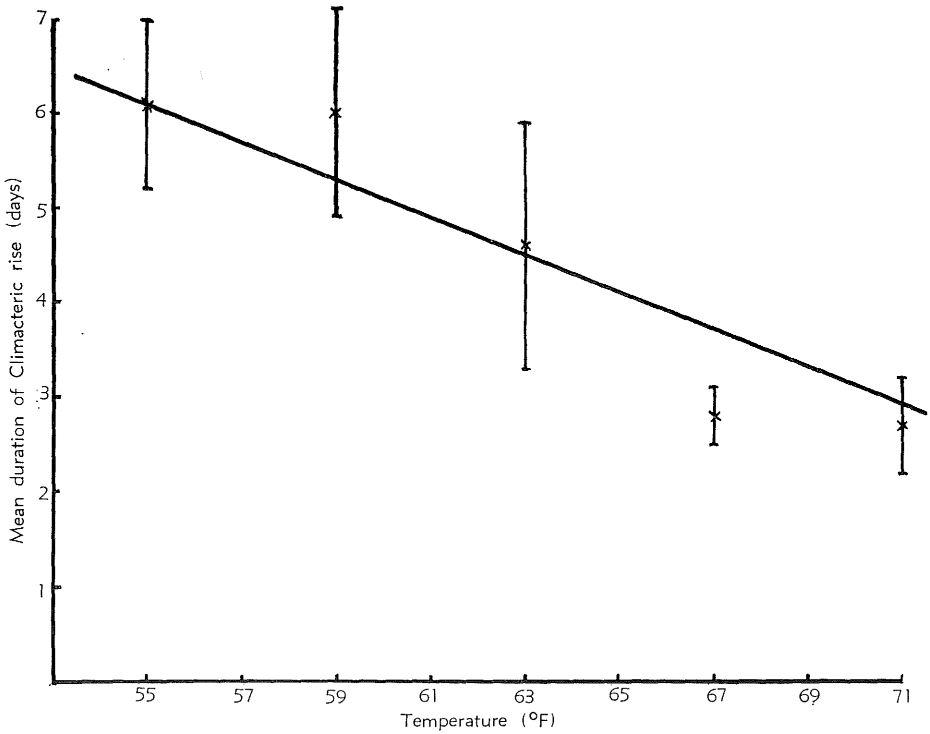

Fig. 6.—Effect of temperature on the duration of the climacteric rise (results for experiment 1), showing standard deviations.

TABLE 6

TIME (DAYS) FROM MATURITY TO THE CLIMACTERIC PEAK IN RELATION TO TEMPERATURE

Temperature (°F)	Exp. 1		Exp. 2		Exp. 3		Exp. 4	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
71	2·7	0·5	2·4	0·3	3·9	0·4	3·8	0·7
67	2·8	0·3	3·5	0·5	4·3	0·7	3·6	0·6
63	4·6	1·3	4·5	0·6	5·1	0·8	5·2	0·8
59	6·0	1·1	5·4	0·6	6·6	0·8	6·4	1·1
55	6·1	0·9	6·7	1·5	8·6	0·9	8·2	0·7
CLTC (app.)	− 0·21	. .	− 0·27	. .	− 0·29	. .	− 0·28	. .

$$\text{Approx. CLTC} = \frac{m_{55} - m_{71}}{55 - 71}$$

TABLE 7

AMOUNT OF CARBON DIOXIDE (mg/g) PRODUCED FROM HARVEST TO MATURITY (a) AND FROM HARVEST TO CLIMACTERIC PEAK (b) IN RELATION TO HOLDING TEMPERATURE

Temperature (°F)	Exp. 1				Exp. 2				Exp. 3				Exp. 4			
	a		b		a		b		a		b		a		b	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
71	10·3	1·3	17·0	1·1	26·34	2·63	31·93	1·85	4·7	0·3	11·2	0·4	6·9	0·5	15·3	1·2
67	10·5	1·4	16·0	1·6	25·20	0·61	31·92	2·85	5·4	0·6	11·3	1·3	8·1	0·6	14·8	1·3
63	10·5	0·6	17·9	2·2	24·45	0·30	30·69	1·15	5·5	0·3	11·1	0·6	8·0	0·8	14·9	0·3
59	10·6	0·4	18·0	1·8	21·66	0·62	27·67	0·57	6·6	0·3	12·7	0·6	8·6	0·3	14·9	0·7
55	8·9	0·5	14·0	0·7	18·93	0·25	25·20	2·89	6·5	0·3	12·2	0·9	8·0	0·5	14·0	0·7

TABLE 8

Regression Constants (a) and Regression Coefficients (b) for the Regressions of Preclimacteric Respiration Rates (mg/kg/hr) on Time from Harvest (days) for Individual Fruit in Relation to Holding Temperature. Also Shown are Respiration Rates (mg/kg/hr) at Maturity (c) and at the Climacteric Peak (d), and the Green-life Values in Days (g), Obtained within Each Immaturity

Immaturity	Holding Temperature 70°F					Holding Temperature 60°F				
	a	b	c	d	g	a	b	c	d	g
M1	15·5 16·0	0·490 0·400	19·3 19·4	148·5 151·0	7·7 8·7	9·1 10·2	0·417 0·337	15·1 15·3	74·5 71·0	14·5 15·3
M2	19·8 18·4	0·440 0·652	24·8 22·8	171·0 173·0	11·2 11·6	11·2 12·4	0·284 0·187	16·6 16·4	79·5 85·0	19·1 21·7
M3	16·1 15·1	0·309 0·585	18·9 21·3	163·5 172·0	9·1 10·7	9·3 8·7	0·412 0·392	18·0 17·4	75·5 75·5	20·9 22·2
M4	21·6 22·9	−0·022 0·187	21·2 25·6	175·5 162·5	14·1 14·8	12·3 12·8	0·278 0·197	20·2 18·5	86·5 86·5	28·4 29·0
M5	16·4 20·2	0·959 0·586	32·0 30·7	155·0 175·0	16·2 18·0	14·2 12·9	0·274 0·177	22·1 18·1	80·0 83·0	28·8 29·0
M6	21·3 20·3	0·419 0·164	28·8 23·4	167·5 144·0	17·8 18·8	. . . .	. . . .	. . . .	. . . .	. . . .
M7	19·7 21·2	0·307 0·303	25·4 26·7	151·0 153·0	18·5 18·2	10·8 11·1	0·232 0·293	17·5 19·8	80·0 82·0	29·0 29·9
M8	15·6 17·1	0·733 0·440	28·4 25·8	176·0 158·0	17·5 19·7	11·7 10·9	0·187 0·264	17·3 20·1	86·5 85·5	30·1 35·1
M9	19·5 19·3	0·400 0·357	27·2 26·1	162·0 161·0	19·5 19·1	12·0 11·4	0·099 0·157	15·7 16·9	85·5 89·5	37·6 34·9
M10	22·0 23·1	0·181 0·154	26·1 26·1	171·0 170·0	22·9 19·2	12·9 11·9	0·164 0·198	18·6 19·4	82·5 80·0	35·1 38·2
M11	19·0 18·2	0·305 0·315	26·2 25·7	. . . .	23·8 23·7	13·0 11·6	0·108 0·150	17·5 18·1	85·0 83·0	41·5 43·4
M12	19·5 21·6	0·138 0·146	23·2 22·8	182·5 156·0	26·6 27·8	. . . .	. . . .	. . . .	. . . .	. . . .

A figure reflecting the effect of temperature on the duration of the climacteric has been calculated by presuming linearity over the range considered and dividing the difference in duration of the climacteric by the number of degrees of temperature difference. The figure produced is called the climacteric life temperature coefficient (CLTC—Table 6).

The mean quantities of carbon dioxide produced by the bananas from harvest to maturity and from harvest to the climacteric peak, calculated as areas under the curves, are approximately constant within each experiment over the temperature range examined (Table 7).

(b) Experiment 5

The respiration rates obtained at maturity and at the climacteric peak ('c' and 'd' respectively in Table 8) show no apparent relationship to immaturity. Respiration rate was again found to increase linearly with time until maturity was reached. The corresponding regressions were calculated and the resulting coefficients and constants are also shown in Table 8, as are the actual green-lives obtained within each immaturity.

A plot of these regression coefficients against immaturity measured as green-life at 60° F reveals a linear relationship (Figure 7), with the rate of increase of preclimacteric respiration rate with time being least in the more immature fruit. The regression equation for this relationship is $b = -0 \cdot 009g + 0 \cdot 506$ (where b = regression coefficient and g = green-life), with the data having a correlation coefficient of $-0 \cdot 7862$, which is significant at the $0 \cdot 1\%$ level.

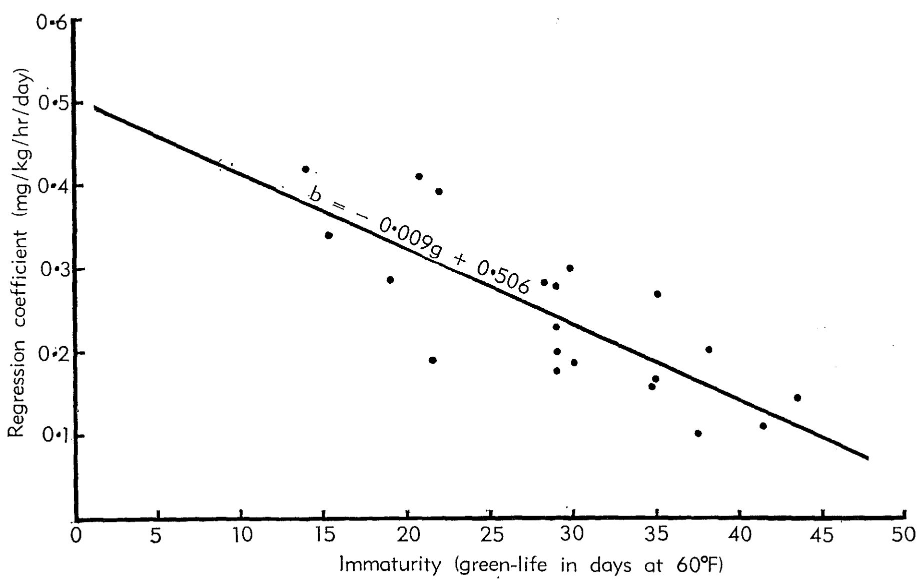

Fig. 7—Effect of immaturity on the rate of change of preclimacteric respiration rate.

TABLE 9

MEAN GREEN-LIFE (g), IN DAYS, OF EACH IMMATURITY AT TWO TEMPERATURES, WITH THE RESULTING GREEN-LIFE TEMPERATURE COEFFICIFNT (DAYS/°F)

Immaturity	g (60°F)	g (70°F)	GLTC
M1	14·9	8·2	0·67
M2	20·4	11·4	0·90
M3	21·6	9·9	1·17
M4	28·7	14·5	1·42
M5	28·9	17·1	1·18
M6	. .	18·3	. .
M7	29·5	18·5	1·11
M8	32·6	18·6	1·40
M9	36·3	19·3	1·70
M10	36·7	21·1	1·56
M11	42·5	23·8	1·87
M12	. .	27·2	. .

$$\text{GLTC} = \text{Green-life temperature coefficient} = \frac{g60 - g70}{60 - 70}$$

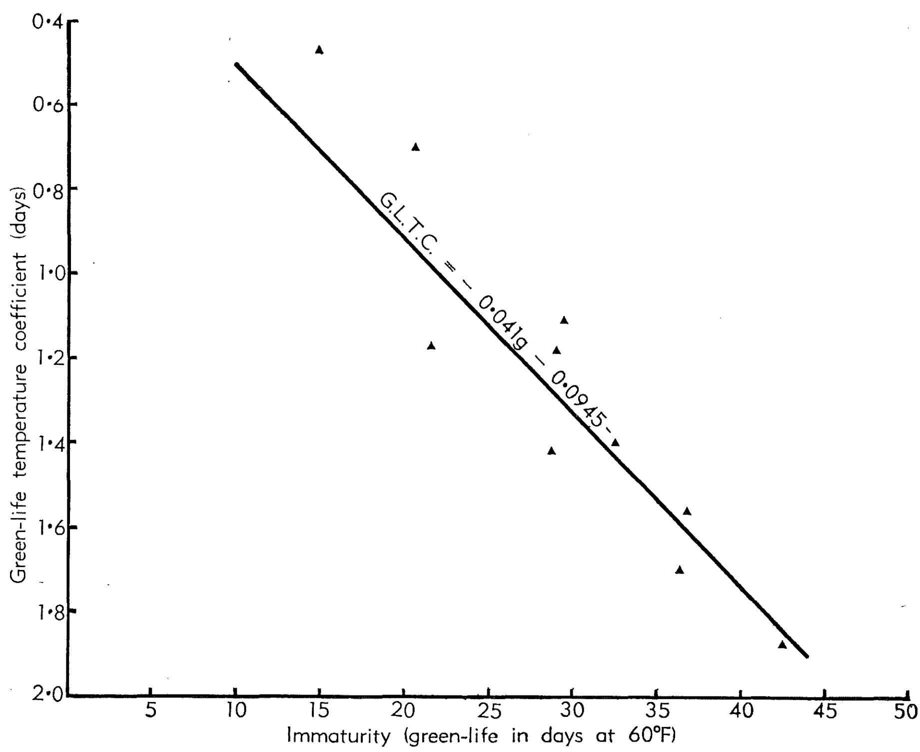

Fig 8.—Effect of immaturity on the green-life temperature coefficient.

The immaturities of the fruit selected are shown in Table 9 in the form of mean green-lives at 70 and 60° F, where each mean is obtained from two fruits. Calculated green-life temperature coefficients (Table 9) are found to vary linearly with immaturity (Figure 8). The regression equation for this relationship is:

GLTC = —0·041g — 0·0945 (where GLTC = green-life temperature coefficient and g = green-life at 60°F). The data have a correlation coefficient of —0·9464, which is also significant at the 0·1% level.

The amount of carbon dioxide produced up to maturity is shown in relation to immaturity in Figure 9. The correlation coefficient for these data is 0·9816, which is significant at the 1% level.

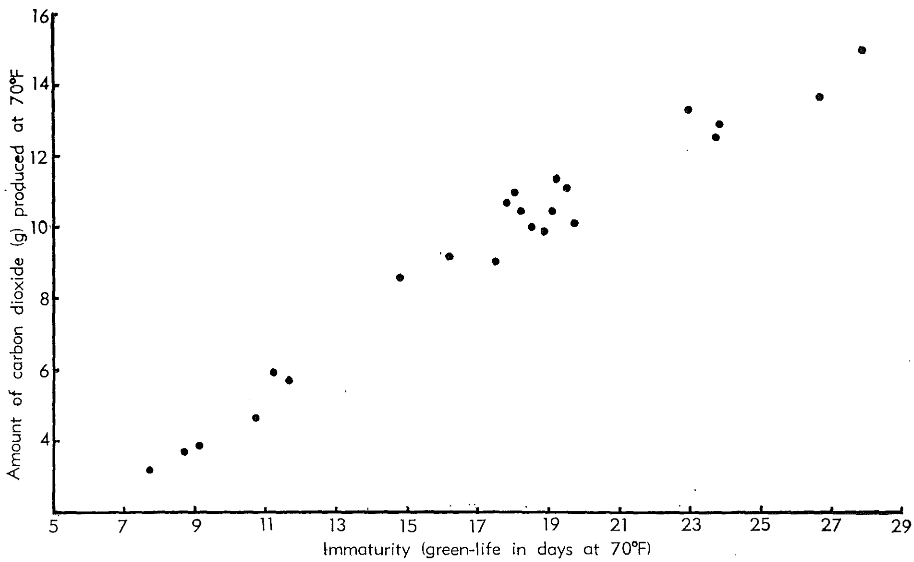

Fig. 9.—Effect of immaturity on the amount of carbon dioxide produced up to maturity.

V. DISCUSSION

(a) Respiration Rate During the Preclimacteric Phase

Biale (1960) stated: "The characteristic respiratory features of the climacteric include a slow decline in oxygen uptake and carbon dioxide evolution following harvesting, until the climacteric minimum is reached". The existence of a climacteric minimum has been reported by several other workers (Deullin 1952; James 1953; Wardlaw 1961; Burg and Burg 1962). In the present work, the respiratory data give no indication of such a minimum. From 48 hr after harvest, respiration rate increased linearly with time over the remainder of the preclimacteric period (Figure 1). This result is in agreement with the results of Burg and Burg (1965) for apple bananas and is also indicated by the results of Tsalpatouros (1956*a*). As is shown in Figure 2, this rate of increase is dependent on temperature, probably being exponentially related to it.

The rate of change of preclimacteric respiration rate has also been shown to be a function of the immaturity of the fruit (Figure 7). There is a linear relationship between this rate of change and immaturity, with most immature fruit exhibiting the slowest rate of change.

(b) Respiration Rate at Maturity

Respiration rate has been shown to vary exponentially with temperature (Gore 1911; Gane 1936; James 1953; Tomkins 1966). For such a result to have physiological significance, the fruit used would need to have been of the same physiological age (Forward 1960). Therefore in such studies the length of time fruit were held at any temperature would have to have been kept to a minimum, since the rate of physiological ageing has a high sensitivity to temperature (Forward 1960). Blake and Peacock (unpublished data), using preclimacteric bananas, have confirmed that an exponential relationship is obtained, but only if the length of time fruit are held at each temperature is kept as short as possible; otherwise the relationship departs from a truly exponential one.

In the present study, the technique used has produced respiration rate data at a common physiological stage (at maturity), but at different points in time, and it could be expected that these data would also show an exponential relationship with temperature. However, this was not the case, a linear relationship being obtained (Figure 3). This result is supported by data taken from Tsalpatouros (1956*a*, Figure 10).

(c) Relationship between Green-life and Temperature

With climacteric-type fruit there have been very few investigations where the effects of temperature on the duration of the preclimacteric state have been determined. There have been several studies concerning the effect of temperature on the time taken for fruit to become eating ripe (Kidd and West 1942; Tindale, Trout and Huelin 1938). However, in these studies the fruit passed through both the preclimacteric and the climacteric states, during which the effects of temperature can be different (Biale 1960).

The results reported here show that over the temperature range examined there is an inverse and linear relationship between temperature and green-life (Figure 4). The slope of this relationship has been called the green-life temperature coefficient. Kidd and West (1930) with apples, and Kidd and West (1936, 1942) and Tindale, Trout and Huelin (1938) with pears, have shown that the storage life/temperature relationships for these fruits is a curvilinear one. Also, Simmonds (1959), quoting Gane, indicates that a similar result holds for bananas. It is difficult to compare their results with those presented here, since in these cases storage life was defined on an economic or human preference basis, the fruit actually passing through several distinctly different physiological states. Another factor which could account for this relationship difference is the temperature range used in the present work. Over this temperature range the results of the above workers could be regarded as linear.

The results have also indicated that the green-life temperature coefficient is a linear function of immaturity (Figure 8); hence for bananas a given temperature change will give a constant proportional change in green-life. This result could logically be expected.

The apparent shortening of life which occurred at 55 and 59°F in experiment 2 (Table 4) suggests that the fruit was being stimulated to ripen (senesce) by the low temperatures. Although no injury was apparent in these bananas, it could be that this stimulation represents the first stage of low-temperature injury. It has been shown that apples susceptible to low-temperature injury depart from the normal storage life/temperature relationship for this fruit (Kidd and West 1927). The results for experiment 2 represent a similar deviation from a normal pattern. It would be logical to expect that low-temperature injury would be a time x temperature effect. Hence the appearance of abnormal behaviour in experiment 2 is probably due to the fact that these fruit were of such an immaturity that they could remain in a green condition at 55 and 59°F long enough to be affected. Fruit with a shorter green-life would probably behave in the same way if exposed to a suitable low temperature.

(d) Respiration Rate at the Climacteric Peak

As would be expected, climacteric peak respiration rates were dependent on temperature (Figure 5). Variability of data and the small temperature range involved (55–71°F) make it impossible to determine whether this relationship with temperature is logarithmic or linear. The data appear to more closely fit a logarithmic relationship, which would be in agreement with Simmonds (1959). From the data in Table 10, climacteric peak respiration rates bear no relationship to fruit maturity.

(e) Relationship Between the Duration of the Climacteric and Temperature

A plot of the data in Table 6 shows an approximately inverse linear relationship between the duration of the climacteric and temperature (Figure 6). Kidd and West (1936) found this result with apples and pears. Gane (1936), using bananas, claimed that the relationship is an exponential one, and that $\log 1/t = b\,\theta$, where t is the duration of the climacteric in days and θ is temperature (°C). The narrow temperature range and data variability make it difficult to distinguish between the two.

Kidd and West (1936, 1937), working with Doyenne du Comice and William's Bon Chretien pears respectively, noted that the effect of temperature on the duration of the preclimacteric period is small compared to its effect on the duration of the climacteric. This result is in direct contrast with the regression equations for green-life on temperature and the data shown in Table 6. The regression coefficents are the green-life temperature coefficients obtained in experiments 1–4. Comparing these with the climacteric-life temperature coefficients (Table 6), it can be seen that a reduction in temperature affects the duration of the preclimacteric period between three and four times more than it affects the duration of the climacteric.

(f) Carbon Dioxide Production

The production of carbon dioxide by the banana is approximately constant within each experiment over the temperature range examined (Table 7). A similar result was obtained with apples (Kidd and West 1930) and with cucumbers (Eaks and Morris 1956). However, the quantities of carbon dioxide produced at 55 and 59°F in experiment 2 depart from constancy. These decreased values are interpreted as being a result of the earlier initiation of senescence believed to have occurred in these instances. The quantity of carbon dioxide produced at 55°F in experiment 1 also appears abnormally low. This may indicate that the onset of senescence was accelerated in this instance also. Reduced total carbon dioxide production at low temperatures has also been shown to occur with cucumbers (Eaks and Morris 1956).

These results are not in agreement with those of Tsalpatouros (1956*a*), who quoted figures for the preclimacteric period which show that the amount of carbon dioxide produced up to maturity decreases continuously over the range 88 to 54·5°F (see Figure 10).

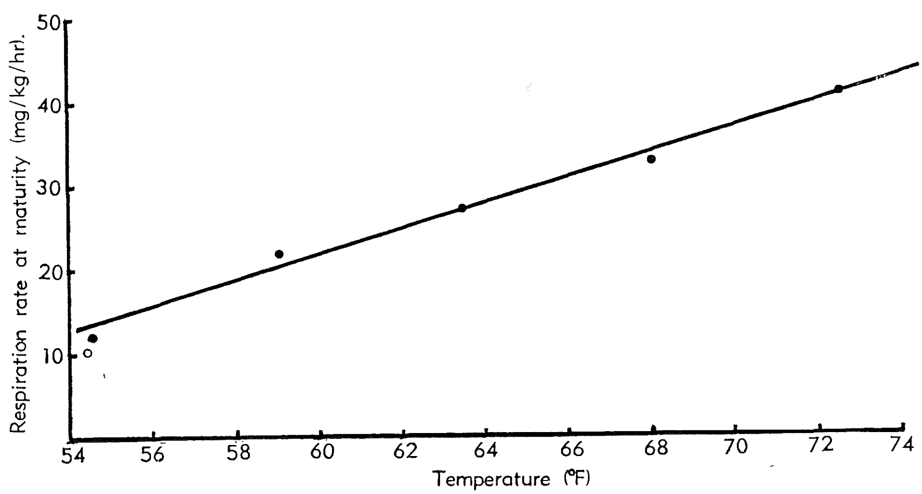

Fig. 10.—Relationship between respiration rate at maturity and temperature obtained from data presented by Tsalpatouros (1956A).

From the results of experiment 5 (Figure 9), the amount of carbon dioxide produced up to maturity is a function of the immaturity of the fruit, at least over the range of immaturities examined. If the amounts of carbon dioxide produced at 71°F in experiments 1–4 (Table 7) are compared to the green-life of the fruit used in each experiment (page 155), it can be seen that the amounts produced do rank in the same order as the green-lives and approximate the relationship shown in Figure 9.

VI. ACKNOWLEDGEMENTS

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