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THE NUTRITIONAL VALUE OF MARINE ZOOPLANKTON WITH A CONSIDERATION OF ITS USE AS AN EMERGENCY FOOD [1]

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INTRODUCTION

It has long been realized that the waters of the earth contain a larger total amount of living organisms than does the land because of their much greater extent, and therefore offer a larger potential food supply for man and other terrestrial organisms. This aquatic food resource has been drawn upon by man chiefly in the form of his catch of fish, mollusks, and the higher crustacea. These animals form only a small part of the life in the sea. Furthermore, such organisms are either at the end or near the end of the aquatic food chains. From an understanding of the dynamics of production, we know that organisms near the beginning of the food chains are produced at a higher rate and their standing crop is often greater (Clarke, '46). In an effort to improve the efficiency with which we use the food resources of our marine and inland waters, we should therefore consider whether we could not utilize to some extent organisms near the base of the production pyramid, such as the plankton,[3] as well as those at its peak. Only a small fraction of the populations at the lower trophic levels actually go into the formation of the fish and other animals now harvested by man.

The possibility has been discussed previously of obtaining plankton of a suitable nature and in sufficient abundance to serve as a source of food for man or domestic animals (Clarke, '39; Hardy, '41; Juday, '43; and Shropshire, '44).[4] However, practically no information has been available on the nutritive value which could be derived from the plankton by terrestrial animals, and more information was needed on the variations in the availability and chemical composition of the plankton before any general conclusions could be reached. The present investigation was undertaken to secure pertinent data on these points. The nutri-

[1] This investigation was made for the Woods Hole Oceanographic Institution under contract with the Air Material Command (Aero-medical Laboratory) of the Army Air Force, Wright Field, which has given permission for its publication. The opinions presented here are those of the authors and do not necessarily reflect the official opinion of the Army.

[2] Contribution No. 425.

[3] Since the preparation of this report we have been informed by Dr. S. P. Chu of the National University of Shantung that along the northern coast of China a "shrimp paste" is made from the plankton and this serves as a "main accessory food" for the poor people all over China, especially in winter. In preparing the paste, salt is added which enables the material to keep indefinitely, and an oil is extracted which is sold separately. Whether the organisms which form this paste can be compared with the general offshore plankton is not known. Various kinds of small marine crustacea are eaten in the Scandanavian countries.

[4] Since the preparation of the present paper a report has appeared on the use of plankton as food during an experimental raft drift of several thousand miles westward from Peru (Heyerdahl, 1947). Plankton obtained by towing a regular silk plankton net was found by four members of the six-man expedition to be "exceptionally palatable" either raw or cooked and to "satisfy hunger." No information is given, however, as to (1) the amount of plankton eaten per man per day, (2) the amount of other food also eaten, and (3) the amount of fresh water taken with the plankton.

tive value of plankton for rats was determined by direct feeding trials. In addition, tests were made of the feasibility of the use of marine plankton as a source of food under emergency conditions at sea, as for example, by life raft occupants.

In the present investigation tests were confined to the zooplankton which is retained by a coarse plankton net. Although the standing crop of diatoms or of flagellates is sometimes greater than that of the larger plankton, the difficulty (Clarke, '37) and possible danger (see below) of obtaining the marine phytoplankton and nannoplankton in sufficient quantities would probably make the use of these forms impractical. The findings are discussed in relation to the general problem of the direct and indirect use of plankton by man.

Detailed information on the abundance and variability of plankton in a rich marine area was obtained from the eleven surveys of Georges Bank made from 1939 to 1940 (Clarke, Pierce, and Bumpus, '43). Direct tests on the amount of plankton obtainable from a life raft under known conditions of abundance were made from Woods Hole during July, 1945. Tests on the feeding of plankton to rats were conducted at Woods Hole during November, 1945. Chemical analyses of the plankton were carried out in the laboratories of Dr. A. M. Butler, Department of Pediatrics, Massachusetts General Hospital, and of Dr. Philip H. Smith, Agricultural Experiment Station, Amherst, Massachusetts. The authors are indebted for assistance to Dr. A. D. Bajkov and Sergeant J. B. Chadwick of the Air Technical Serv-

TABLE I. *Zooplankton volumes for Georges Bank region*

Volumes were obtained by displacement measurement of drained plankton and are expressed as cubic centimeters of plankton per cubic meter of sea water. Plankton taken by plankton sampler with No. 2 silk net. Nineteen hauls in which diatoms comprised an important fraction were omitted; Numbers of hauls on which values are based ranged as follows: Shallow, 21–52; Second Depth, 21–36. Deep, 8–20. For further details see: Clarke, Pierce and Bumpus (1943).

Date	Value	Shallow	2nd Depth	Deep	Date	Value	Shallow	2nd Depth	Deep
Sept. 1939	Max.	4.4 cc.	1.3* cc.	— cc.					
	Min.	.1	.07*	—					
	Av.	.9	.4*	—					
Jan. 1940	Max.	1.8	.5	1.2					
	Min.	.06	.05	.04					
	Av.	.3	.2	.1					
Mar. 1940	Max.	3.6	3.7	1.1	Mar. 1941	Max.	1.0 cc.	0.4 cc.	0.5 cc.
	Min.	.1	.03	.03		Min.	0.1	0.03	0.04
	Av.	.6	.6	.2		Av.	0.3	0.2	0.1
Apr. 1940	Max.	5.9	3.1	3.7	Apr. 1941	Max.	6.2	7.3	0.8
	Min.	.1	.05	.1		Min.	0.2	0.1	0.1
	Av.	1.2	.9	.6		Av.	1.6	1.2	0.3
May 1940	Max.	3.4	4.1	3.8	May 1941	Max.	6.4	3.1	2.6
	Min.	.3	.2	.1		Min.	0.5	0.3	0.1
	Av.	1.4	1.0	0.8		Av.	1.9	1.2	0.7
June 1–8, 1940	Max.	5.3	4.9	1.5	June 1941	Max.	7.2	5.5	5.4
	Min.	.08	.04	.04		Min.	0.4	0.3	0.1
	Av.	1.7	1.2	.5		Av.	1.9	1.8	0.9
June 19–27, 1940	Max.	10.1	4.0	3.6					
	Min.	.06	.08	.04					
	Av.	1.7	1.1	.5					

* 2nd Depth and Deep hauls combined.

ice Command, and to Dr. Y. H. Edmondson, Mr. G. C. Whiteley, and Mr. D. F. Bumpus of the Woods Hole Oceanographic Institution. Dr. Butler kindly assisted in the interpretation of the results from the viewpoint of the water balance of the body.

Abundance and Availability of Plankton

On the basis of a four-year survey of the relatively rich coastal area between Cape Cod and Chesapeake Bay, Bigelow and Sears ('39) reported that the average concentration of zooplankton in the upper water layers during the season of maximum production was about 0.5 to 0.8 cc./m^3. Comparison with other investigations showed that the plankton of European waters was little, if any, richer. There is no evidence that the plankton of the Pacific Ocean in general is significantly more abundant than that of the Atlantic. Polar seas have been reported to be richer in plankton than oceanic areas of lower latitude (Bajkov, '45).

A more intensive survey of the abundance of zooplankton and of its variation was made during eleven cruises to Georges Bank, off Cape Cod, between September, 1939 and June, 1941. On each cruise a network of stations was occupied and the abundance of the zooplankton accurately determined by means of Plankton Samplers (Clarke and Bumpus, '40) equipped with No. 2 silk nets (22 strands/cm.). The volumes of drained plankton (measured by displacement) varied greatly both in time and in space (table 1). An example of the variation from station to station during one cruise is given in figure 1 which represents a period of high plankton abundance. However, it is obvious that the area as a whole is generally richer than that reported by Bigelow and Sears

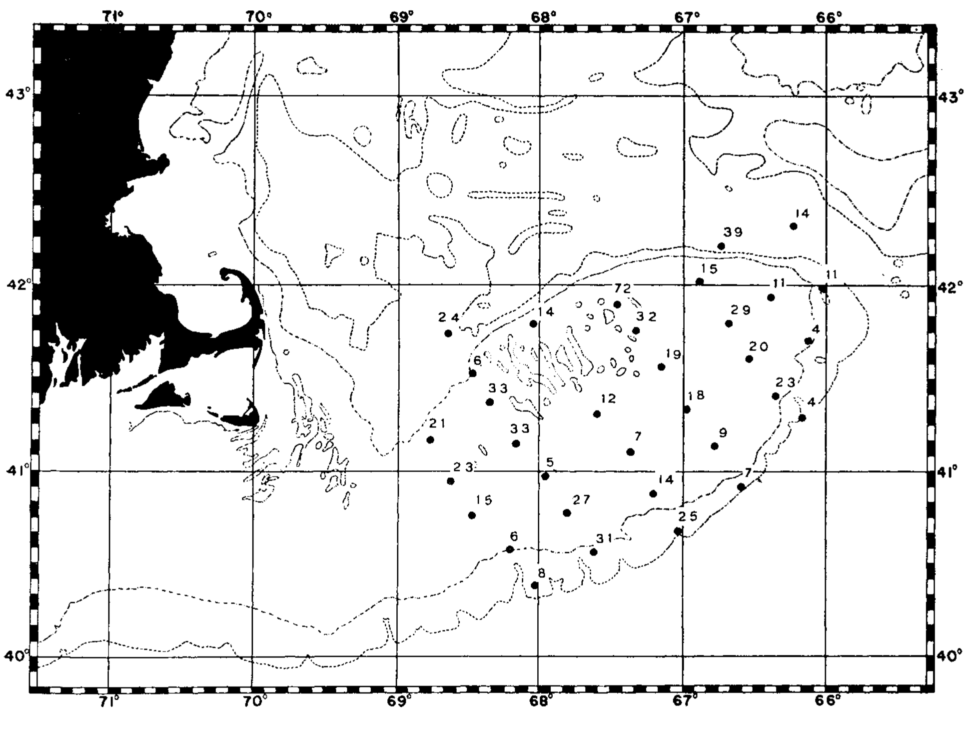

FIG. 1. The abundance of zooplankton in cubic centimeters (displacement volume) per 10 m.^{3} in the Shallow stratum (0–25 m.) on Georges Bank during the cruise of May 28–June 4, 1941.

TABLE II. *Locations and abundance of plankton for tests with life rafts*

Test	Date	Location	Wind	Sea	Plankton abundance
1	July 20, 1945	Vineyard Sound off Quicks Hole	5 knots	Smooth	0.72 cc./m.^{3}
2	July 26, 1945	Vineyard Sound off Tarpaulin Cove	10	Slight	1.12
3	July 27, 1945	Cape Cod Bay near Canal Whistle Buoy	18	Waves up to 4 ft.	0.45

and probably has as large a standing as any temperate area of comparable size. The amounts of zooplankton found here may therefore be taken as a rough measure of the maximum which could be expected in temperate oceanic regions.

A comparison of the plankton catches from the three strata into which the water was divided (for procedure see Clarke, Pierce, and Bumpus, '43) reveals the fact that in most cases the animals were most abundant in the "Shallow" stratum, which extended from 0 to 25 m. There would thus be no advantage in attempting to obtain plankton in quantity from the deeper layers. For the "Shallow" stratum the average size of the hauls for each cruise ranged from 0.3 to 1.9 cc. of plankton per cubic meter of sea water. Out of the 367 individual "Shallow" hauls in which zooplankton predominated and from which the averages of table I are taken, only seven hauls had volumes greater than 5 cc./m^3. If 19 additional hauls are included which contained large amounts of diatom material, the number with total volumes greater than 5 cc./m^3. is increased to thirteen.

The amounts of plankton which could actually be obtained from a life raft by using a plankton net to replace the sea anchor, or drogue, were determined under conditions of plankton abundance comparable to the average richness of Georges Bank. The abundance of the plankton was determined by means of hauls with the Plankton Sampler made before and after the life raft tests (table II).

The plankton obtained from a Mark IV raft with one occupant (except in one case, as noted) under the conditions indicated and with nets of various materials are presented in table III. These tests showed that nets made of No. 2 silk were the most efficient for obtaining the existing type of plankton in which small copepods were the most abundant organism (see below). With the coarser nylon netting a large proportion of the plankton was not retained and with the finer No. 10 silk the amount of water filtered was reduced. Experience showed that with the strength of winds encountered in these tests the filtering rate of the nets could be increased by paddling or improvising a sail

TABLE III. *Amounts of plankton obtained from life raft*

Test	Diameter of net, cm.	Material	Threads per cm.	Duration of haul, minutes	Approx. speed, knots	Actual catch, cc.	Conditions
1	30	No. 10 silk	43	45	1	6.2	Improvised sail
	50	Nylon	8	60	—	1.0	Drifting
	50	Nylon	8	15	—	<1.0	2 men paddling
2	45	No. 2 silk	22	90	1	150	Improvised sail
3	45	No. 2 silk	22	30	0.5	20	Smaller improvised sail

TABLE IV. *Comparison of theoretical and actual catches of plankton*

	Test 1	Test 2	Test 3
Mesh of silk	No. 10	No. 2	No. 2
Area of net opening—m.²	.07	.16	.16
Volume filtered per mile—m.³	135	289	289
Volume of plankton/m.³ of water—cc.	0.4	1.0	0.3
Plankton obtainable per mile—cc.	54	289	87
Miles drifted in 24 hours	24	24	12
Plankton obtainable per 24 hours—cc.	1296	6936	1040
Actual catch, 24-hour basis—cc.	200	2400	960
Efficiency—per cent	15	34	92

to cause the raft to move more rapidly through the water.

Calculations of the amount of plankton which could be obtained on a 24-hour basis and of the efficiency of the nets are presented in table IV. The volume of water which would theoretically pass through an area equal to that of the opening of the net in 24 hours at the approximate rate of drift observed is determined as representing 100 per cent filtering efficiency for the net. The amount of plankton which would be obtained from this volume of water is then calculated from the plankton sampler data to provide a value for the maximum possible catch under the circumstances. This value is then compared with the actual catch on a 24-hour basis to obtain the filtering efficiency of the net as used.

The filtering efficiency of the No. 10 silk net was found to be low compared with that of the No. 2 silk net. The wide variation in the values for the latter are probably due in part to lack of precision in measuring the speed of the raft drift and in part to the larger amount of water which fails to enter the mouth of the net at the higher speed because of back pressure. There is thus a limit to the augmentation of the yield which is obtainable by increasing the rate of raft drift.

As the plankton accumulates in nets which are being towed, the filtering capacity is progressively reduced. This loss of efficiency may continue to some extent even if the catch is removed periodically because it is impossible to wash the mesh clean and because the thread itself swells and frays. There is thus some danger in projecting the results of tests of short duration for periods of 24 hours or more. For this reason the greatest value for the volume of the catch on a 24-hour basis of 2400 cc. may be higher than could actually be obtained.[5]

Chemical Analysis of the Plankton

A knowledge of the chemical composition of the plankton was desired as a means of calculating its potential nutritive value, and its possible effect on the water balance and salt balance of the body of the consumer. Plankton for chemical analysis was obtained during both the July and the November tests by towing several nets of No. 2 silk, 75 cm. in diameter, from the power vessel at 1 to 2 knots. In Test 1 (Sample A) aggregate towing time was equivalent to 1 net towed for 5⅓ hours and yielded 785 cc. of plankton. In Test 3 (Sample B) the towing time was equivalent to 5 hours and yielded 800 cc. of plankton. The towing time for the November collection was not recorded, but 1185 cc. of plankton were available for the analysis (Sample C).

[5] Since the preparation of the present paper, Heyerdahl (1947) has reported that during his experimental drift on a 45-foot raft under sail he obtained 2½ to 5 kg. of plankton per day for food using a silk plankton net of the same diameter and mesh as the one used in our tests No. 2 and No. 3. He states that the biggest catches were made in the cooler water near the Peruvian coast and that "copepods, pelagic crabs, and other crustaceans as well as eggs and larvae" were obtained. The coelenterates were always removed from the catch before eating as "they were found bitter."

TABLE V. *Species composition of the plankton*

The number of individuals of each species is given as per cent of the total

Sample A		Sample B	
Copepods		Copepods	
Centropages hamatus	75	*Arcartia tonsa*	69
Other species	15	Other species	7
Cladocera	7	Cladocera	16
Fish eggs	3	Fish eggs	8
Total per cent	100	Total per cent	100
Gastropods, Fragments of algae, Detritus	<1	No plant material or Detritus	

Identification and aliquot count of the organisms present in the July samples showed that crustacea greatly predominated both in volume and in number of individuals, as shown in table V. In each sample, a single species of copepod (individuals about 1 mm. in length) outnumbered all other organisms combined. The composition of the plankton obtained in November was about 95 per cent copepods (largely *Centropages* sp.) with small percentages of other crustacea, worms, pelecypods, and fish larvae. In these samples for analysis the plankton was predominately crustacean and was therefore typical of the usual oceanic plankton.

Each sample was divided into three parts which were treated as indicated at

TABLE VI. *Weights and chemical composition of plankton samples*

Treatment of Subsamples:

A-1: Drained, weighed wet, dried at 65° to 85° C. for about 65 hours, and weighed dry.
A-2: Drained, washed by pouring 600 cc. of fresh water over it, allowed to drain, weighed wet, dried, and weighed dry.
A-3: Drained, excess water squeezed out by hand through netting with moderate pressure, weighed wet, dried for 17 hours, placed in desiccator for 48 hours, weighed dry.
B-1: Drained, bottled and placed in refrigerator.
B-2: Drained, excess water squeezed out by hand, bottled and placed in refrigerator.
B-3: Drained, squeezed as before, stirred in 2 liters of fresh water for about 3 minutes, drained and squeezed again, bottled and placed in refrigerator.
C-1: Drained for 20 minutes, weighed wet, placed in oven and dried at 80° C. for 189 hours and weighed dry.
C-2: Washed with 1000 cc. of distilled water, drained 20 minutes, weighed wet, dried at 80° C. for 188 hours and weighed dry.
C-3: Drained for 20 minutes, squeezed in No. 2 silk netting with moderate pressure, weighed wet, dried at 80° C. for 188 hours and weighed dry.

Sample	Treatment	Volume, cc.	Wet wt., grams	Dry wt., grams	N	P	Ca	K	Mg	Na	Cl
					Milligrams per gram dry weight						
A-1	Drained	260	261	29.5	90	8.5	5.2	6.6	8.4	64	125
A-2	Washed-drained	260	272	24.7	100	9.2	3.8	3.9	4.9	30	53
A-3	Drained-squeezed	260	147	21.3	98	8.3	3.6	3.9	6.4	44	82
B-1	Drained	250	214*	20.4	77	13.9	—	4.7	—	—	139
B-2	Drained-squeezed	250	166	21.4	91	11.7	—	—	—	—	89
B-3	Squeezed-washed-squeezed	250	126	13.2	105	10.0	—	—	—	—	25
C-1	Drained	393	395	38.9	84	7.6	9.6	14.2	12.9	83	147
C-2	Washed-drained	392	372	29.7	95	7.6	10.0	10.1	7.8	36	58
C-3	Drained-squeezed	400	224	33.6	90	7.6	10.0	10.0	9.6	53	92

* Some of liquid lost in transit.

the top of table VI to ascertain to what extent adhering salt water and/or salt body fluids could be eliminated from the plankton by procedures which might conceivably be practicable for life-raft occupants. In the case of each part the plankton was first allowed to drain on a piece of the No. 2 silk netting and its volume measured by displacement.

The chemical analyses of Samples A and B were carried out at the Massachusetts General Hospital and that of Sample C at the Massachusetts Agricultural Experiment Station (table VI). It is clear that the analyses of the three samples are in very good general agreement and the subsamples which received the same treatments show comparable differences. The amount of nitrogen present was similar for all three samples and the protein content may be calculated from it. No explanation is apparent for the greater amount of phosphorus in Sample B than in the other samples. Of the other elements analyzed the chlorine and the sodium were the most abundant in all cases.

A more detailed analysis of the constituents of the plankton from the nutritional viewpoint was carried out for Sample C (table VII). The percentage of protein in the dried material which ranged from 52 to 59 per cent in this sample (and from 46 to 63 per cent in the other samples) agrees closely with previous reports (see below), but the proportion of fat and ash is lower. The sodium chloride was reduced from about 22 per cent in the drained subsample to about 14 per cent in the squeezed subsample, and to about 9 per cent in the subsample which was washed with fresh water.

The effects of the different treatments of the subsamples are most clearly shown when the data are placed on a relative basis, as in tables VIII and IX. The specific gravity of the drained plankton is obviously very nearly 1 since the wet weight in grams is essentially equal to the volume in cubic centimeters. Squeezing the plankton reduced the wet weight of the sample by one-third to one-half. The weight of dry material obtainable from 100 cc. of plankton was similarly reduced from 11.0 g. for a sample which was simply drained to 5.3 g. for the sample which was squeezed, washed, and squeezed again. The dry weight of the plankton varied from 8 to 15 per cent of the wet weight depending upon the treatment.

The reductions in dry weight following washing and squeezing are presumably

TABLE VII. *Nutritional constituents of plankton*

Components of Sample C expressed as per cent of total weight of sample dried at 80° C.

	Subsample C-1 (drained)	Subsample C-2 (washed-drained)	Subsample C-3 (drained-squeezed)
Protein (N × 6.25)	52.6	59.1	56.2
Fat	1.4	4.2	4.1
Total ash	32.9	19.4	24.1
Carbohydrate (by difference)	13.1	17.3	15.6
Total per cent	100.0	100.0	100.0
Insoluble ash	2.7	3.9	3.5
Chlorine	14.9	5.8	9.2
Chlorine (Est. as NaCl)	24.2	9.6	15.2
Sodium	8.3	3.6	5.3
Sodium (Est. as NaCl)	21.1	9.1	13.4
Phosphorus	0.76	0.76	0.76
Potash	1.42	1.01	1.00
Calcium	0.96	1.00	1.00
Magnesium	1.29	0.78	0.96
Sulphur	0.71	0.46	0.55
Carotene—p.p.m.	3	4	4

TABLE VIII. *Relative compositions of plankton following various treatments*

Sample	Treatment	Wet weight of 100 cc., grams	Dry weight of 100 cc., grams	Dry weight / Wet weight per cent	Protein of 100 cc., grams	Protein* per cent dry weight	Protein* per cent wet weight	Chloride per cent dry weight	Chloride† per cent wet weight
A-1	Drained	100	11.0	11.0	5.9	54	5.9	12.5	1.4
A-2	Washed-drained	105	9.5	9.1	5.8	60	5.5	5.3	0.5
A-3	Drained-squeezed	57	8.2	14.0	4.7	59	8.3	8.2	1.1
B-1	Drained	86 **	8.2	9.5	3.8	46	4.4	13.9	1.3
B-2	Drained-squeezed	66	8.6	13.0	4.7	55	7.1	8.9	1.2
B-3	Squeezed-washed-squeezed	50	5.3	10.6	3.3	63	6.7	2.5	0.25
C-1	Drained	101	9.9	9.9	4.9	50	4.9	14.7	1.6
C-2	Washed-drained	95	7.6	8.0	4.4	57	4.6	5.8	0.5
C-3	Drained-squeezed	56	8.4	15.0	4.5	54	8.1	9.2	1.4

* Assuming 6 grams protein for 1 gram nitrogen.
† Chloride in sea water from Vineyard Sound (Salinity = 32°/00) = 1.8 per cent.
** Liquid lost in transit affects figures for this subsample.

TABLE IX. *Relative abundance of elements*
Adjusted to sodium = 100 grams

Element	A-1 Drained	A-2 Washed	A-3 Squeezed	C-1 Drained	C-2 Washed	C-3 Squeezed	*Calanus** (copepod)	Whole fish*	Sea water*
Chlorine	188.0	171.0	191.0	178.0	161.0	174.0	194.0	—	180.0
Sodium	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Magnesium	12.9	15.8	14.5	15.5	21.6	18.1	5.6	36.0	12.1
Potassium	10.1	12.6	8.9	17.1	28.0	18.9	53.7	383.0	3.6
Calcium	8.0	12.3	8.2	11.6	27.8	18.9	7.4	52.0	3.8
Phosphorus	13.0	29.8	18.9	9.2	21.1	14.3	24.1	256.0	0.0001
Nitrogen	138.0	322.0	222.0	101.0	264.0	170.0	280.0	1276.0	0.001
Nitrogen/ Phosphorus	10.6	10.8	11.7	11.0	12.5	11.9	11.6	5.0	—
Chlorine/ Nitrogen	1.4	0.53	0.86	1.8	0.63	1.0	0.69	—	—
Magnesium/ Nitrogen	0.094	0.049	0.065	0.15	0.082	0.11	0.020	0.028	—

* From Table 50, Sverdrup, Johnson, and Fleming (1942).

due chiefly to the elimination of the salts contained in the adhering salt water, but some body fluids may have been pressed out as well. A certain amount of nitrogenous material was also lost as a result of squeezing since the amount of protein obtained from 100 cc. of plankton was reduced from 5.9 g. and 4.9 g. in Samples A-1 and C-1 respectively to 4.7 g. and 4.5 g. in Samples A-3 and C-3 which were squeezed. From 100 cc. of Sample B-3, which was subjected to the double squeezing process, only 3.3 g. of protein was obtained. Since the percentage of protein in the dry material was greater for the squeezed than for drained subsamples whereas the reverse was true in the case of the chloride, it is obvious that the loss of chloride was relatively much greater.

The chloride present in the subsamples of the plankton following the various treatments designed to eliminate salt water composed from 2.5 per cent to 14.7 per cent of the dried material, and from 0.25 per cent to 1.6 per cent of the wet weight. Since sea water of a salinity of 32 per cent (as in Vineyard Sound) contains 1.8 g. of chloride per 100 cc., it is evident that in consuming drained plankton, about 80 per cent as much chloride would be taken in as if an equal weight of sea water were drunk. This figure is reduced to about 70 per cent for squeezed plankton, to as little as 30 per cent for washed plankton, and to 15 per cent following the double squeezing and washing process.

Other solutes were also reduced in amount by the squeezing and especially by the washing treatment. The differences in the amount of the reduction for the commoner ions may be observed from their relative abundance in the subsamples as shown in table IX. There is little consistent change in the ratio of chloride to sodium but magnesium tended to become relatively more abundant following the squeezing and the washing processes. When compared with nitrogen, which may be taken as an index of the protein present, it is seen that chloride is reduced relatively to about one-third by the washing process and magnesium to about one-half.

The relative abundance of elements in our material may also be compared with the ratios reported for the copepod, *Calanus,* for whole fish, and for sea water (table IX). We have no information as to the manner in which the *Calanus* material was treated before analysis, but it is clear that the ratios of chlorine, calcium, phosphorus, and nitrogen to sodium are similar to our values. The value for magnesium is much lower and the value for potassium is much higher. The analysis for fish shows all ratios considerably higher, and indicates that sodium is relatively low. When compared with sea water, our drained subsamples (A-1 and C-1) exhibit a close agreement for the ratios of chlorine and magnesium to sodium, but potassium and calcium are considerably higher. The relative abundance of magnesium increased noticeably for the squeezed and washed samples. The ratio of magnesium to potassium both in sea water and in the plankton is much higher than in the body fluids of man. The ratio of nitrogen to phosphorus in the samples of plankton was somewhat higher than that previously reported (Sverdrup, Johnson, and Fleming, '42, table 52).

We may draw the following conclusions from the foregoing analyses and their relative differences. If it is found that the salt content of the plankton is of no consequence to the consumer, then the largest amount of protein per unit volume of plankton catch will be obtained by eating the drained material without further treatment. If, however, it is desirable to eliminate as much of the salt as possible, the plankton should be squeezed, or, if possible, washed with fresh water. Squeezing may cause the loss of some 20 per cent of the protein, but a larger percentage of the salts will be lost. Washing causes little loss of protein and about 65 per cent of the chloride and 55 per cent of the magnesium will be removed (or more with the double squeezing and washing process). The concomitant increase in the ratio of magnesium to sodium must be kept in mind as of possible importance in the salt balance of the consumer.

Feeding Experiments with Rats

The foregoing chemical analysis gives maximum figures for the nutritive content of plankton but yields no information on the portion of the plankton which could actually be assimilated by man or other terrestrial animals, nor on any possible harmful effects. Preliminary experiments were therefore undertaken on the effect of feeding plankton to rats. Both adult and weanling white rats (Wistar stock) were used for these tests and were maintained in Dawson type cages, loaned by the Biological Laboratories of Harvard University. One or two adult rats, or one to three weanlings, were kept in each cage.

The plankton used for feeding was obtained from Vineyard Sound and most of it was frozen at $-18°$ to $-20°$ C. immediately upon reaching the laboratory, but supplementary tests were conducted with fresh and with cooked plankton. The plankton fed the experimental animals was squeezed with moderate pressure in No. 2 silk netting to remove excess sea water. Tests showed that the dry weight of this material was about 14 per cent of the wet weight. Diet mixtures were prepared on the basis of the dry weight of the plankton. Control food consisted of Purina-Growena meal and Purina dog chow checkers. The type of plankton used was found to have an average energy content of about 4 calories per gram of dry weight (see below) which was assumed to be comparable to the energy content of the control food.

The main series of experiments consisted of comparing the growth rates of rats fed on full and partial diets of control food with those fed on plankton alone, and on diets of ⅔ and ⅓ plankton with the balance made up with control food. The average intake of control food which resulted in the maximum growth rate of weanling rats was found to be 13 grams of Purina-Growena meal per rat per day. With more supplied, considerable quantities were left in the cage; with less supplied, the growth curve fell off. In all cases the animals had access to an adequate supply of water from bottles in which the consumption could be estimated.

The growth rate of weanling rats fed on a full diet of meal was first compared with the rates for animals fed on a diet of ⅔ meal plus ⅓ plankton and for animals fed on a deficient diet of ⅔ meal and no plankton. The rats consumed 32 g. of wet squeezed plankton mixed with 8.5 g. of meal per rat per day which was calculated to be equivalent to 4.5 g. dry plankton plus 8.5 g. of meal. Although the growth of the rats fed plankton was more irregular than that of the controls, the average rate for the former over the 13-day period of the experiment was essentially the same as for the controls (fig. 2). Since the growth of the rats fed ⅔ of the normal amount of meal

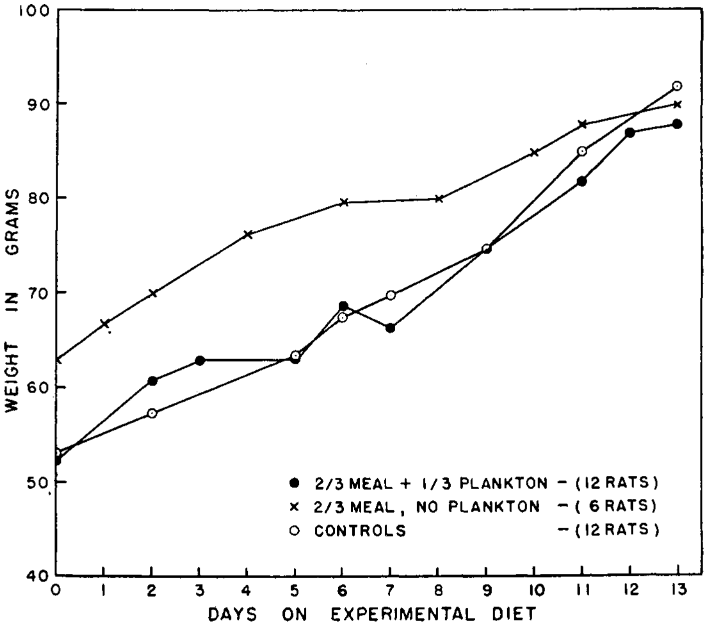

FIG. 2. Growth curves of weanling rats fed on the indicated diets. The average values for each group of animals are plotted.

alone was definitely depressed, it is clear that some nourishment was derived from the plankton which was added to the diet.

In the next experiment the growth of weanling rats fed on a diet of ⅓ meal plus ⅔ plankton was compared with that of rats on a diet of ⅓ meal and no plankton. The animals in the first group received 60 g. of wet squeezed plankton (equivalent to 8.5 g. dry plankton) plus 4.5 g. of meal per rat per day. The rats in this group actually consumed only about ⅔ of the food which was offered them although the full amount was theoretically required for their nutritive requirements. The growth of these animals stopped abruptly on the first day on which they were placed on the diet with plankton. The rats, nevertheless, succeeded in maintaining their original weight for 7 days. The animals of the second group, which received no plankton to supplement their ⅓ diet of meal, lost weight during the same period (fig. 3). This result again shows that some nourishment is derived

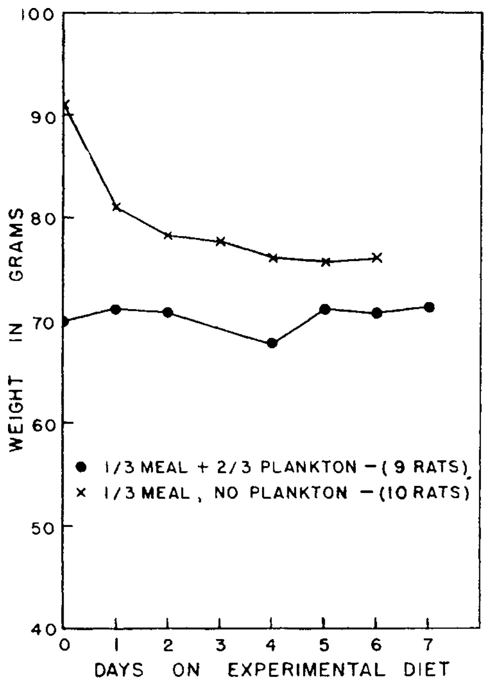

FIG. 3. Weight records of weanling rats fed on the indicated diets.

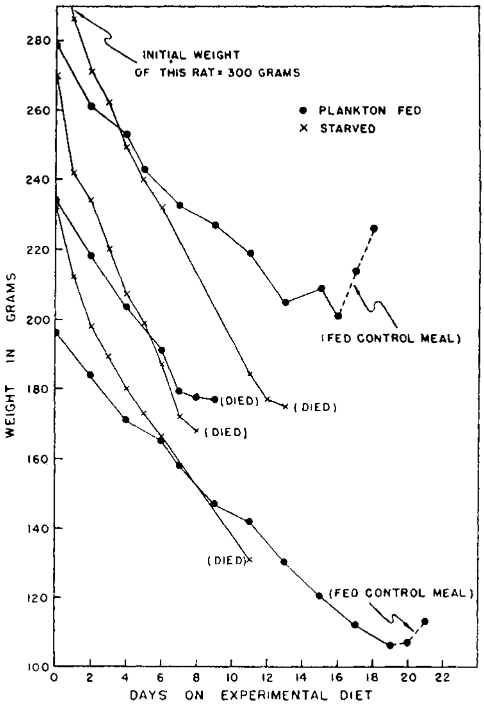

FIG. 4. Weight records of adult rats fed on plankton and of starved rats.

by the rats from plankton, but when as much as ⅔ of the diet is composed of plankton, normal growth does not take place. The inadequacy of the diet with plankton may be due partly to the refusal of the rats to eat a sufficient amount. That it is also due in part at least to their inability to assimilate from the plankton a sufficiently large fraction of the energy which it contains is shown by the fact that these rats which consumed ⅔ of their ration of mixed food did not do as well as those in the previous experiment which ate ⅔ of a ration composed entirely of control food.

When rats were fed a diet consisting entirely of plankton, they not only failed to grow, but lost weight rapidly and eventually died. They survived for a longer period, however, than rats which were given no food at all. Weanling rats showed a loss in weight of 5 to 10 grams after the first day on the plankton diet and succumbed within four or five days. Adult rats fared better on plankton than did weanling rats. The longest survival times for adult rats on a full plankton diet were 18 and 19 days. Starved rats, of equivalent initial weights, given adequate water lived for a maximum of 13 days (fig. 4). The amount of plankton eaten by these rats was quite variable. The normal intake of control meal for adult rats maintaining a steady growth was found to be 20 g. per rat per day. Although 90 to 100 g. of wet squeezed plankton was offered per rat per day, adult rats on a full plankton diet consumed something less than 60 g. per day and this would be equivalent to only about 7 g. of dry plankton.

To reveal any possible adverse condition of the frozen and stored plankton which was used in the foregoing feeding tests, a further series of experiments was run with fresh plankton, brought into the laboratory just prior to feeding. Portions of this plankton were prepared simply by squeezing out the excess salt water, other portions were washed with distilled water, and others were washed and cooked for 20 to 30 minutes. Weanling rats were supplied with all the plankton prepared in these various ways which they would eat. The animals consumed an average amount of washed plankton equivalent to 12 g. of dried material per rat per day, but the average intake of cooked plankton was equivalent to only 8 g. of dry food, and that for fresh, unwashed plankton was equivalent to about 7 g. In spite of the fact that the amounts of plankton eaten under these circumstances in some cases approached the dry weight which would be adequate for control meal, all the rats lost weight rapidly and died after a few days (fig. 5). Weight loss was not quite as severe when washed and cooked plankton was fed as when untreated plankton was used. Animals fed on the latter material fared little, if any, better than those which were starved.

An ample supply of water was available to the rats in all experiments at all times. The rats which were fed whole or partial plankton diets were found to consume on the average about the same quantity of water from the water bottles as the controls. The plankton-fed rats thus took in 86–90 g. of water with every 100 g. of squeezed plankton. Since this plankton contains about 86 per cent water, it is clear that the animals on this diet were taking in a larger total amount of water. Whether or not this larger total water intake was necessary was not determined. Theoretical aspects of the water balance of the body on a plankton diet are considered below.

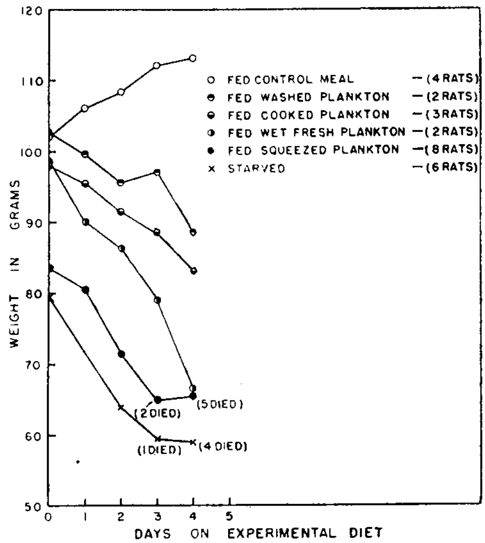

FIG. 5. Weight records of weanling rats fed on plankton treated as indicated.

Autopsies on plankton-fed rats showed few abnormalities. The most consistent and prominent symptom was a marked congestion of faecal material in the caecum and hind intestine. It is not clear whether the accumulation of indigestible matter was a contributing factor to death, or whether the general weakness and loss of muscle tone resulted in faulty elimination, incidental to the cause of death. The kidneys appeared quite normal. For a day or so prior to death the rats were anemic, weak, and lacked coordination.

These feeding experiments show in general that the rats will usually not eat an amount of plankton which would contain the requisite energy to permit normal growth. In those cases in which the rats were induced to eat an amount of plankton which would appear adequate or nearly so, on a dry weight basis, the animals nevertheless failed to grow. Only a small fraction of the energy contained in the food, therefore, appears to be utilized. Since the reduction in growth rate is immediate, a vitamin deficiency as the chief harmful effect is contraindicated. That some nutriment is derived from the plankton is shown by the longer survival of plankton-fed rats than starved rats, and by the lesser reduction in the growth rate for rats fed on a quantitatively deficient diet of meal plus plankton than for animals fed on the deficient meal diet alone.

Discussion

Variation in plankton type and abundance

In discussions of the use of plankton as food, there has existed a tendency to refer to plankton as if it were uniform in nature and abundance. Nothing could be further from the truth. The kind of organism which dominates the plankton differs markedly from place to place and from time to time (Sears and Clarke, '40). A pronounced change in the composition of the plankton may sometimes occur within a few miles or less, but on other occasions it may be uniform for large areas. At any one point the interval of time for a significant change in the plankton may be as short as a few days or as long as several weeks. Frequently the type and abundance of plankton at night differs from its complexion during the day as a result of diurnal migrations to and from the surface of the sea (Clarke, '34).

The animals which are usually most abundant in the zooplankton are the crustacea and particularly the copepods, although on occasion euphausids may predominate. In some situations medusae, salps, siphonophores, sagittae, or other soft-bodied animals may comprise more than 90 per cent of the zooplankton.

At certain seasons of the year and in certain localities, the phytoplankton may greatly outweigh the zooplankton. Species provided with long spines and those which grow in chains are often retained in coarse-mashed plankton nets intended for zooplankton. Under these circumstances diatoms may clog the pores of plankton nets to such an extent that the filtering efficiency is reduced nearly to zero.

The variability of the plankton is such that it would be exceedingly difficult to predict what type and what amount would be encountered in any given situation, at least until that area had been studied for a long time. The kinds of organism which will predominate in the plankton haul will depend upon which happen to be most abundant at the time, and to a certain extent upon the mesh of the net used. It is impossible to avoid catching undesirable species entirely.

The favorable conditions of slight sea, moderate wind, and rich plankton (1.0 cc. per m^3.) which existed for the present raft tests will not always be encountered. The abundance of the plankton in the open sea is ordinarily much less than that in coastal regions and values obtained in most tropical areas are regularly smaller than those of temperate or polar regions. An investigation extending over a period of a year and a half at stations in (1) the coastal water, (2) the "slope" water, and (3) the Sargasso water between Montauk Point, New York, and Bermuda revealed that the average volume of zooplankton in the slope water was only about one quarter as great as that in the coastal area, and the volume in the Sargasso water was only about one quarter as great as that in the slope water (Clarke, '40).

It is apparent that even in the richest coastal areas, plankton volumes as great as 1.0 cc. per cubic meter will not be encountered on every occasion and farther off shore such abundance will be found less and less frequently. The amount of plankton taken by the raft during Test 2 should therefore be regarded as a maximum probable value rather than as a representative value.

Occurrence of poisonous species

Although only one species of plankton organism in the sea (*Gonyaulax catenella*) is known which produces a poison fatal to man, there are no doubt other forms which are more or less harmful. It has been suggested that the chitinous exoskeletons of the crustacea would be injurious in large quantities but this is probably not the case because of the ability of orientals to eat whole shrimps and grasshoppers. The sharp siliceous valves of diatoms have also been regarded as a danger, but these forms have long been eaten with impunity as part of the stomach contents of oysters, clams and other shellfish. It is not proposed to catch phytoplankton in large quantities, although this might be unavoidable in some situations. The recent outbreaks of the dinoflagellate, *Gymnodinium* sp. ("Red tide"), along the Florida coast have resulted in extensive fish mortality, but it is not known whether this organism is poisonous to terrestrial animals (F. G. W. Smith, 1947).

Dead and decomposing plankton is sometimes encountered in large quantities in the sea and fragments of dead fish, or of flotsam and jetsam, might be picked up undetected by the plankton net. Whether such material would be harmful to man is not known. In inland waters the decomposition of some of the blue-green algae is accompanied by the formation of hydroxylamine, a highly toxic substance for most domestic animals. Many deaths assigned to this cause have been reported from the middle western states where the animals had access to pond water in which blooms of blue-green algae were decomposing (Juday, private communication).

A more probable danger in the sea is the occurrence of stinging forms in the plankton. Certain jellyfish and other types of plankton are known to produce serious stings to the skin and these are sometimes followed by a general reaction of the whole body. Tentacles of the dangerous Portuguese Man-O-War, which may stream out for 30 feet or more, are often picked up by plankton nets. The results of swallowing any of these stinging forms might be still more serious than contact with the skin.

The planktonic flagellate, *Gonyaulax catenella,* is responsible for the poisonous quality of certain shellfish, particularly the mussel found on the coast of California and elsewhere (Sommer, Whedon, Kofoid, and Stohler, '37). The poison is accumulated in the digestive glands of the mussels, and has also been found in the digestive glands of such organisms as the sand crab, *Emerita*. It is also easily adsorbed on sand and the same, or a similar poison, has been obtained from mud on at least one occasion on the Atlantic Coast. The poison has been found to constitute approximately 6.5 per cent of the weight of *Gonyaulax* as a maximum. A variation in the poison content of 1 to 100 has been reported.

From the foregoing data and from the amounts of poison in mussels which are lethal, it may be calculated that a few million cells of *Gonyaulax catenella* could be fatal to man if ingested directly. The number of cells of this flagellate in sea water is subject to extreme variation, from none at all up to several million per liter. Blooms of 20 to 40 million cells per liter have been reported. When the concentration approaches one million cells per liter, this organism, like many others, causes the water to become rust red.

Gonyaulax catenella is described as a neritic, or coastal, species although it occurs in the "open ocean" rather than in enclosed bays and estuaries. This species has been reported from many points along the Pacific Coast, including the Gulf of California, Monterey, San Francisco, Washington, Canada and Alaska. *Gonyaulax catenella* has not been positively identified from the Atlantic Ocean, although it has been "tentatively identified" from Nova Scotian and Belgian waters. It may appear also in other parts of the world where the plankton has not yet been thoroughly studied. Other species of *Gonyaulax* occur in both the Atlantic and the Pacific but there is no evidence that these species can produce the toxin.

Even with the use of relatively coarse zooplankton nets, quantities of the smaller plankton, such as *Gonyaulax,* will unavoidably be taken when such species are very abundant. In towing the No. 2 silk net for only one hour in Test 2 (table IV), 289 m^3. of sea water were theoretically filtered. As the pores of the net became clogged, the phytoplankton from far more than one liter would be retained in the catch, and we have seen that under some circumstances a liter of water could contain more than a lethal dose of *Gonyaulax catenella.* There would thus be definite danger of unwittingly catching a dangerous amount of this species in certain areas. *In addition, the possibility must be constantly kept in mind that other plankton forms, as yet unsuspected, may be as poisonous to man as is* Gonyaulax catenella.

Palatableness under starvation conditions

A major consideration in the provision of an emergency source of food is its palatableness under starvation conditions. If the material suggested for food is revolting because of its taste, smell, or appearance, it may cause nausea especially under conditions tending to produce seasickness. In such cases the food would lose whatever value for improving morale it might otherwise have.

Several tablespoonfuls of the drained plankton obtained in Tests 1, 2, and 3 were eaten by the individuals conducting the tests without ill effect. The plankton had a mildly pleasant taste, being somewhat reminiscent of shrimp or raw oysters. Six or eight other members of the ship's company who were definitely prejudiced against the idea at the outset, tasted the plankton and pronounced it either good or not objectionable. The plankton was also tasted after various treatments, such as being washed with fresh water, spread on bread or crackers with and without butter, or fried. Some subjects found that the plankton was most palatable in its original condition, but others preferred it after it had been treated with fresh water.

Larger quantities of the plankton obtained during the November collection were consumed by three of the investigators. No toxic effects developed after eating 100–200 grams (wet weight) of the material during the course of a day. The maximum quantity eaten by any one of the subjects at one time was 100 grams. Larger amounts were definitely unacceptable and distasteful. It is probable that psychological factors entered into the matter of the palatableness and digestibility of the plankton in the laboratory and at sea. Such factors are not easy to evaluate. It was certainly true that a quantity of only 30–40 grams of plankton gave the impression of remaining undigested in the stomach for several hours after eating.

Other types of plankton may be much less palatable than the samples consumed in the present case which were dominated by the shrimp-like copepods. The abundant presence of jelly-like organisms may produce a decidedly objectionable taste.

The reaction to a plankton diet of a starved individual adrift on a raft may be quite different. The experience of castaways has shown that, under the distress of starvation and thirst, the condition of the mouth and throat is such that certain types of materials cannot be swallowed, especially if there is no drinking water to accompany them. In the present investigation even small quantities proved to be nauseating if taken while collecting in a rough sea.

Nutritive value of plankton and effect on water balance

The composition of plankton in respect to potentially nutritive substances will be expected to vary widely because of differences in the types of organisms present. The percentage of organic material on a volume or wet weight basis will be lower when jelly-like species are abundant and may differ considerably on a dry weight basis. A typical zooplankton catch (Sample C, table VII), consisting chiefly of copepods, yielded the following analysis when dried: fat 1–4 per cent, protein 52–59 per cent, carbohydrate 13–17 per cent, and total ash 19–33 per cent. The fat content of samples of copepod plankton was reported as 7 per cent by Johnstone ('08) and as 15–22 per cent by Vinogradov ('35 and '38), and may sometimes exceed 30 per cent. Vitamins and mineral salts useful from the nutritive standpoint are also present. However, it has been seen that rats could not assimilate the whole of these organic materials. Whether man or other terrestrial forms could do so remains to be determined. It is obvious that fish and other marine organisms which live largely, or entirely, on zooplankton are able to assimilate it satisfactorily. It would be desirable to ascertain the differences in the digestive processes of these forms and of rats.

To gain a rough idea of the maximum nutriment which might be obtained from eating plankton, we may assume that all the organic matter contained could be assimilated. On the basis of the foregoing analyses, and allowing 9 calories per gram for fat, and 4 calories for protein and carbohydrate, we may assign an approximate maximum energy content of 4 calories per gram dry weight for this type of plankton. Using the data of Sample A–3 (table VIII), in which the plankton was squeezed, 1000 cc. of plankton, yielding 82 grams of dried material, would provide 328 calories of energy. The 2400 cc. of plankton caught from the raft in Test 2, when calculated on a 24-hour basis, would have provided 788 calories if the whole amount could have been eaten and assimilated without harmful results (see below). This would represent about one-quarter of a man's average daily requirement under conditions of moderate activity (Clarke, '39). Considerably less energy might be required by life-raft occupants under some circumstances.

The facts thus far available indicate that it will never be possible to catch from a raft, consume and assimilate enough plankton to provide the entire energy of a maintenance diet. The amount of energy which can be obtained from this source will relieve the body of drawing upon its reserve supply of fat and other tissues to a corresponding extent. Survival without any food is possible for 30 days or more. During studies conducted by Dr. A. M. Butler, tests performed at the Harvard Fatigue Laboratory showed that an individual's physicial ability is not impaired after 6 to 8 days of very deficient intake of water and food. A partial diet may be of some physical benefit for longer periods and may possibly have morale value from the beginning. In regard to the use of plankton as an emergency food the essential question to be decided is whether a partial relief of the drain on the body's reserves is worth the difficulty and danger, if any, of catching and consuming plankton.

An approximate calculation may be made of the effect of a plankton diet on the water balance of the body on the basis of the chemical composition of squeezed plankton (Sample A–3) which represents the type of treatment most likely to be feasible on a life raft. Exact values cannot be obtained without actual trials with human subjects since the osmotic effect per gram of each solute found in the dry material is not known. However, an approximation of the water required for the renal excretion of a gram of plankton may be estimated as follows. Using the analytical data for Sample A–3, table VI, the milliosmols per gram are roughly:

	Mg.		Milliosmols
N	98.0	—	3.3 (as urea)
P	8.3	—	0.2
Na	44.0	—	1.9
Cl	82.0	—	2.3
			7.7 milliosmols

Allowing a small amount for other solutes, the total solute content may be considered as equivalent to 8 milliosmols per gram of dry weight. Since the maximal concentration of solutes in the urine which can be attained by the kidney is taken as 1.4 osmolar, the minimal volume to which the urine can be reduced without causing dehydration may be found by dividing the total solutes in the plankton by this value (Gamble and Butler, '44):

$$\frac{8.0}{1.4} = 5.7 \text{ cc.}$$

This means that about 5.7 cc. of water must be available to make possible the excretion of the metabolites resulting from the combustion in the body of each gram of plankton. Since the squeezed plankton contained 86 per cent water (table VIII), about 6 cc. of water would be taken in with each gram of dry material. In addition about one-third of a gram of metabolic water would be produced by the oxidation of each gram of plankton with a composition similar to that of Sample C (assuming values of 0.41 g. of water per g. for protein, 0.56 g. for carbohydrate, and 1.07 g. for fat). It is therefore possible that, in general, plankton may contain as much water as would be required for the excretion of all of its breakdown products. If this should be found true, any quantity of plankton could be eaten without disturbing the osmotic water balance of the body. Perhaps for this reason the whales which live on plankton diets may not require any modification in this respect of their mammalian type of kidney.

There is doubt that large amounts of plankton could be eaten by man for other reasons. When more than 500 cc. of sea water is drunk per day, diarrhea or vomiting may supervene and themselves cause dehydration (Butler and Gamble, personal communication). Since the salt content of squeezed plankton is about 70 per cent of that of an equal volume of sea water (table VIII), it might be impossible for a man to eat more than about 700 grams of wet plankton (i.e., the squeezed plankton from about 1200 cc. of drained plankton) per day without harmful results. The fact that the plankton is not in liquid form might allow these amounts to be increased somewhat.

The ratio of magnesium to potassium in sea water, and in the plankton analyzed in the present investigation (table IX), is much higher than in the body fluids of man. The consumption of large quantities of plankton, or its continued use, might therefore result in disturbing the salt balance of the body.

The possible effects of these differences in ionic ratios, and perhaps of others, are not known but must be considered. The high magnesium content of sea water may be the cause, in part, of the diarrhea produced in man by excessive intake of sea water. Unless the human consumer were informed of these possibilities, he might eat a harmful amount of plankton without realizing it. However, certain of the domestic animals might not be disturbed by these differences and, in contrast to the rat, might be found to thrive on a partial or a complete diet of plankton. Such a possibility should be examined in the future as it would enable man to make use indirectly of the tremendous potential food source represented by the plankton.

Summary

1. Observations are reported on the abundance and variability of the marine zooplankton, its chemical composition, its nutritional value when fed to rats, and its palatableness to man. In tests on the feasibility of the use of plankton as an emergency food, a maximum of 100 cc. of plankton, with dry weight of 5 to 11 g. according to treatment, was found to be obtainable per hour from a life raft.

2. The dry plankton was composed of 52–59 per cent protein, 1–4 per cent fat, 13–17 per cent carbohydrate and 19–33 per cent ash. The chloride content of the drained plankton was about 1.4 per cent of the wet weight, or about 80 per cent of that contained in an equal volume

of sea water, and was reduced to 0.25 per cent of the wet weight by washing and squeezing. The magnesium content, which was initially high, became relatively greater, following this treatment.

3. Estimation of the osmotic effect of the solutes present indicated that plankton may contain as much water as is required for the excretion of all its breakdown products when consumed by man. The high ratio of magnesium to potassium, however, might disturb the salt balance of the body.

4. Rats fed on plankton lost weight rapidly and died within 4 to 19 days but survived about 30 per cent longer than starved rats. Rats fed on a diet composed of ⅔ meal and ⅓ plankton, and of ⅓ meal and ⅔ plankton, failed to grow as fast as rats on a full diet of meal but fared better than those on the fractional diet of meal only. The rats therefore derived some nourishment from the plankton but were able to assimilate only a small fraction of the food energy which it contained.

5. Plankton with the observed chemical composition was calculated to have an approximate maximum energy content of 4 cal./g. dry weight. The 2400 cc. of plankton which could theoretically be obtained from a life raft in 24 hours would thus provide 788 calories, if it could all be assimilated, or about ¼ of a man's average daily requirements. The advantages, difficulties, and possible dangers because of poisonous species, of the direct and indirect use of plankton by man are discussed.

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