A STUDY OF DEVELOPMENTAL CHANGES IN COMPOSITION OF THE MACADAMIA[1]

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(WITH SIXTEEN FIGURES)

Introduction

In recent years the macadamia [*Macadamia ternifolia* F. von Mueller, var. *integrifolia* (Maiden and Betche) Maiden] has assumed increasing commercial importance in the Hawaiian Islands. The Hawaii Agricultural Experiment Station has placed emphasis on establishing varieties and developing improved cultural practices, and toward the latter end it has become desirable to secure knowledge concerning the normal physiological development of this interesting fruit. The present paper sets forth results of a study on the changes in size, weight, and chemical composition of the macadamia fruit from flowering to maturity.

Preliminary work (**7**) has shown that this fruit requires from 215 to 230 days after flowering to reach maturity, and that the mature dry embryo contains about 75 per cent. oil. Very few studies have been reported on the physiological development of perennial oil-seed fruits since THOR and SMITH (**11**) reported on the pecan. Studies on oil-seeds have been largely confined to quick growing crops such as cotton (**4**), flax (**2**), rape, hemp, poppy, and sunflower (**5**). CHEEL and MORRISON (**1**) describe some characteristics of macadamia oil, but, other than a preliminary paper by the writer (**7**), no physiological account of fruit development in macadamia has thus far appeared.

Materials and methods

Fruits were collected at five intervals from flowering to maturity from five well-bearing seedling trees, selected on a basis of apparent uniformity in fruiting characteristics, in a commercial orchard near Honolulu. Figure 1 shows the approximate size of the macadamia at the various stages of maturity selected for analyses.

The first samples were taken approximately 90 days after flowering; before this time the embryos were too small to analyze. One hundred fruits from each tree were used for the first two samplings and fifty for the later samples. The sample from each tree was weighed and the average weight of the fruit determined. Each fruit was sliced through the middle; the diameter of the unhusked nut, the thickness of the shell, and the diameter of the embryo were measured. The material was then separated into husks,

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shells, and embryos[2] and the fresh weights of the fractions from each tree obtained. Dry weights were obtained after the fractions had been held at 100° C. for 2 to 3 hours and under vacuum at 80° C. for 48 hours.

Preliminary work (7) has shown that the husk and shell change in composition very little during the growth and maturity of the macadamia; thus in the present study chemical analyses were made of the kernel (embryo) only.

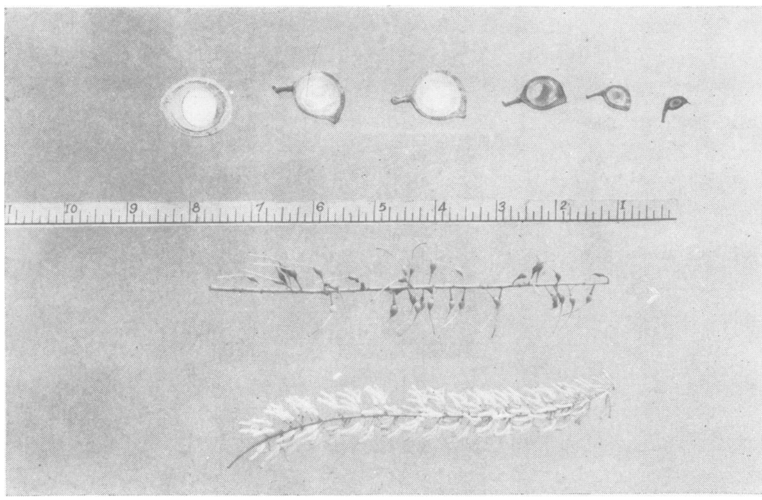

FIG. 1. Lower, macadamia flower cluster; middle, cluster of young nuts; upper, cross section of fruit showing stages at which samples were taken (fruit at extreme right too small for sampling).

OIL

After the first two samples the embryos could not be ground without loss of oil, so the samples were chopped with a sharp knife. The finely chopped material was re-dried in a vacuum oven at 80° C. for 24 hours, and 2.5-gm. aliquots were weighed into alundum cups and extracted for 6 hours with anhydrous alcohol-free ether in a continuous drip extractor. The ether was then removed, and the extract dried, weighed, and reported as oil.

SUGARS

The oil-free residue was extracted with 80 per cent. alcohol. An aliquot of the extract was cleared with neutral lead acetate and potassium oxalate; reducing sugars were determined by the method of STILES, PETERSON, and FRED (10). Sucrose was obtained by the same method after inversion with invertase.

[2] The so-called nut of the macadamia is a true seed; the shell is composed of the outer integument while the edible portion, or kernel, is the embryo (6).

NITROGEN

Soluble nitrogen was determined on aliquots of the alcoholic extract by the reduced-iron method of PUCHER, LEAVENWORTH, and VICKERY (9), adapted to the micro-Kjeldahl method described by PREGL (8). Insoluble nitrogen was determined on the residue from the alcoholic extraction by the micro-Kjeldahl method of PREGL. At all times the embryo gave a negative test with diphenylamine, indicating the complete absence of nitrate from this organ.

Presentation and discussion of data

The environmental conditions prevailing during the growth of the fruit, including the weekly average day and night temperatures, the weekly average of sunlight intensity, and the weekly rainfall, are shown in figure 2.

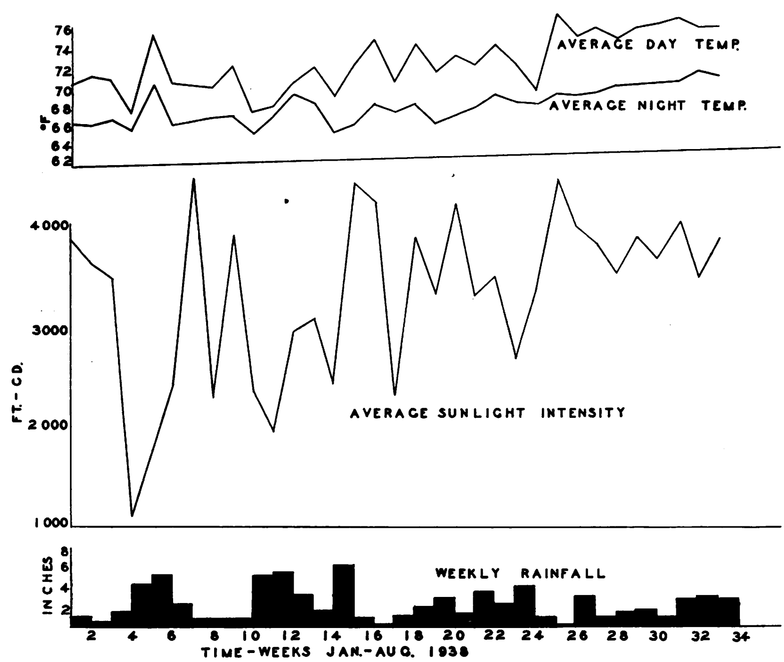

FIG. 2. Rainfall, sunlight, and temperature at Nutridge, Oahu.

The accumulation of dry matter in the macadamia fruit and its parts is shown in tables I and II and figures 3 and 4. The remainder of the analytical data are presented graphically in figures 5 to 16. The graphs show the curves for the individual seedling trees so that the variations are more, in some cases, than if a single clone had been available or if the fruit from several trees had contributed to a single sample. In most instances, however, the trends of development are similar.

TABLE I

SIZE CHANGES IN THE MACADAMIA FRUIT DURING DEVELOPMENT

Date	Days after flowering	Tree no.	Average fresh weight of whole fruit	Average diameter of unhusked nut	Average diameter of embryo	Average thickness of shell	Condition of shell
			gm.	*mm.*	*mm.*	*mm.*	
4–13–38	90	2	3.02	17.92	9.08	2.32	Soft
5– 4–38	111		8.64	24.56	16.68	2.10	"
	111		9.30	25.44	16.88	2.06	Hard—white
5–19–38	126		10.24	26.09	16.86	2.29	" —light brown
7–13–38	185		11.32	26.98	17.38	1.83	" —brown
8–22–38	215		12.37	27.76	17.54	2.15	" —dark brown —nuts mature
4–13–38	90	4	3.61	17.44	9.64	2.12	Soft
5– 4–38	111		7.76	23.68	15.92	2.24	"
	111		8.58	24.44	16.00	2.14	Hard—white
5–19–38	126		10.70	26.91	17.95	2.51	" —light brown
7–13–38	185		12.42	28.24	17.76	2.36	" —brown
8–22–38	215		13.52	28.91	18.20	2.74	" —dark brown —nuts mature
4–14–38	90	6	7.33	24.02	15.92	1.97	Soft
5– 5–38	111		12.92	27.48	18.42	2.13	Hard—white
5–20–38	126		10.29	26.26	17.60	2.08	" —light brown
7–14–38	185		13.72	28.68	18.08	2.12	" —brown
8–23–38	215		13.51	28.70	18.18	2.17	" —dark brown —nuts mature
4–14–38	90	7	6.60	22.14	14.24	2.09	Soft
5– 5–38	111		13.08	28.38	18.42	2.61	Hard—white
5–20–38	126		14.14	28.94	19.00	2.43	" —light brown
7–14–38	185		17.10	30.70	19.62	2.28	" —brown
8–23–38	215		17.26	30.82	20.00	2.32	" —dark brown —nuts mature
4–14–38	90	9	4.32	19.28	11.00	1.75	Soft
5– 5–38	111		13.32	28.70	18.94	2.15	Hard—white
5–20–38	126		13.92	28.78	18.88	2.22	" —light brown
7–14–38	185		14.70	29.64	18.90	1.86	" —brown
8–23–38	215		16.00	30.22	19.76	1.93	" —dark brown —nuts mature

GROWTH OF THE MACADAMIA FRUIT

The data of table I show the changes with time in size and fresh weight of the fruit. In no case had the shells hardened in the 90-day sample; at 111 days it will be noted that all the fruit from trees 2 and 4, although of the same age, were not at the same stage of development. The shell was soft on a part of the fruit and on the remainder the shells had hardened; all of the fruit from trees 6, 7, and 9 had hard shells at 111 days. From table I it is apparent that by the time the shell hardened the fruit had reached approximately 70 per cent. or more of its final fresh weight. After the shell hardened the diameter of the embryo and the thickness of the shell increased only slightly.

TABLE II

DRY WEIGHT CHANGES IN THE MACADAMIA FRUIT

Date	Days after full flower	Tree no.	Average dry weight per fruit of				Relation to total dry weight of		
			Whole fruit	Husk	Shell	Embryo	Husk	Shell	Embryo
			gm.	*gm.*	*gm.*	*gm.*	%	%	%
4–13–38	90	2	0.59	0.46	0.12	0.01	77.6	20.2	2.2
5– 4–38	111		1.32	0.95	0.48	0.09	62.3	31.7	6.0
	111		2.47	1.06	1.40	0.21	42.9	48.6	8.5
5–19–38	126		3.59	1.17	1.99	0.43	32.6	55.4	12.0
7–13–38	185		5.32	1.58	2.40	1.34	29.7	45.1	25.2
8–22–38	215		6.31	2.00	2.84	1.47	31.7	45.0	23.3
4–13–38	90	4	0.64	0.46	0.15	0.02	72.6	23.8	3.6
5– 4–38	111		1.37	0.80	0.48	0.09	58.4	35.1	6.5
	111		1.49	0.50	0.83	0.16	33.7	55.4	10.8
5–19–38	126		3.32	1.02	1.86	0.44	30.8	55.9	13.3
7–13–38	185		6.37	1.48	3.40	1.49	23.2	53.4	23.4
8–22–38	215		9.38	3.82	3.85	1.71	40.7	41.1	18.2
4–14–38	90	6	1.41	0.92	0.40	0.09	65.4	28.2	6.4
5– 5–38	111		4.28	1.26	2.16	0.86	29.5	50.5	20.0
5–19–38	126		3.87	1.06	1.93	0.88	27.4	49.8	22.8
7–13–38	185		4.48	1.76	0.80	1.92	39.3*	17.9*	42.8*
8–22–38	215		6.59	1.91	2.84	1.84	29.0	43.1	27.9
4–14–38	90	7	0.84	0.52	0.26	0.06	62.0	31.0	7.0
5– 5–38	111		4.96	1.47	2.59	0.90	29.6	52.3	18.1
5–19–38	126		6.08	1.48	3.31	1.29	24.3	54.4	21.3
7–13–38	185		8.68	2.38	4.06	2.24	27.4	46.8	25.8
8–22–38	215		8.89	2.47	4.11	2.31	27.8	46.2	26.0
4–14–38	90	9	0.90	0.69	0.17	0.04	76.8	19.1	4.1
5– 5–38	111		4.08	1.60	1.94	0.54	39.2	47.5	13.3
5–19–38	126		5.40	1.83	2.61	0.96	33.9	48.3	17.8
7–13–38	185		6.21	2.02	2.64	1.55	32.5	42.5	25.0
8–22–38	215		6.90	2.31	2.98	1.61	33.5	43.2	23.3

* It may be seen from table I that the fruits in this particular sample were small with thin shells, hence the seeming discrepancies in these figures.

The data of table II show the changes in dry weight with time in the macadamia fruit, while the graphs of figures 3 and 4 show the moisture changes. It will be noted from table II that there was an increase in total dry weight of the fruit and its parts from the first to the last sampling date (except for the 4th sample in tree no. 6 in which the sampled nuts were small (see table I). This is in contrast to the total fresh weight shown in table I, in which the increase was slight after the shells became hard and light brown. Figures 3 and 4 indicate a marked decrease in moisture content of the embryo and shell, which accounts for the lack of increase in total fresh weight even though the dry weight is increasing.

CHEMICAL CHANGES IN THE MACADAMIA EMBRYO

OIL.—Figures 5 and 6 present the data on oil formation in the macadamia embryo. During the first 90 days after flowering there was very little oil formation and only slight enlargement of the embryo. Thereafter the embryo began to enlarge, and oil formation was rapid so that 40 days later, or about 130 days after flowering, the oil had reached more than half of the final concentration. During the last 30 days before maturity there was very little increase in the percentage concentration of oil. There is much more variation between the individual trees on the basis of total oil per fruit than

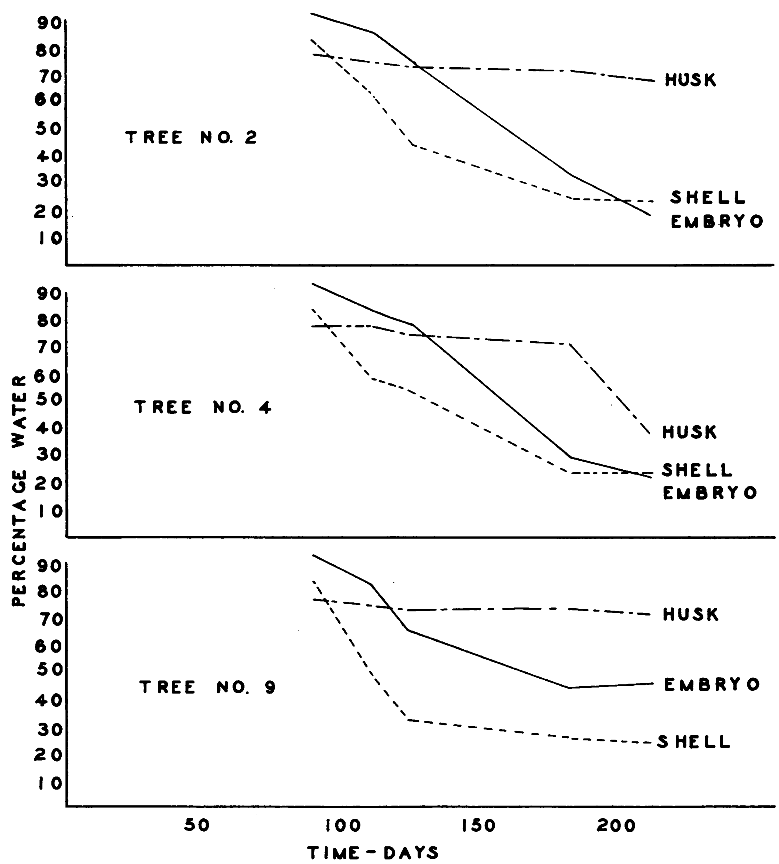

FIG. 3. Moisture changes in the parts of the macadamia fruit, trees 2, 4, 9.

there is on the percentage basis, as seen from a comparison of figures 3, 4 and 5. This difference is attributable to the variations in the size of the fruit.

In three cases the quantity of oil per embryo increased until the time of harvest, while in two cases there were slight drops. In considering an average of the five trees, however, the total oil per embryo showed an almost straight line increase from the beginning of oil formation at 90 days after flowering until maturity 215 days after flowering. This uniform gain is in

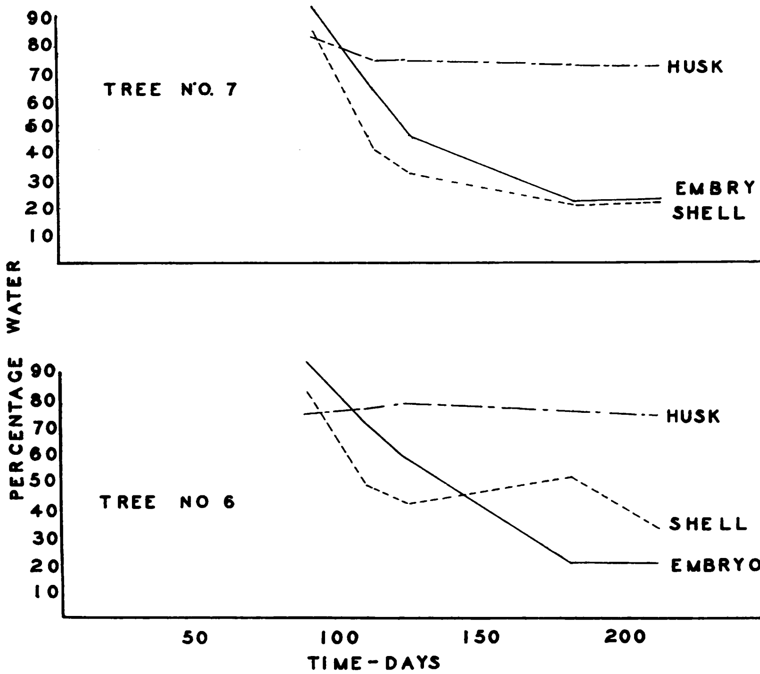

FIG. 4. Moisture changes in the parts of the macadamia fruit, trees 6, 7.

contrast to the pecan (**11**) which shows no increase in amount of oil per nut during the 25 days preceding harvest. Why the total oil per embryo of two trees should have decreased is not clear, although it is possible that the phenomenon will prove to be related to the beginning of germination of the embryo. Since a part of the fruit for the last sample was harvested from the ground, in the commercial manner, and since the macadamia germinates

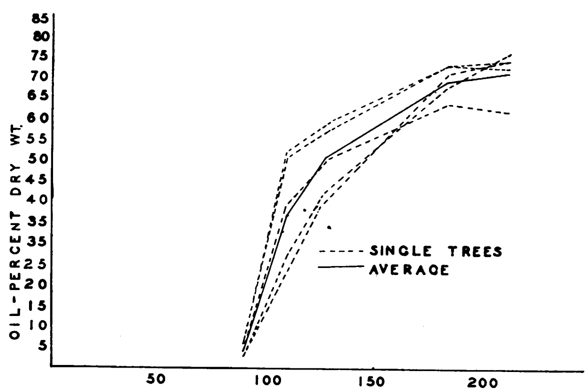

FIG. 5. Changes in oil content during development of the macadamia embryo.

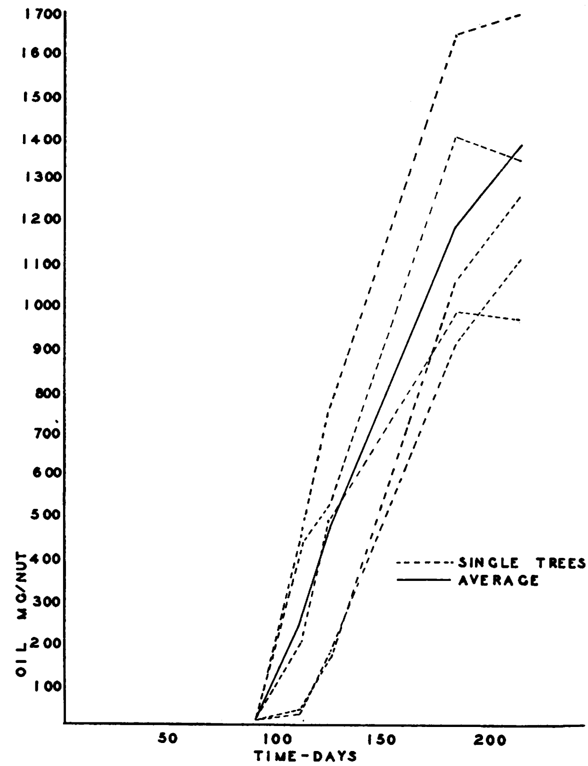

FIG. 6. Changes in oil content during development of macadamia embryo.

readily (in some cases before the nuts drop), some germination may have begun in these two samples although no detectable growth had occurred.

OIL-FREE SOLUBLE SOLIDS

Figures 7 and 8 show the changes in oil-free soluble solids of the embryo. On the dry weight percentage basis, there was a rapid decrease from the 90th to the 111th day and then a more gradual decrease until the 215th day, at which time the fruits were considered mature. On the basis of milligrams per embryo, however, the oil-free soluble solids showed an increase until the fourth sampling date, 185 days after flowering, followed by a slight decrease between the 185th and 215th days. The variation between these two figures demonstrates the danger of expressing data on a percentage of dry weight basis, especially when there is a second factor (the rapidly increasing oil in the present case).

SUGARS

Figures 9, 10, 11, and 12 show the sugar changes in the macadamia embryo during development. From figure 9 it is noted that the percentage of reducing sugar fell to a low level at 126 days and remained low until the 185th day; thereafter a slight increase occurred to the last harvest at 215 days. The explanation for this increase in reducing sugar is not clear. As discussed under oil, it might have been caused by the beginning of germination. Another plausible explanation is that, after the rate of formation

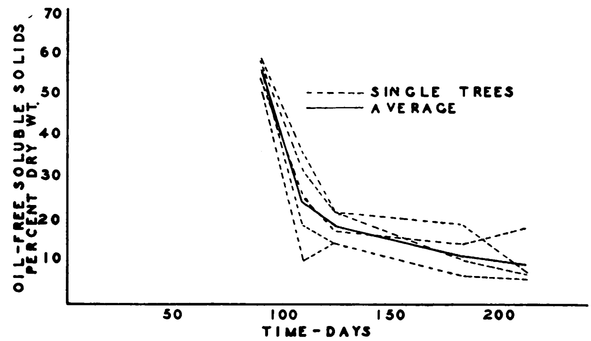

FIG. 7. Oil-free soluble solids.

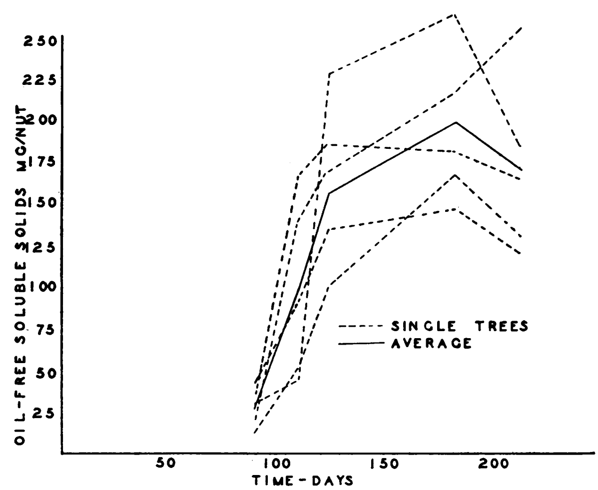

FIG. 8. Oil-free soluble solids.

of oil has decreased, the movement of carbohydrates into the fruit is not retarded proportionally so that reducing sugars accumulate in the embryo. No starch was found in the embryo at any time. Figure 11 shows the quantity of reducing sugar per embryo. The average for the five individual trees shows an increase in total amount up until the 126th day. Beginning at 126 days there was a decrease to the 185th day and then a marked increase to maturity.

Figure 10 shows that sucrose increased, on a percentage basis, until about the 126th day and then gradually decreased to a minimum at maturity. The quantity of sucrose per embryo (fig. 12) also increased until about the 126th

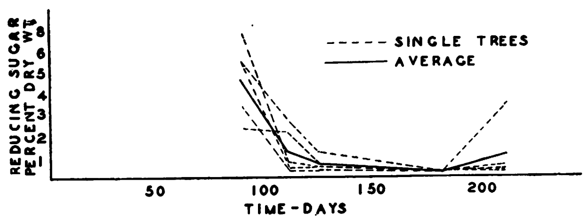

FIG. 9. Changes in reducing sugar content during development of the macadamia nut.

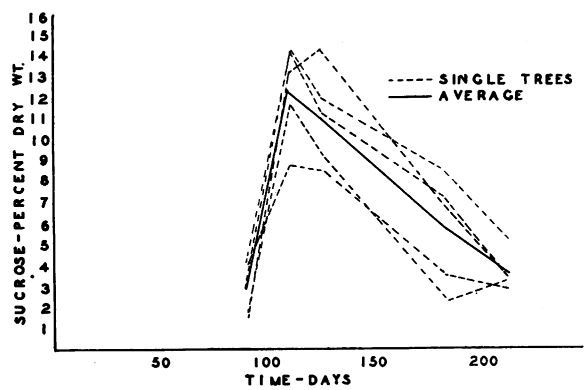

FIG. 10. Changes in sucrose content during development of the macadamia nut.

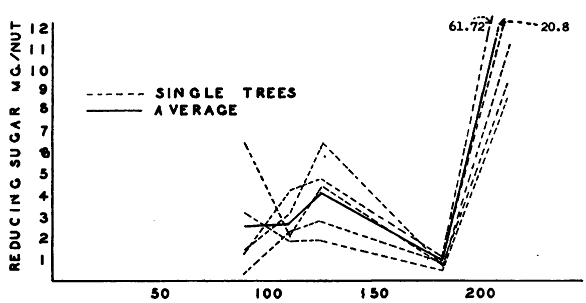

FIG. 11. Changes in reducing sugar content during development of the macadamia nut.

day after flowering, but the total amount remained more or less constant until the 185th day, after which there was a slight decrease to maturity.

NITROGEN

Figures 13 to 16 present the data on changes in nitrogen during development of the embryo. Nitrate-free soluble nitrogen maintained a constant low percentage value after 126 days but on the basis of quantity per embryo it reached a minimum at 111 days and then increased to the 185th day. There was a slight drop between the 185th and 215th days. Insoluble nitrogen (fig. 14), on a percentage basis, reached a maximum at 126 days, de-

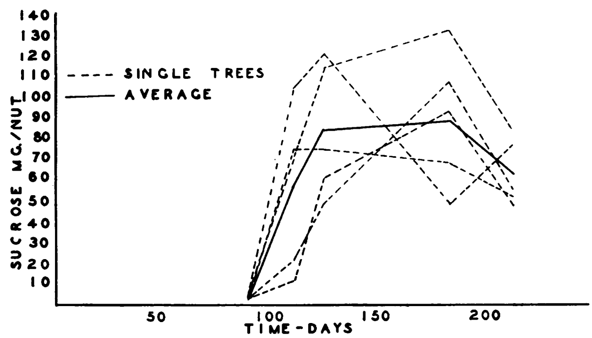

FIG. 12. Changes in sucrose content during development of the macadamia nut.

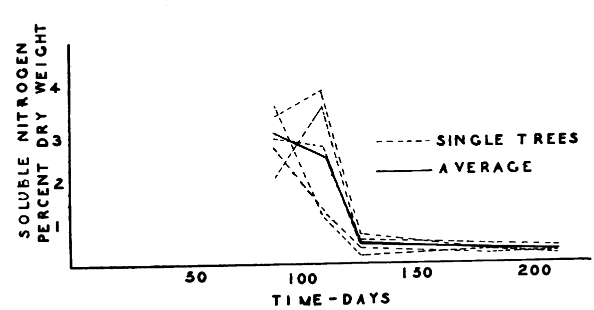

FIG. 13. Changes in soluble nitrogen during development of the macadamia nut.

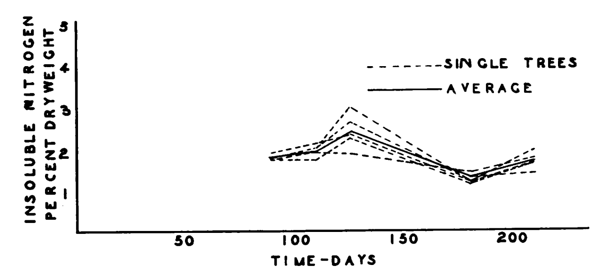

FIG. 14. Changes in insoluble nitrogen during development of the macadamia nut.

creased to the 185th day, then increased slightly to maturity. When the total weight of insoluble nitrogen per embryo (fig. 16) is considered, there was an increase from the first to the last sample. The total amount of nitrogen (insoluble plus soluble) per embryo also increased throughout the development of the fruit.

Summary

1. A study was made of the physiological development of the macadamia embryo. No chemical analyses are presented for any parts of the fruit other than the embryo, since preliminary work has shown very little change in the husk and shell except during early stages.

2. The development of the fruit is characterized by two distinct periods:

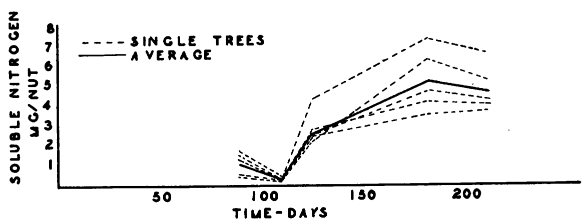

FIG. 15. Changes in soluble nitrogen during development of the macadamia nut.

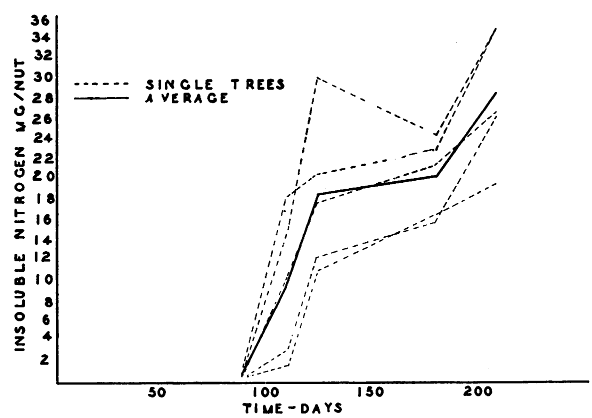

FIG. 16. Changes in insoluble nitrogen during development of the macadamia nut.

the first is from flowering to the end of 90 days, during which very little oil is formed and the embryo does not enlarge sufficiently for analysis; the second is from 90 days to maturity, a period of about 125 days, during which oil is formed and the major expansion of the embryo occurs.

3. The total amount of sugar present increases during the early oil formation but decreases as maturity is attained.

4. Protein synthesis occurs during the same period as oil synthesis.

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