AN ABSTRACT OF THE THESIS OF

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(Name of student) (Degree)

in Agricultural Economics presented on 12/17/74
(Major department) (Date)

Title: ECONOMIC ANALYSIS OF OYSTER PRODUCTION UNDER CONTROLLED CONDITIONS

Abstract approved: ______________________
Frederick J. Smith

Efforts in this study were directed towards:

(1) gaining insights into the recent North American oyster industry trend,

(2) identifying problems that may be solved by oyster production under controlled conditions,

(3) biological literature reviews to determine the critical controllable variables for production function estimates,

(4) the estimation of relationships among identified variables,

(5) the estimation of costs associated with these controllable variables, and

(6) the economic feasibility of oyster production under controlled conditions with respect to these controllable variables.

The U.S. oyster industry production has been declining for 20 years. The major problems of the industry identified in this study

were as follows:

(A) the random fluctuations in natural seed supply on which the industry is heavily dependent,

(B) natural disasters and predators, particularly on the East Coast,

(C) pollution,

(D) oyster disease (e.g., MSX),

(E) limited changes in technology,

(F) stringent regulation regarding the use of common property,

(G) an increasing demand for alternate use of common property, and

(H) increasing oyster imports from foreign countries.

Among identified problems, oyster production under controlled conditions could overcome (A), (B), (C), (D) and (E), and possibly (F) and (G).

The following variables were identified as biologically critical in order to achieve production under controlled environmental conditions:

W = water flow (milliliters/oyster/minute)

F = feeding [organic carbon (μg)/oyster/minute]

T = temperature (degrees centigrade)

O_2 = dissolved oxygen (micromilliliters/oyster/minute)

P = pH

S = salinity (ppt)

A general oyster production function was of the form:

$$Y = f\,(W,\ T,\ F,\ O_2,\ P,\ S,\ X_1,\ \ldots,\ Xn)$$

where Y = yield

Xi = unspecified environmental factors affecting oyster growth.

However, the relative significance of dissolved oxygen, pH and salinity were found to be less critical in terms of costs. Thus, the framework of oyster production was expressed as follows:

$$Y = f\,(W,\ T,\ F \mid O_2,\ P,\ S,\ X_1 \ldots,\ Xn)$$

These models were fitted to the data obtained from the experiments conducted by the Department of Fisheries and Wildlife, Oregon State University at Newport over a two year period from 1973 to 1974.

The original hypothesis was designed to test whether oyster production under controlled conditions is economically feasible. The results of the analysis indicated that the costs of heating and algae must be near zero to make production under controlled conditions economically feasible. Future research will be able to improve the biological basis for economic analysis; however, the basic procedures and critical variables identified in the analysis can be applied to the new data.

The weaknesses of the analysis principally stem from the lack of reliability of the biological experiments. Since inputs--except temperature and water flow--were not controlled, substitution among controlled and uncontrolled variables may have occured. An identification of the exact impact of each variable was not made. General recommendations for future studies concerned with oyster culture under controlled conditions can be summarized as follows:

(1) to increase different levels of temperature and water flow for factorial experiments which will increase the estimating equations' precision,

(2) to concentrate biological observations in the relevant economic area (stage II) particularly at temperature levels above 15°C, water flow levels above 30 milliliters per oyster per minute and organic carbon levels above 40 μg per oyster per minute,

(3) to control, or at least monitor, critical variables,

(4) to control experiments by artificial feeding so that effects of other unknown variables will be minimized in determining the effect of feeding, and

(5) to conduct experiments at different stages of oyster growth.

Economic Analysis of Oyster Production Under Controlled Conditions

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1975

APPROVED:

Associate Professor of Agricultural Economics
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Date thesis is presented 12/17/74

Typed by Velda D. Mullins for Hisashi Ishiyama

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ACKNOWLEDGMENTS

The author wishes to extend appreciation to those people who helped in the preparation of this work. The major part of the guidance on this study came from Dr. Frederick J. Smith, my major professor, under whom this project was initiated and completed. His patience and careful guidance have been invaluable.

The author is also grateful to Mr. Robert E. Malouf, Graduate Student in the Department of Fisheries and Wildlife, who provided the basic biological data to this study, to Drs. Richard S. Johnston and Richard E. Towey for their critical review in preparation of the manuscript, to Dr. William G. Brown for his statistical assistance, and to my wife, Humi, whose encouragement made my graduate work possible.

ECONOMIC ANALYSIS OF OYSTER PRODUCTION UNDER CONTROLLED CONDITIONS

I. INTRODUCTION

Study Objectives

The production of oysters under natural conditions is greatly affected by predation, disease, silting, toxins produced by planktonic activities, and pollutants. However, under controlled environmental conditions, many hazardous natural and man-made factors which adversely affect oyster growth and quality can be reduced or eliminated. Under controlled conditions, one can (1) increase the growth rate of oysters, (2) maintain the availability of top-quality oysters throughout the year, (3) greatly reduce the mortality rate of oysters between the seed and the harvesting stage of the crop, and (4) increase the volume and regularity of the supply of oysters.

The general objective of this study is to investigate the economic feasibility of oyster production under controlled environmental conditions. Specifically, the study will:

(1) estimate biological relationships from empirical studies,

(2) determine the critical controllable variables,

(3) estimate relationships among these variables and

production, and

(4) estimate variable costs associated with these controllable variables.

However, in order to further justify this research, the following topics will be also investigated:

(1) the trend of the oyster industry in North America, and

(2) the problems of the oyster industry.

Aquacultural Concepts

A definition of aquaculture is given by Ryther et al. (1968, p. 1) i.e., "the rearing of aquatic organisms under controlled conditions using techniques of agriculture and animal husbandry." Some advantages of aquaculture are well recognized: for example, controllability of property rights of marine resources vis-à-vis open access marine resources, and the protection of the organisms from natural and man-made disasters. However, there exist few species of aquatic organisms which can meet what Bardach (1968, p. 6) called "the biological properties of organisms that would lend themselves most ideally to intensive culture."

> "(1) They should reproduce in captivity or semi-confinement or yield easily to manipulations that result in the production of their off-spring.
>
> (2) Their eggs or larvae should be hardy and capable of being hatched or reared under controlled conditions.

(3) The food habits of larvae or young should be such that they can be satisfied by operations which can increase their natural foods or they should be able to take prepared foods from their early stages.

(4) They should gain weight and nourish themselves entirely or in part by food items that are abundantly available, that can be supplied to the organisms cheaply or that can be readily produced or increased by the people in the area where cultured species lives."

These four criteria can not only be applied to the biological properties of aquaculture but also give an economic limitation on the development of aquaculture, i.e., any difficulty in one of those conditions will increase the cost of production.

The oyster is one of the few shellfishes that satisfies in great degree the biological properties of aquatic organisms applicable for aquaculture development. (1) Oysters can easily be induced to reproduce in captivity at any time of the year, (2) oyster eggs, larvae and seed are hardy under controlled conditions, (3) larvae and seed can be easily reared on cultured algae, and (4) oysters can grow and nourish themselves entirely by algae and other food sources naturally abundant in the tide water.

Recent History of the U.S. Oyster Industry

The oyster industry of North America is comprised primarily of four species. Ranked in order of commercial importance, these are the American oyster or Eastern oyster (*Crassostrea* virginica), the Pacific oyster (Crassostrea gigas), the Olympia oyster (Ostrea lurida) and the European flat oyster (Ostrea edulis). The American and the European flat oysters are extensively cultured on the East Coast and the Gulf of Mexico. The Pacific and the Olympia oysters are cultured mainly on the West Coast. But the relative significance of the Olympia oyster has dwindled since the importation of the Pacific oyster from Japan in the late 1910's.[1/]

Oyster production volume in the U. S. has diminished by roughly 50 percent since the 1920's. Major declines have taken place in such areas as Chesapeake Bay and New England. The present production in Chesapeake Bay and New England is approximately 20 and 8 percent of their 1920 production, respectively.

The future survival of the oyster industry in the New England region is in question (Wallace, 1960). On the other hand, the production of oysters in the Gulf of Mexico has been increasing, and the South Atlantic and Pacific regions have maintained a constant production level for the last two decades (Fig. 1).

During the last 20 years, ex-vessel prices of oysters have risen from 38.7 cents to 54.4 cents a pound on the national average (Table 1). As a result, the total value of the domestic landings has

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[1/] The most important cause of the phenomenon is that it takes 6-7 years for the Olympia oyster to reach market size, whereas the Pacific oyster reaches market size in 3-4 years.

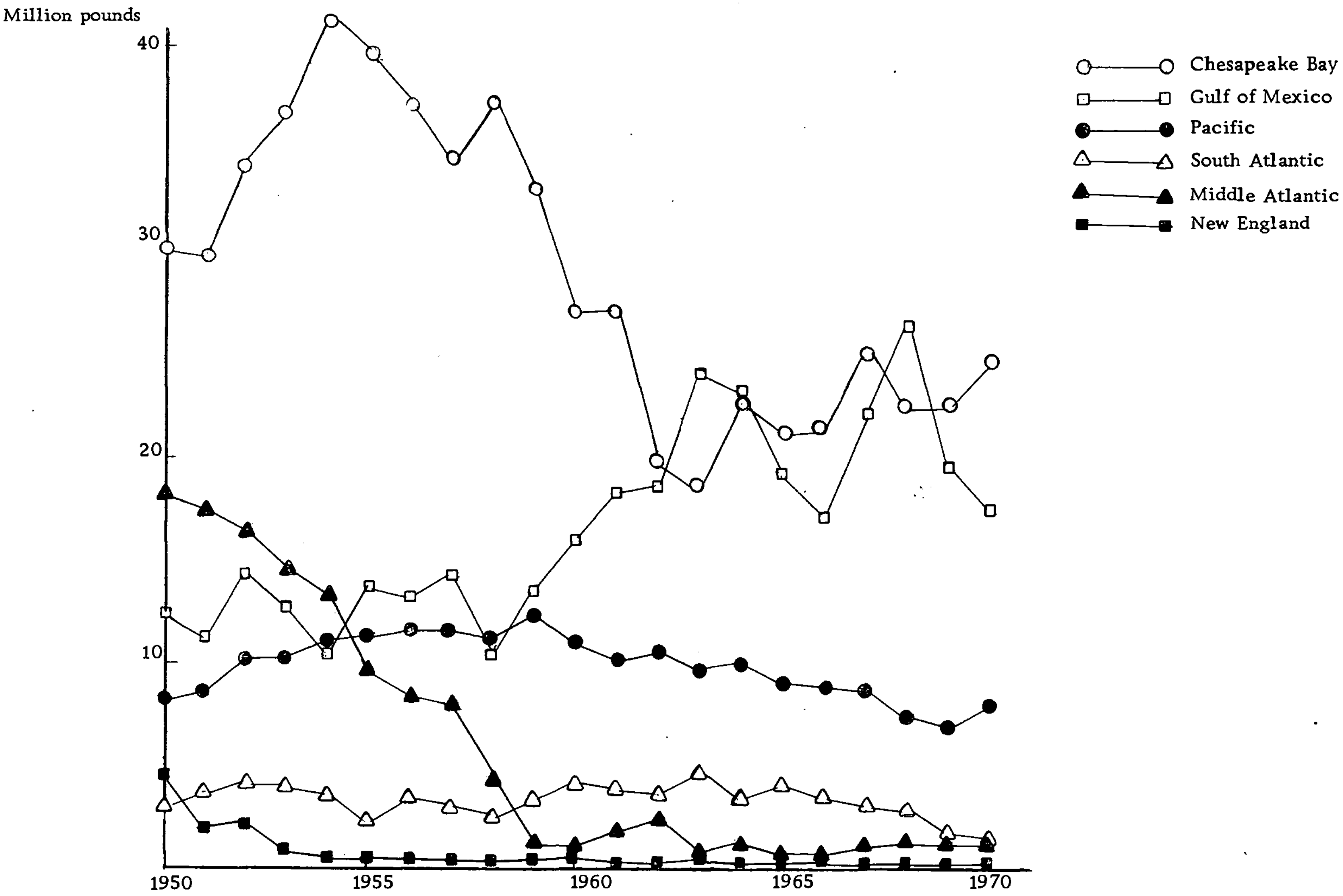

Figure 1. U.S. oyster landings by regions, 1950-70. Source: Fishery Statistics of the U.S., U.S.D.C., 1950-70.

Table 1. U.S. Oyster Prices by Regions, 1950-73 (dollars per pound)

Year	New England	Middle Atlantic	Chesapeake Bay	South Atlantic	Gulf Coast	Pacific Coast	Domestic	Imports
1950	.36	.53	.36	.33	.33	.27	.39	.75
1951	.50	.56	.37	.32	.28	.23	.40	.50
1952	.45	.54	.41	.29	.27	.20	.39	.67
1953	.60	.50	.40	.25	.28	.17	.37	.58
1954	.71	.59	.45	.26	.27	.17	.40	.54
1955	.83	.54	.45	.30	.27	.21	.39	.46
1956	.80	.56	.50	.27	.27	.24	.41	.42
1957	1.00	.63	.50	.29	.23	.19	.41	.37
1958	1.00	.79	.55	.30	.26	.20	.46	.30
1959	1.25	.93	.62	.29	.29	.19	.46	.33
1960	1.20	1.00	.71	.39	.28	.21	.49	.33
1961	1.00	1.05	.79	.45	.28	.20	.53	.31
1962	1.33	1.08	.80	.45	.31	.24	.52	.36
1963	1.00	1.00	.75	.43	.30	.26	.46	.36
1964	1.33	1.00	.71	.43	.27	.26	.46	.36
1965	2.33	1.38	.79	.37	.30	.24	.51	.37
1966	2.00	1.33	.68	.43	.38	.35	.54	.38
1967	2.33	1.00	.67	.44	.38	.44	.64	.36
1968	2.50	1.00	.67	.50	.39	.38	.52	.39
1969	2.00	1.00	.63	.61	.49	.37	.53	.38
1970	2.00	1.30	.61	.62	.43	.46	.55	.54
1971	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	.55	.69
1972	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	.64	.66
1973	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	.72	.58

Source: Compiled from Fishery Statistics of the U.S., U.S.D.C., 1950-73.

risen slightly. However, the regional variations in price are rather significant. In the Middle Atlantic states ex-vessel prices have risen from 36 cents per pound in 1950 to $1.30 per pound in 1970. The price per pound of oysters in New England has increased from 52 cents in 1950 to $2.00 in 1970. The total value of production in the Middle Atlantic states has decreased significantly from 9.6 million dollars in 1950 to 1.8 million dollars in 1970 in spite of a surge in price and, in the New England region, the value of production has declined from 1.7 million dollars to 0.4 million dollars over the same period.

Oyster production in the Chesapeake Bay and South Atlantic regions has declined slightly over the last two decades. Production has decreased in Chesapeake Bay from 30 million pounds in 1950 to 24.7 million pounds in 1970. However, the value of production has increased from 11.1 million dollars to 15.1 million dollars during the same period.

Oyster production of the Pacific region has been rather stable for the last 20 years. The production has not changed much in volume, while 1970 oyster prices have increased about 70 percent from 1950. The Gulf Coast is the only region where total production as well as total value has increased in the last two decades (Table 2).

There are several price elasticities of demand for oysters. The Gulf Coast produces, mostly, shucked oysters where an

Table 2. U. S. Oyster Landings by Regions, 1950-73 millions of pounds (meat weight) and millions of dollars

Year	New England		Middle Atlantic		Chesapeake Bay		South Atlantic		Gulf Coast		Pacific Coast		Total dom. landings		Imports		Total supply		Imports as a % of total value
	Qty.	Value	Qty.	Value	Qty.	Value	Qty.	Value	Qty.	Value	Qty.	Value	Qty.	Value	Qty.	Value	Qty.	Value	
1950	4.7	1.7	18.2	9.6	30.0	11.1	3.0	1.0	12.3	4.0	8.2	2.2	76.4	29.6	0.4	0.3	76.8	29.9	1.0
1951	2.0	1.0	17.4	9.7	29.6	12.0	3.8	1.2	11.6	3.2	8.7	2.0	73.0	29.1	1.0	0.5	74.0	29.6	1.7
1952	2.2	1.0	16.8	9.1	34.4	14.9	4.1	1.2	14.6	4.0	10.1	2.0	82.2	32.3	0.6	0.4	82.9	32.7	1.2
1953	1.0	.6	14.5	7.3	26.9	14.7	4.0	1.0	12.8	3.6	10.4	1.8	79.7	29.1	0.7	0.4	80.4	27.3	1.4
1954	.7	.5	13.4	7.5	41.6	18.9	3.8	1.0	11.4	3.1	11.0	1.9	81.9	32.8	1.1	0.6	83.1	33.4	1.8
1955	.6	.5	9.8	5.3	39.2	17.8	2.3	0.7	13.9	3.7	11.7	2.5	77.5	30.5	1.5	0.7	79.0	31.1	2.3
1956	.5	.4	8.5	4.2	37.1	18.7	3.7	1.0	13.5	3.1	11.9	2.8	75.1	30.8	1.9	0.8	77.1	31.7	2.5
1957	.4	.4	8.0	5.0	34.2	17.2	3.1	0.9	14.3	3.7	11.7	2.2	71.7	29.4	2.7	1.0	74.3	30.4	3.3
1958	.3	.3	4.3	3.4	37.5	20.8	2.7	0.8	10.4	3.0	11.2	2.2	66.4	30.4	5.4	1.6	71.8	32.0	5.0
1959	.4	.5	1.4	1.3	33.3	20.6	3.5	1.0	13.7	3.8	12.4	2.3	64.7	29.5	6.0	2.0	70.6	31.4	6.4
1960	.5	.6	1.2	1.2	27.1	19.3	4.1	1.6	16.1	4.3	11.0	2.3	60.0	29.2	7.0	2.3	67.0	31.5	7.3
1961	.5	.5	1.9	2.0	27.5	21.7	4.0	1.8	18.2	5.1	10.2	2.0	62.3	33.2	7.7	2.4	70.0	35.6	6.7
1962	.3	.4	2.4	2.6	19.9	16.0	3.8	1.7	18.8	5.9	10.8	2.6	56.0	29.1	7.8	2.8	63.9	31.9	8.8
1963	.5	.5	1.0	1.0	18.3	13.7	4.8	2.0	24.1	7.2	9.8	2.5	53.4	27.1	8.5	3.1	66.9	36.2	10.3
1964	.2	.3	1.4	1.4	22.1	15.8	3.5	1.5	23.4	6.3	10.0	2.6	60.5	27.9	8.0	2.9	68.5	30.8	9.4
1965	.3	.7	.8	1.1	21.2	16.7	4.1	1.5	19.2	5.7	9.2	2.2	54.7	27.9	8.6	3.2	63.3	31.1	10.3
1966	.4	.8	.9	1.2	21.2	14.5	3.7	1.6	17.2	6.5	7.8	2.7	51.2	27.4	12.0	4.5	63.2	31.9	14.1
1967	.3	.7	1.2	1.2	25.4	17.1	3.2	1.4	21.2	8.0	8.8	3.9	50.0	32.2	16.1	5.8	76.1	38.1	18.0
1968	.2	.5	1.5	1.5	22.2	14.9	3.0	1.5	26.7	10.3	7.8	3.0	61.9	32.0	14.5	5.6	76.4	37.7	14.9
1969	.2	.4	1.3	1.3	22.2	14.0	1.8	1.1	19.8	8.1	7.0	2.6	52.2	27.5	16.7	6.4	68.9	33.9	18.8
1970	.2	.4	1.4	1.8	24.7	15.1	1.6	1.0	17.7	7.5	8.0	3.7	53.6	29.5	15.0	8.1	68.6	37.6	21.5
1971	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	54.6	30.4	9.5	6.7	64.0	37.0	18.1
1972	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	52.5	33.8	20.8	13.8	73.4	43.6	27.8
1973	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	48.6	35.2	19.9	11.6	68.5	46.3	24.8

Source: Fishery Statistics of the U.S., U.S.D.C., 1950-73.

increase in oyster production has been accompanied by a more than proportionate increase in total receipts. On the other hand, the Pacific region and the domestic aggregate supply have not only decreased but also their total receipts have increased over the two decades (Table 2). However, caution should be exercised in the interpretation of the price elasticities of demand. Each product such as shucked, half-shell, or smoked oysters may show a different price elasticity of demand.

Oyster Industry Problems

The problems dealt with in this section may be specific to a particular region in the U.S. or applicable to the entire U.S. oyster industry. These problems (Wallace, 1960; Engle, 1966; Windham, 1968; Matthiessen, 1970; Sokoloski, 1970; Bardach et al., 1972) are as follows:

(1) The supply of oyster seed: Oyster seed, in most areas, depends entirely upon natural settings, and is greatly affected by environmental factors.[2/] The natural settings in some areas like New England, Middle Atlantic and Chesapeake Bay have not been favorable because of the lack of sufficient numbers of mature oysters

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[2/] The Pacific oyster industry is heavily dependent upon imports of oyster seed from Japan.

to produce enough seed for the industry. Yet, oyster seed hatcheries have not shown the capacity to supply more seed to the industry. Perhaps oyster seed hatcheries have such potential, but uncertainties in natural settings are likely to be an impediment to the establishment of hatcheries, since good natural settings would probably bring a far lower price for seed than for the product of hatcheries.

(2) Natural disaster and predators: Since 1950, New England oystermen have sustained tremendous losses from hurricanes, starfish and oyster drill. No commercial seed set was recorded until 1957 in these areas (Matthiessen, 1970). Delaware Bay had an almost total destruction of its oysters in 1957-60 by starfish, oyster drill and MSX.

(3) Pollution: An increasing number of human and industrial wastes will be accompanied by a larger amount of pollutants. Increased pollution precludes many uses of estuaries including oyster production.

(4) MSX: This oyster disease caused a tremendous reduction in oyster production in Chesapeake Bay and the Middle Atlantic states during the 1950's and 1960's. Thus far, no definite solution to the MSX problem has been found. The development of a MSX-resistant strain is a possible solution.

(5) Technology: There has been little technological change in harvesting and distribution. In some areas, a reduction in the scale of operation due to a decrease in oyster production by disease and hurricanes has forced the use of (less efficient) tongs instead of dredges. However, a considerable breakthrough in productivity could have a substantial effect on the industry.

(6) Regulatory structure: Present regulations concerning the use of state and local estuaries have emerged over the past several decades, and the conditions for the lease of common property for private use have become extremely stringent in some areas such as New England. Matthiessen states (1970, p. 10) that:

> "In States such as Rhode Island and Massachusetts, it is exceedingly difficult to obtain exclusive fishing rights to areas of coastal water. Legislation regarding private lease is restrictive, and there are increasing conflicts between commercial and recreational interests."

(7) Competition for resources: Changes in technology, population and social values have brought new competition for the use of common properties. The majority of the oyster beds in the U.S. are public grounds (Bardach, 1968, p. 1). Oyster growers must compete with nonfishery uses of the resource base. As social opportunity costs for public property becomes higher, the public authorities become reluctant to lease the common property for a low rent.

(8) Consumption patterns: It seems that there has been a gradual change in the U.S. consumers' tastes toward less consumption of oysters (Sokoloski, 1970, p. 4). The income elasticity of demand for oysters has been estimated at 0.25 (Bell, 1969, p. 7), i.e., the consumption of oysters is less than proportional to income increase.[3/] New marketing and distribution changes, and perhaps new product forms could reverse this relationship.

(9) Role of imports: Imports of oyster products in the U.S. market have increased from 5.8 million pounds, valued at 0.6 million dollars in 1950, to 19.9 million pounds valued at 11.6 million dollars in 1973. The total market share of imports surged from 1.0 percent to 24.8 percent in the same period (Table 2). Oyster imports consist of four major items: fresh and frozen, canned, seed, and oyster juice (U.S.D.C., 1973). Canned items such as smoked and cooked oysters constituted 97 percent of the imported value in 1972. In that year half of the canned items were consumed in the Pacific region. The major suppliers of these products in 1972, in order of importance, were Japan, Korea, and Hong Kong. Prices of imports have been considerably lower than the average

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[3/] This statement may be misleading in the sense that a lumped estimate does not reflect the true estimate of each product.

domestic price except in the Pacific and Gulf Coast regions (Table 1). The low-priced imports have been increasingly dominating the U.S. canned oyster market (Figs. 2 and 3, Table 3). The production of U.S. canned oysters has decreased, particularly regular packed oysters (Table 4). However, the production of fresh and frozen oysters in the last 10 years has been rather stable (Fig. 4).

High labor costs in the U.S. for shucking small-size oysters for the canned market resulted in a comparative advantage to change in favor of Japan, Korea, and Hong Kong where labor costs are considerably lower than those of the U.S.

Barrett (1963), Sokoloski (1970, p. 3) and Matthiessen (1970, p. 31-2) indicated that imports of canned oysters in areas such as the Pacific and the Gulf Coast regions forced a structural change in production patterns, i.e., a change from the canned to the fresh and frozen oysters through the 1950's and 1960's. Sokoloski (1970, p. 3) reported that cold storage was increased in the Gulf Coast and the Pacific regions due to an influx of imports in the 1960's.

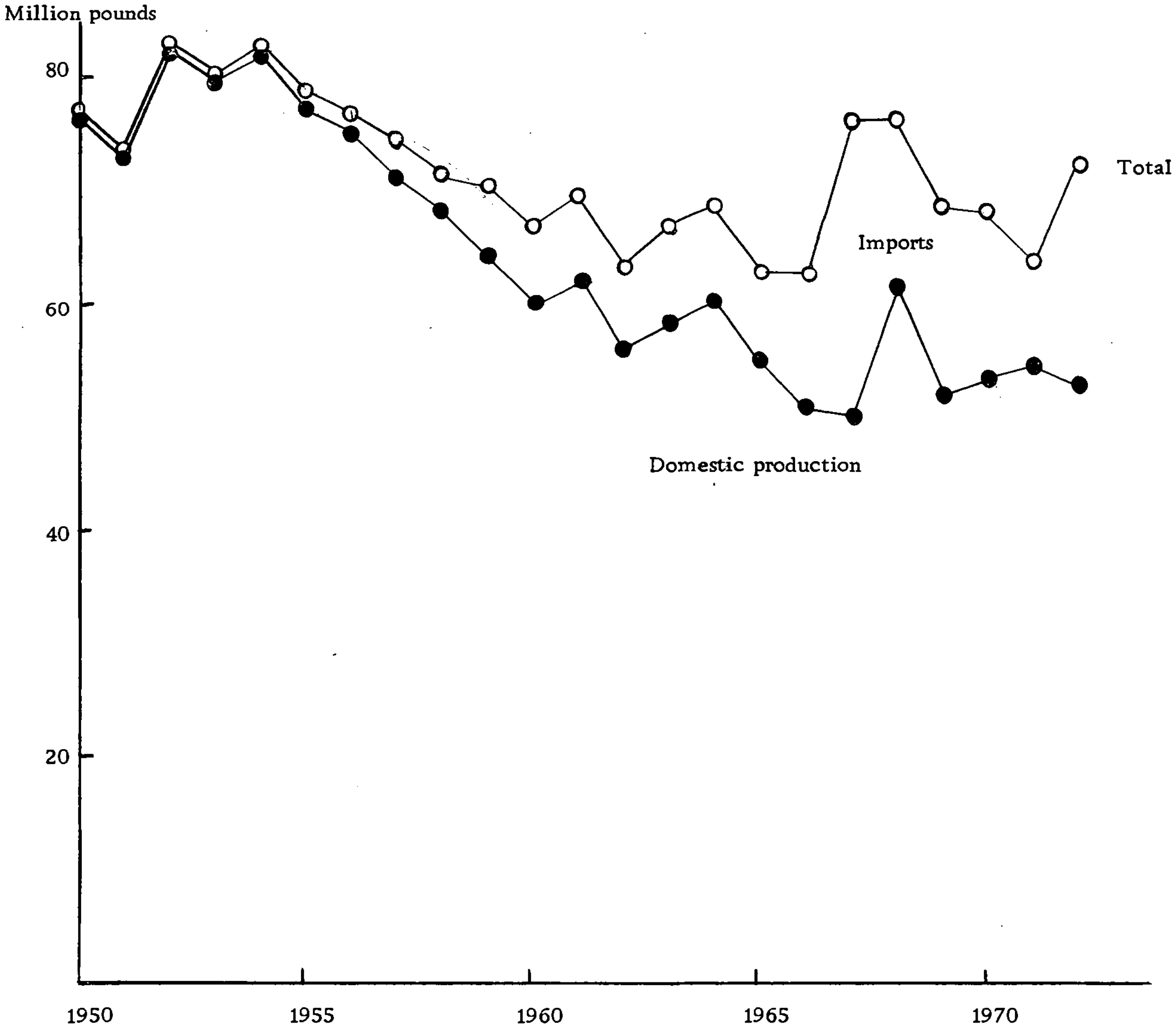

Figure 2. U. S. oyster production and imports, 1950-72. Source: Fishery Statistics of the U. S., U. S. D. C., 1950-72.

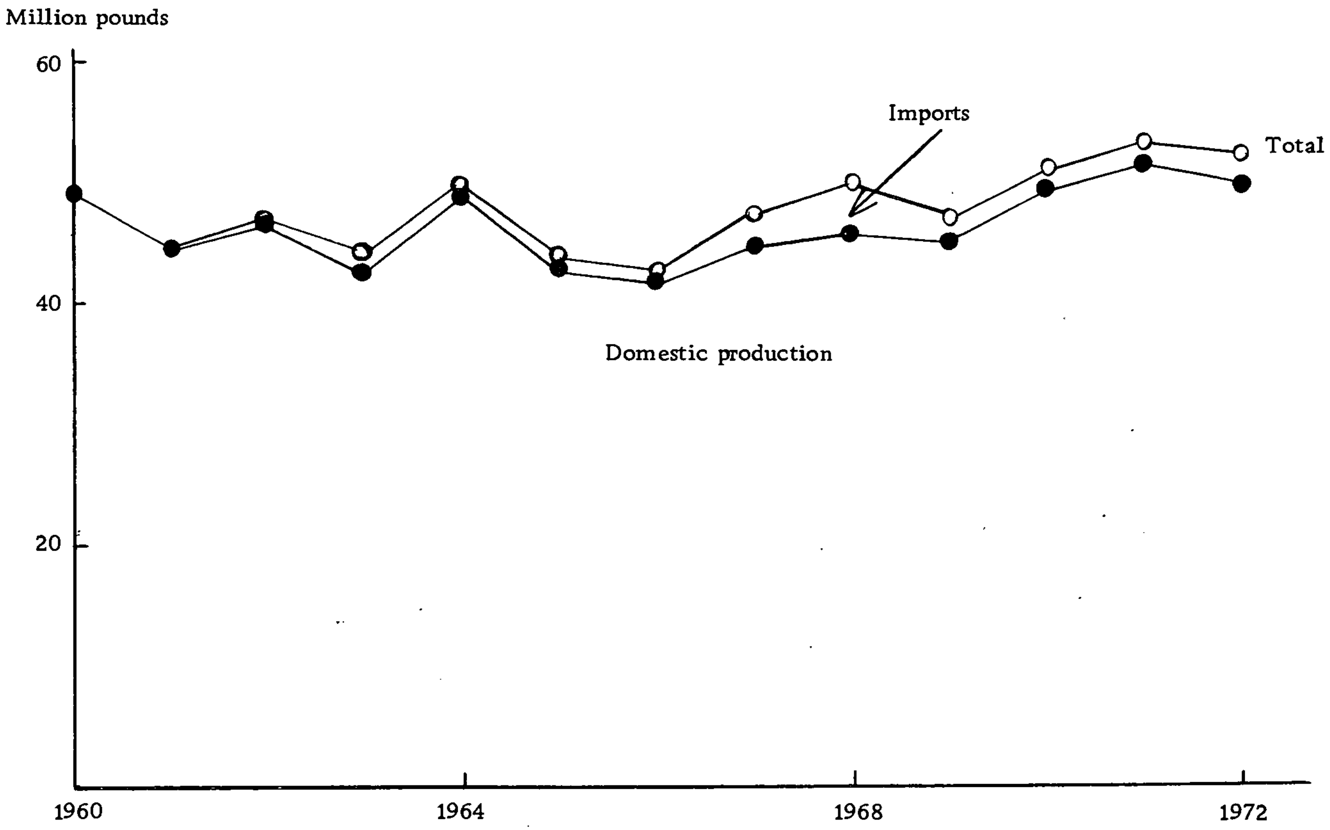

Figure 3. U. S. fresh and frozen oyster production and imports, 1960-72.
Source: Current Fishery Statistics of the U. S., U. S. D. C., 1973.

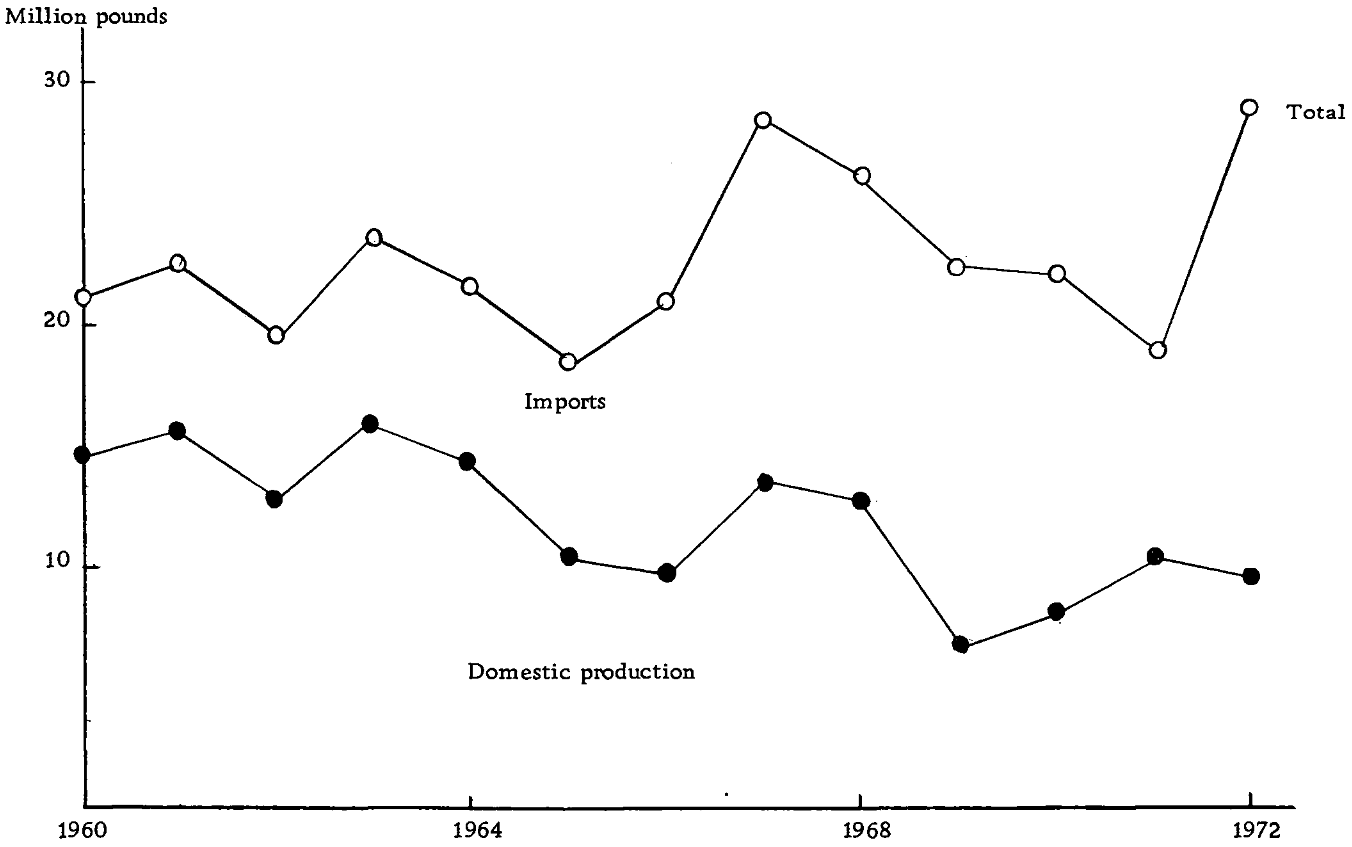

Figure 4. U. S. canned oyster production and imports, 1960-72.
Source: Current Fishery Statistics of the U. S., U. S. D. C., 1973.

Table 3. U.S. Canned Oyster Production and Imports, 1960-72 (millions of pounds) a/

Year	Pack					Total	Canned imports	Total supply
	Regular							
	East and Gulf	West Coast	Smoked	Stews	Bisque and soup			
1960	8.8	3.8	0.2	1.7	c/	14.5	6.5	21.0
1961	10.6	2.6	0.1	1.9	c/	14.3	7.2	22.5
1962	6.8	3.0	0.2	2.2	c/	12.3	7.3	19.5
1963	10.4	2.9	0.1	2.4	c/	15.8	7.9	23.7
1964	10.1	2.4	0.1	1.6	c/	14.2	7.4	21.6
1965	8.1	b/	0.1	2.1	c/	10.3	8.0	18.8
1966	5.8	b/	0.1	3.9	c/	9.8	11.2	21.0
1967	9.8	b/	0.1	3.4	c/	13.3	15.0	28.2
1968	9.5	b/	1.4	2.8	c/	12.6	13.5	26.1
1969	4.2	b/	0.0	2.2	0.2	6.6	15.6	22.1
1970	4.1	b/	0.1	3.7	0.1	8.0	13.9	21.9
1971	7.2	b/	0.1	2.9	c/	10.2	8.8	18.9
1972	5.9	b/	0.1	3.6	c/	9.5	13.4	28.9

a/ Meat weight

b/ West Coast included with East Coast and Gulf

c/ Less than 0.05 million pounds

Source: Current Fishery Statistics of the U.S., U.S.D.C., 1973

Table 4. U. S. Fresh and Frozen Oyster Production and Imports, 1960-72 (millions of pounds) a/

Year	Shucked	Steamed	Breaded	Specialties	Domestic supply	Imports	Total supply
1960	46.1	.8	1.6	0.2	48.8	0.1	48.8
1961	41.7	.8	1.4	0.2	44.1	0.1	44.2
1962	44.4	.7	1.4	0.0	46.5	0.1	46.6
1963	40.9	.1	1.7	0.2	42.9	1.0	44.0
1964	46.1	.1	1.9	0.2	48.4	0.7	49.2
1965	39.6	.9	1.9	0.3	42.6	1.0	43.6
1966	38.4	1.0	2.2	0.1	41.8	0.9	42.6
1967	40.3	1.3	2.5	0.2	44.2	2.7	46.9
1968	43.2	1.5	3.1	0.2	47.9	2.1	50.0
1969	42.7	b/	2.7	0.1	45.4	1.1	46.5
1970	46.5	b/	2.9	0.2	49.7	1.6	51.2
1971	48.4	1.0	2.4	0.1	52.0	0.9	52.9
1972	45.5	1.0	2.5	0.1	49.1	2.9	52.0

a/ Meat weight

b/ Less than three plants producing

Source: Current Fishery Statistics of the U. S., U. S. D. C., 1973

II. DATA SOURCES

The data used for the economic analysis in this study were obtained from secondary sources, particularly from experiments conducted by the Department of Fisheries and Wildlife, Oregon State University, from 1973 to 1974 at Newport, Oregon. These experiments were intended (1) to examine the effect on salmon and oyster production of effluent from a possible nuclear power plant on the Pacific Northwest, (2) to investigate season changes in oyster growth patterns due to a change in natural food supply, and (3) to identify what constitutes the biologically optimum water flow and temperature for oysters without artificial feeding.

Some physiological research of the Pacific oyster lacks necessary information for economic analysis (e.g., specifications of critical variables). This information was supplemented by data for other species of oysters, e.g., American and European oysters.

Current Physiological and Biological Knowledge

The Pacific oyster, Crassostrea gigas (Thunberg) is native to Japan from which it was imported in the late 1910's. It is widely cultivated on the West Coast of the U.S. and Canada as well as in Japan. Although the Pacific oyster has acclimatized to a new environment, only a few places in Washington and British Columbia have sufficiently high enough water temperatures to permit reproduction.

Under natural conditions on the West Coast of the United States and Canada, the life cycle of the Pacific oyster starts in June with spawning of the eggs by the female and the fertilization of those eggs by the male. After 24 hours or so the eggs hatch into free-swimming larvae. About three weeks later the larvae attach themselves to a smooth hard surface. Thereafter, the oysters grow rapidly until the water temperature reaches 22 to 23°C. The growth of the oysters is suspended twice a year, once due to spawning activities, and the other due to hibernation. These behavioral changes are caused by changes in environmental temperature.

Growth

Many different criteria have been used to measure the growth of oysters. As a basic criterion for growth measurement, biologists tend to use shell length. However, the growth of oysters is most accurately measured by (1) the condition index (the condition index refers to the ratio of the dry meat weight to the 'interior' shell volume times 1, 000), or (2) (a better measure of growth) the total energy content of the body (Warren and Davis, 1967) of oyster is apparently most advantageous. However, there are some serious difficulties when the oysters must be measured on a continuous basis in a controlled population.

In general, growth rates of oysters vary with size and age. The growth rates of oysters decrease as oysters increase in size, since an increase in total weight would require more energy to maintain their bodies.

Environmental Factors

Oyster growth is interrelated with many known and unknown environmental factors. Variations in growth rate among the same species are evidenced by the existence of different physiological races of oysters. However, many biologists agree that temperature, food supply, salinity, pH and dissolved oxygen in sea water play a major role in the growth rate of oysters (Pereyra, 1962; Chew, 1963; Matthiessen and Toner, 1966; Claus and Alder, 1970). Environmental factors identified from literature reviews are as follows:

(1) Temperature of water (°C)

(2) Salinity (ppt)

(3) pH [4/]

[4/] The term pH is used to indicate the degree of acidity of a solution by measuring the quantity of free hydrogen ions (H^+).

(4) Food supply (organic carbon or equivalent cell number/oyster/minute)

(5) Water supply (milliliters/oyster/minute)

(6) Dissolved oxygen, 0_2 (micromilliliters/oyster/minute)

(7) Oyster wastes

The parameters that affect oyster growth play a different role among the physiological races. In order to see the contribution of each parameter, it is desirable to use controlled environments. However, it is extremely difficult to evaluate the complexity of biochemical interactions that can occur, and to measure the ability of shellfish to improvise when the quantity of a particular substance is low or zero. Little information is available to substantiate the detailed analysis of interactions.

Temperature in Relation to Growth

The relationship between growth and water temperature has been the subject of numerous studies on fishes as well as on shellfishes. Biologists have been successful in describing major temperature effects on behavior and rates of various biochemical processes. Temperature plays an important role in physiological activities, and ultimately in the biochemical reactions of animals. It regulates rate of digestion and consequently maximum daily food consumption.

Sparks and Chew (1961) studied the monthly increase in length, width and depth of a population of the Pacific oyster when transplanted to different locations in the State of Washington. Their studies seem to indicate that at each location, the growth of oysters (measured in length, width and depth) occurred only during the months from April-May to September. Quayle (1951) studied the seasonal growth rate of the Pacific oyster in British Columbia in 1949, and found that the greatest growth in shell dimensions took place during the period from April to October. Imai and Sakai (1961) investigated the growth of the Pacific oyster (Kumamoto, Hiroshima, Miyagi and Hokkaido, and their hybrids) in different locations. The oysters transplanted to the northern part of Japan increased considerably in length from March-April to September. However, the oysters transplanted to the southern part of Japan grew continuously at a decreasing rate but general cessation of growth was observed during July and August due to spawning activities. The authors in these studies indicate that temperature is the major factor for stimulating growth, if there is abundant food available to the oysters.

Matthiessen and Toner (1966) found that temperature appears to be the dominant factor governing oyster growth because temperature regulates digestion and food consumption. Matthiessen and Toner reported an 18 to 25°C range for the American oyster, while

Loosanoff and David (1950, 1952) indicated an optimum temperature range of 16 to 25°C for stimulating growth. However, optimum temperature ranges vary between physiological races. Under natural conditions, the oysters (*C. gigas*) would start growing rapidly if the temperature were above 10°C. The growth rate reaches a maximum before spawning at 22 to 25°C. The optimum temperature without inducing spawning activities seems to be about 18 to 21°C.

Salinity in Relation to Growth

Salinity plays an important role in maintaining metabolism, growth and fattening. But the critical salinity level depends upon where the oysters are grown. Amenia (1928) found *C. gigas* (the Kumamoto type) living in ranges from 7 to 29 ppt under natural conditions. Quayle (1969) reported that salinity ranges from 10 to 28 ppt in Canada. However, the effect of osmotic pressure on the oysters depends also upon the temperature of water. Feng (1968) concluded that a salinity in the range of 23 to 28 ppt would provide a suitable activity level. Seno (1926) stated that the range of 23.3 to 28.5 ppt would constitute an optimum level for *C. gigas.* The effects of salinity on European flat oysters are shown in Table 5. According to these data, the optimum range of salinity for this species would appear to be from 22.5 to 27 ppt.

Table 5. Relationship Between Salinity and Growth Rate (European Flat Oyster)

Salinity (ppt)	Growth (Micron) in 10 days
27	252
25	250
22.5	247
20	223
17.5	210
15.0	190

Source: Davis et al., 1962

pH in Relation to Growth

Apparently changes in pH value affect pumping activities and oxygen uptake (Goftsoff, 1964). Table 6 indicates that normal pumping occurs at a pH level of 7.75, whereas at pH levels below 7.00 the pumping rate is reduced. Loosanoff and Tommers (1947) reported that the oyster's rate of pumping is affected by pH value, and suggested that a pH range of 7.5 to 8.2 would constitute an optimum value for adult oysters.

Table 6. Effect of pH on Pumping Activities of the American Oyster

pH	Remarks
7.75	Normal pumping
6.75-7.00	Vigorous pumping for several hours and then reduction
6.50	Decrease in pumping, and shell opens for less time
4.25	10 percent of normal pumping

Source: Galtsoff, 1964

Food in Relation to Growth

Oysters use numerous substances as sources of food. Oysters filter out planktons, organic detritus, bacteria and dissolved carbohydrate, and reject or discharge unutilized substances (Butler, 1966). Matthiessen and Toner (1966) found approximately 300 species of planktons in the oyster ground, but how many are utilized and which are best for oyster growth is not known. However, it appears that the combination of different kinds of species meet the nutrient requirements of the oyster. Matthiessen and Toner (1966) stated that the consumption of 1.1×10^9 cells per oyster per day and Dean (1957) indicated that the consumption of 2.4×10^8 cells per oyster per day is the optimum feeding rate for adult oysters.

Water Supply in Relation to Growth

The water supply serves three functions for oysters. It carries food and oxygen to oysters, and carries faeces away from oysters. Water requirements are functions of those three variables. But very little is known about the quantity of water required by the adult oysters. Matthiessen and Toner (1966) reported 10.2 liters per oyster per day and Furfari (1966) reported 18.2 liters per oyster per day.

Dissolved Oxygen (O_2)

Oysters utilize oxygen to generate energy and growth. Korringa (1952) reported that oxygen consumption depends upon the temperature of the oysters' environment. Table 7 shows the functional relationship between the temperature and oxygen uptake. At higher temperatures, uptake increases.

Table 7. Temperature and Oxygen Uptake of American Oyster

Temperature (°C)	O_2 Uptake (cc/100g oyster/day)
5	2
10	5
15	10
20	20

Source: Korringa, 1952

Wastes of Oyster

The oysters discharge two main types of waste products, i.e., urine (liquid) and faeces (solid). A few studies have been done on the estimation of these wastes. Biologists were unable to determine the quantity of urine discharged. Solid oyster wastes were estimated by Haven (1966). Table 8 shows the various amounts of faeces ejected by oysters according to oyster weight.

Table 8. Solid Wastes of American Oyster

Mean weight of oysters (grams)	Mean deposition, grams/oyster/ week		
	Faeces	Pseudofaeces	Total
6.6	0.28	0.35	0.63
11.6	0.40	0.50	0.90
33.0	0.90	2.00	2.90
73.3	1.90	2.45	3.55

Source: Haven, 1966

Methodology

Figure 5 illustrates the basic characteristics of the hypothesized process. The relationships among total, average, and marginal products are used to define the three stages of production. In the first stage both average and marginal product curves rise until the total product curve reaches the inflection point, then marginal product declines. But average product still increases at a decreasing rate until it reaches its maximum (stage II).

Increasing average returns to variable input are also associated with negative marginal returns to the fixed inputs (Fig. 6) assuming a linear homogeneous production function. In the third stage both average and marginal product curves decline and marginal product is negative. As seen in the graphs (Figs. 5 and 6), the stage III is the range of negative physical returns in which an

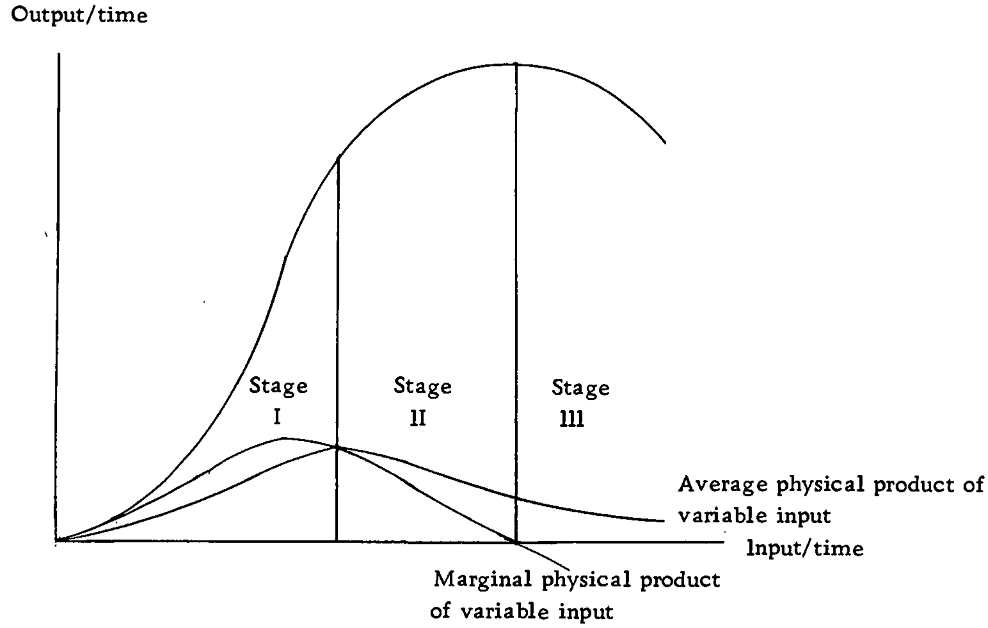

Figure 5. Variable input production stage

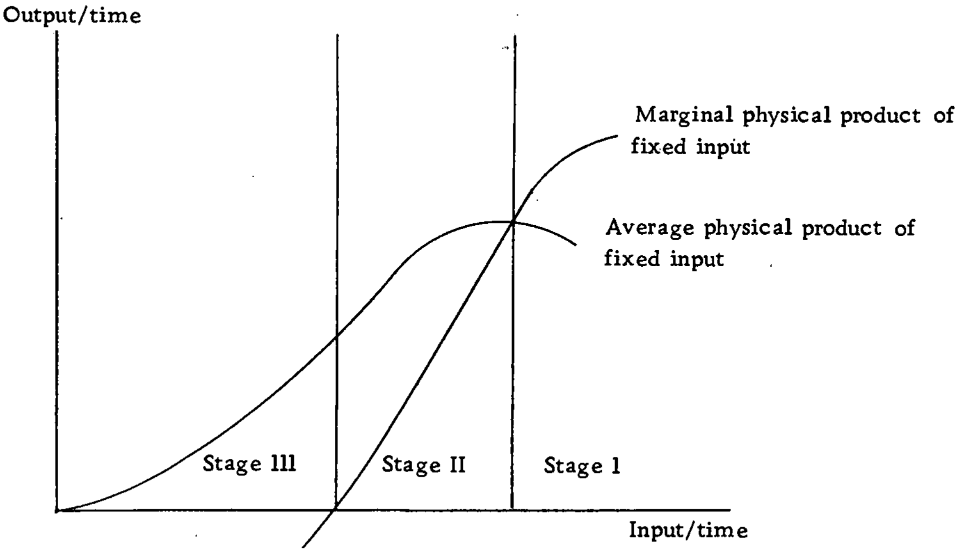

Figure 6. Fixed input production stage

additional input is associated with a decreasing total product. It is obvious that production should not be carried out in this region, unless the input has a negative cost or subsidy.

The previous section explained the one input and one output production situation. But a realistic consideration of production relationships is generally given only by several inputs and one or more outputs. Selection of the least-cost combination requires information regarding the production function, isoquants, and relative input prices. Ferguson (1972, p. 138) defines the production function as such:

> "A production function is a schedule (or table, or mathematical equation) showing the maximum amount of output that can be produced from any specified set of inputs, given the existing technology or 'state of art.' In short run, the production function is a catalogue of output possibilities."

Assuming a continuous production relationship, a general production surface is shown in Figure 7. From the equation derived from the production relationships, the isoquant will be given. Ferguson (1972, p. 172) goes on defining the isoquant as such:

> "An isoquant is a curve in input space showing all possible combination of inputs physically capable of producing a given level of output . . . ."

The isoquant is shown by dropping perpendiculars from the same level of outputs onto the production surface to the input plane (i.e., ABC in Fig. 7).

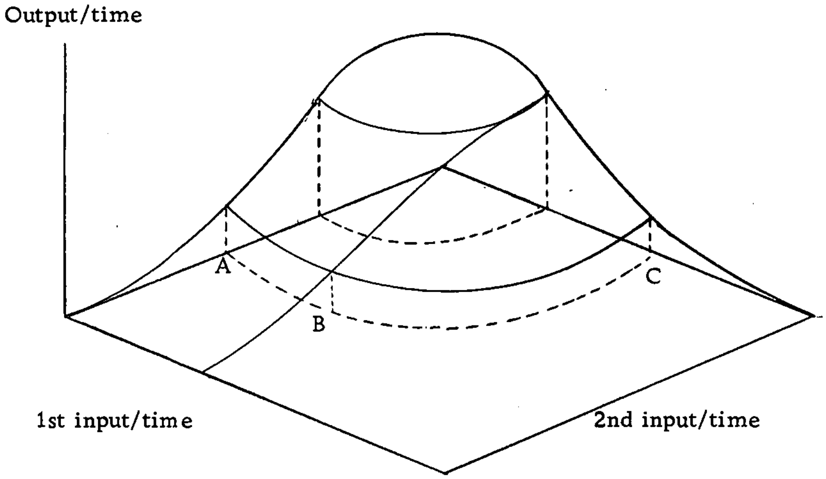

Figure 7. Production surface for a continuous production function showing both substitution and complementarity between inputs

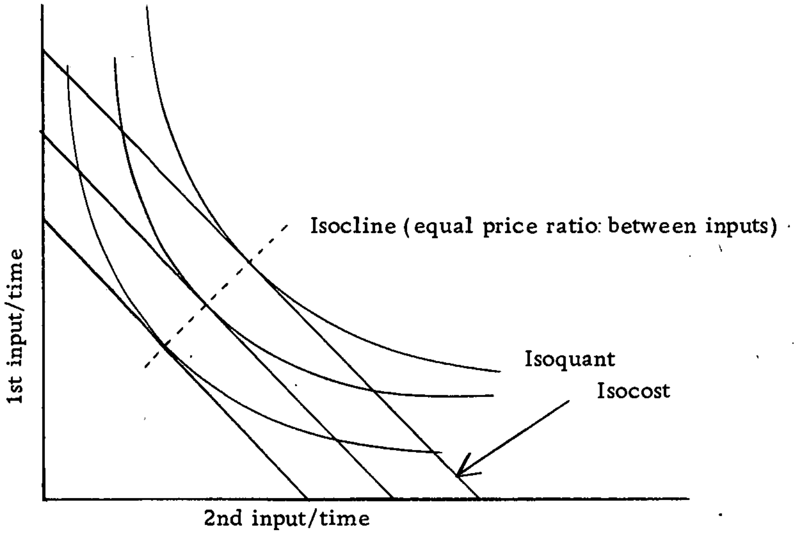

Figure 8. Isoquants and isoclines showing least-cost combinations of inputs with given input prices

Optimum Combinations of Input

The isoquant only tells us various combinations of inputs that produce a constant output. In deriving an optimum input level for that isoquant, the relative prices of inputs must be introduced. Given isoquants, a least-cost combination of factor inputs can be found at the point where the marginal rates of substitution are equal to the inverse of input price ratio, then the various loci of least-cost combinations of inputs when input prices remain constant are called the expansion path.

Mathematical Derivation of Optimum Production Levels and Input Combinations

The discussion of this section is limited to the case of two inputs (x_1 and x_2), and one output (y). It is assumed that the prices of inputs (x_1 and x_2) are functions of the amounts of inputs used but the output can be sold in a perfectly competitive market. The total cost function is given by the following equation:

$$C = (Px_1 \cdot x_1 + Px_2 \cdot x_2 + F.C.) \tag{1}$$

where Px_1 and Px_2 are the functional relationships between the prices of inputs (x_1 and x_2) and the quantities of inputs employed, and F. C. is the fixed cost. Given the production function, f (x_1, x_2)

and the price of output (p_y), the profit (π) would be the difference between total revenue and total costs:

(2) $$\pi = p_y \cdot f(x_1, x_2) - C$$

Substituting C from (1)

(3) $$\pi = p_y \cdot f(x_1, x_2) - (Px_1 \cdot x_1 + Px_2 \cdot x_2 + F.C.)$$

Profit is a function of x_1 and x_2, and is maximized with respect to those two variable inputs. Setting partial derivatives of π with respect to x_1 and x_2 equal to zero.

(4) $$\partial \pi / \partial x_1 = p_y \cdot MPPx_1 - Px_1 + x_1 \frac{\partial Px_1}{\partial x_1} = 0$$

(5) $$\partial \pi / \partial x_2 = p_y \cdot MPPx_2 - Px_2 + x_2 \frac{\partial Px_2}{\partial x_2} = 0$$

(4) and (5) will be zero, when:

(6) $$p_y \cdot MPPx_1 = Px_1 + x_1 \frac{\partial Px_1}{\partial x_1}$$

(7) $$p_y \cdot MPPx_2 = Px_2 + x_2 \frac{\partial Px_2}{\partial x_2}$$

Therefore, value marginal product must equal marginal cost for x_i and x_2.

This tells us that for profit maximization, each input should be utilized up to the point where value of the marginal product is equal to the marginal input cost.

Oyster Production

Figure 9 shows the basic operations of oyster culture under controlled environmental conditions. Mathiessen and Toner (1966) American Cyanamid Company (1968, Volume 2) reported detailed engineering studies on algae and oyster production. They listed the following as major fixed factors for algae and oyster production:

Algae culture (continuous culture)

(1) Illumination
(2) Air compressors
(3) Delivery systems
(4) Structures
(5) Tanks
(6) Pipings
(7) Heat exchangers

Oyster growing tanks

(1) Baskets
(2) Tanks
(3) Pumps
(4) Pipings
(5) Heat exchangers
(6) Structures
(7) Filtration systems

The American Cyanamid Company reports have come up with a cost calculation on the basis of producing 100, 000 bushels of

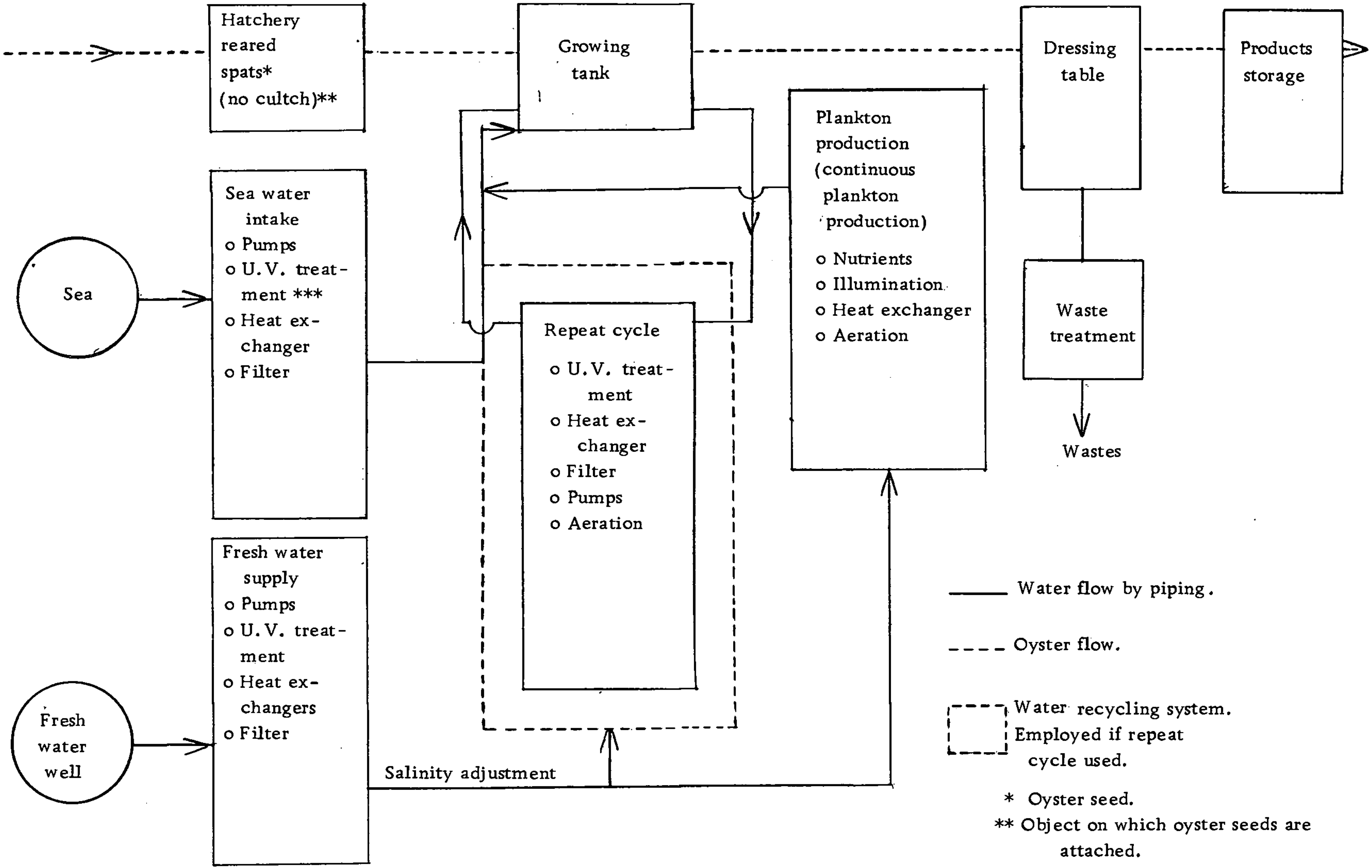

Figure 9. Operation process for oyster production under controlled conditions

oysters per year. Table 9 shows the results of this study.

Table 9 indicates that major costs of producing oysters under controlled environmental conditions are water, algae and growing system. However, the relative significance of water costs, which include the heating of water, are greater than the costs of the algae and of the growing system.

Production Relationships for Oyster

Production Function

Oyster production is a complex process involving may resources of which water flow, temperature and feeding are very important. A general oyster production function can be expressed by the equation shown below:

(8) $$Y = f\,(W,\ T,\ F,\ 0_2,\ P,\ Sa,\ X1,\ \ldots,\ Xn)$$

where

Y = yield (grams/oyster/minute)

W = water flow (milliliters/oysters/minute)

T = temperature

F = feeding [organic carbon (μg)/oyster/minute]

0_2 = dissolved oxygen (micromilliliters/oyster/minute)

P = pH

Table 9. Costs of Producing One Bushel of Oysters

Costs	Growing conditions	
	10°C with stimulants	21°C without stimulants
Initial costs a/		
Water b/	$ 27.93	$ 36.00
Algae	12.78	12.78
Hatchery	2.03	2.03
Growing system c/	17.75	17.75
Processing	0.23	0.23
Total	$ 60.72	$ 68.79
Annual costs		
Water	$ 33.09	$ 46.30
Algae	3.14	3.14
Hatchery	0.47	0.47
Growing system	3.83	3.83
Processing	0.68	0.68
Overhead	1.18	1.18
Depreciation d/	7.07	8.01
Total	$ 49.96	$ 64.11

a/ Includes 5% for instrumentation and 8% for interest during construction.

b/ Water flow rate is 36.000 gpm. No recirculation is used

c/ Includes tanks, pumps and other items listed in Fig. 11

d/ Based on 15 years at 8%

Sa = salinity (part per thousand, ppt)

Xi = unspecified environmental factors affecting oyster growth

Some studies (Pereyra, 1962; Chew, 1963; Burke et al., 1971; Tarr et al., 1971) reveal that in the natural environment of the Pacific Northwest, levels of oxygen, pH and salinity specified in Chapter II,would be fairly constant.[5/] For the reasons shown below, all variables except temperature, water flow and food supply are assumed to be constant:

(1) Under natural conditions, characteristics of sea water such as pH, salinity and other factors do not change much

(2) The cost of adjusting salinity, pH and dissolved oxygen is small, compared with other variables involved.

(3) There are no data available regarding the production relationships between oyster growth, salinity, pH, and dissolved oxygen.

(4) As long as oysters are grown by once-through-sea-water system, those variables (pH, salinity and dissolved oxygen) are assumed to be in stage II under natural conditions. The empirical study (Burke et al., 1971) indicates that those

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[5/] If oysters were cultured under lighting and fed with algae, the algae would generate enough oxygen by phytosynthesis.

variables in Yaquina Bay are highly stable because the size of the bay is large as well as being adjacent to the Pacific where the characteristics of sea water are highly stable.

The framework for oyster production can then be expressed as follows:

(9) $$Y = f(W, T, F \mid 0_2, P, Sa, X_1, \ldots, X_2)$$

Since the water supply is directly correlated with the food supply from sea water, the production function for oysters can be further modified as shown below:

(10) $$Y = f\,[g(w), T \mid 0_2, P, Sa, X_1, \ldots, X_2]$$

However, if the water flow for oysters at a given temperature were specified by the oysters' oxygen requirement and were fed artificially then water flow could be maintained at a minimum as shown in Figure 10. The production function for oysters under those conditions can be expressed as follows:

(11) $$Y = f\,(F, T \mid W, 0_2, P, Sa, X1, \ldots, Xn)$$

The Isoquant Between Water Flow and Feeding

It is true that natural food supply in sea water can be substituted by algae more or less at a constant rate. But it is unlikely that two

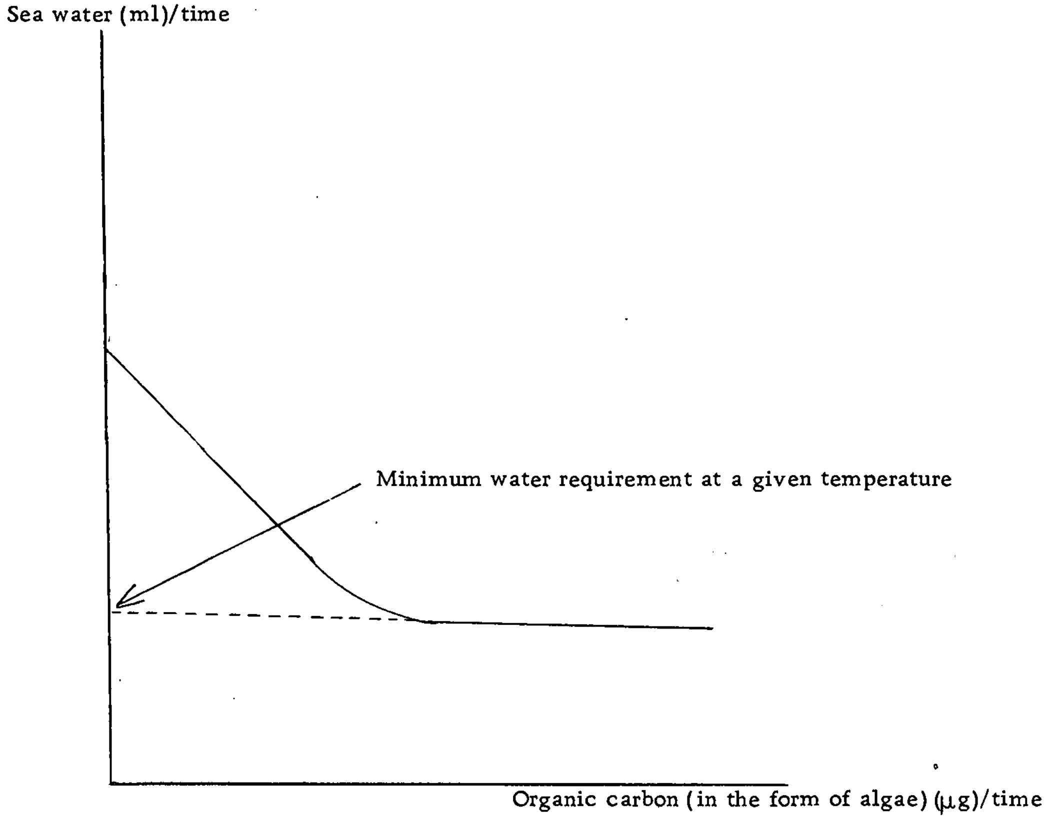

Figure 10. Yield isoquant showing all possible sea water-algae combinations in producing a specified yield.

inputs can be substituted entirely, since oysters require water flow both as an oxygen source and as a source of disposal of faeces. However, feeding can be entirely replaced by supplying increasing volumes of sea water. A model isoquant for these inputs is illustrated in Figure 10.

The Profit-Maximizing Level of One Input for Oyster Production

The profit maximizing level of application of an input could be attained by equating the inverse ratio of the price per unit of oyster (Py) and the prices of inputs (i. e., Pt, temperature; Pw, water flow; Pf, feeding) to the change in yield (∂Y) divided by the change in use of inputs (∂T, temperature; ∂W, water flow; ∂F, feeding).[6/] That is, the marginal physical products ($\partial Y/\partial T$, $\partial Y/\partial W$ and $\partial Y/\partial F$) are equal to the inverse price ratio of input-output of each input employed.

$$\partial Y/\partial T = Pt/Py, \quad \partial Y/\partial W = Pw/Py \text{ and } \partial Y/\partial F = Pt/Py$$

Hence, the optimum level of employment of each input is attained when the (marginal) input cost equals the value marginal product, and returns to all other inputs are maximized. The graphical exposition of these relationships can be shown in Figure 11. The

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[6/] The prices of heating (temperature) and water flow are functions of amount of inputs used whereas the price of feeding is constant regardless of the level of production.

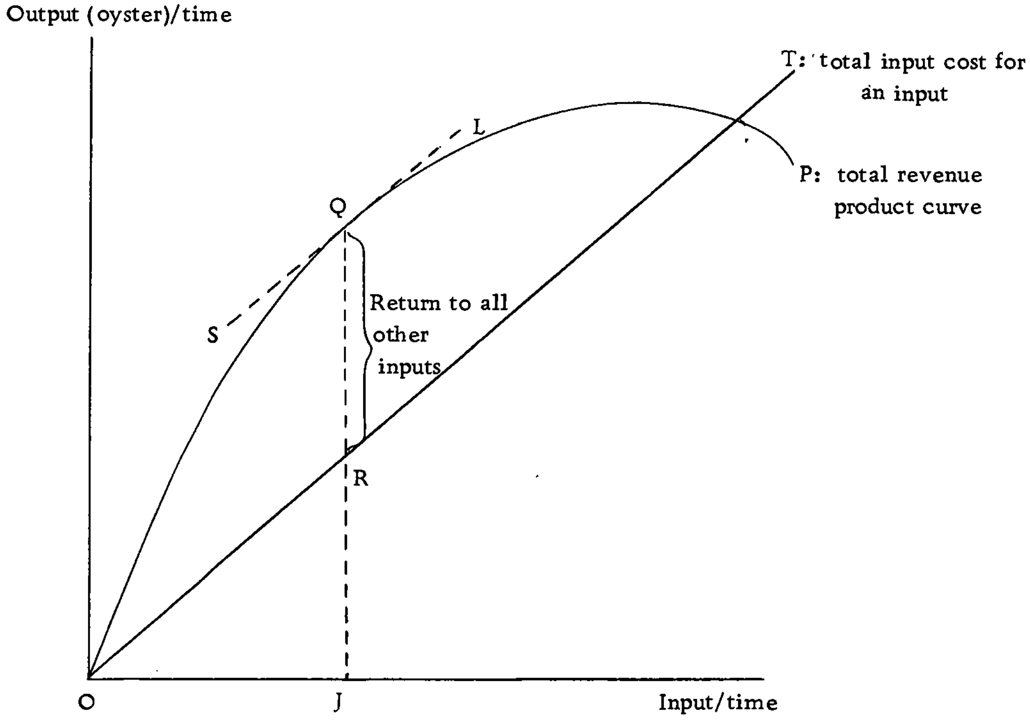

Figure 11. Graphical representation of profit maximizing level of input

curve OP is the total revenue product curve, the slope of which (at a given temperature, water flow or feeding)is $\partial TRP/\partial T$, $\partial TRP/\partial W$ or $\partial TRP/\partial F$ (but the slopes of TRP and total input cost curve may be different) depending on whether T, W or F is being determined.

If the marginal input cost were constant regardless of the level of temperature, water flow and feeding, the line OT, and the curve OP, in Figure 11, should show the relationship between the total revenue product and the total input cost. At a particular slope, the total revenue product curve corresponds to the slope of OT. This is where the marginal input cost equals the value marginal product. Hence, the difference, $QR = QJ - RJ$, is the maximum return to all other inputs. Even if these were fixed inputs, this result would be true, since the fixed inputs would only result in a parallel shift in the OT line.

The Optimum Combination of Two Inputs Over Yield and Gain

Unless temperature, water flow and feeding are combined in fixed proportions, there should be a combination of inputs which minimizes the cost of production at a given level of output. In terms of input cost, the costs are minimized when $\partial Y/\partial T \big/ \partial Y/\partial W = Pt/Pw$ and $\partial Y/\partial T \big/ \partial Y/\partial f = Pt/Pf$ are attained. Thus, the value of one input added just equals the value of the input replaced.

Input Costs

Heating Costs

Heat was assumed to be generated by electric heat exchangers. Since the basic unit of water flow is milliliters, the calorie requirement for raising one milliliter of sea water by 1 °C was estimated.[7/] The price of electricity is a decreasing function of the amount of electricity used. Average costs of electricity are asymptotic to the Kilowatt-hour employed. Water flow costs and corresponding heating costs are a function of water flow rates which are illustrated in Table 10.

Table 10. Pumping Costs and Heating Costs as a Function of Water Flow

Liters/second	Water flow costs (¢/ml)	Heating costs (¢/ml/°C)	Pt/Pw[a/]
100	7.0×10^{-7}	2.3×10^{-5}	0.03
500	4.7×10^{-7}	1.5×10^{-5}	0.03
1000	4.0×10^{-7}	1.3×10^{-5}	0.03
2000	3.7×10^{-7}	1.2×10^{-5}	0.03

[a/] Pw = water flow costs
Pt = heating costs

[7/] Heating and water flow cost calculations were based upon General Lincoln People's Utility District, Rate Schedule No. 200 adopted October 10, 1969. The relationship between the amount of electricity used and total cost is as follows:

$TC = 0.54\sqrt{Kwh}$ where TC = Total cost of electricity
$R^2 = 0.993$ Kwh = Kilowatt-hour

Water Flow Costs

Water flow costs were calculated on the basis of the brake horsepower requirement of pumping up a given quantity of water at the Oregon State University Marine Science Center from the mean tide.[8] However, the price of electricity is a function of electricity consumption. The water flow costs are a function of pumping which is illustrated in Table 10.

Feeding Costs

The feeding costs were estimated from oyster seed hatchery algae production of Isochrysis sp.[9] These costs are also shown in Table 11.

Table 11. Organic Carbon Costs (in form of algae) and Heating Costs

Organic carbon (¢/μg)	Heating costs (¢/ml/°C)	Pc/Pt[a]
2.1×10^{-5}	1.4×10^{-5}	9.1
2.1×10^{-5}	1.2×10^{-5}	17.5

[a] Pc = organic carbon costs
Pt = heating costs

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[8] Tidal Bench Marks, Oregon #13, U.S.D.C., 1971

[9] D. Langmo and K. Im. Unpublished research on feasibility of oyster seed hatchery. Ore. State Univ., Dept. of Agric. Econ. 1974.

Prices of Oysters

Shucked oysters: The prices of oysters shown in Table 12 are predictions for 1976 by 10-year (1965-74) monthly average and the last 3-year (1972-74) monthly average, and the current (1974) price.

Table 12. Current and Predicted 1976 Prices per Gallon and Gram of Shucked Oysters

Prices		
Gallon	Gram	Remarks
$10.00	$0.0055	Predicted by 10-year monthly average
11.55	0.0064	Current price
14.40	0.0079	Predicted by 3-year monthly average

Source: Compiled from Statistics and Market News, U.S.D.C.

Half-Shell Oysters: There has been little trading in the half-shell market in Oregon and Washington. The wholesale prices shown in Table 13 were obtained from the Coast Oyster Company, Seattle, Washington.

Table 13. Spot Prices per Pound and Gram of Half Shell Oysters (as of September 20, 1974)

Prices		
Pound	Gram	Races of oyster
$0.15	$0.00034	Miyagi
1.10	0.00234	Kumamoto

III. PRODUCTION FUNCTION ESTIMATES

The Nature of the Experiments

Newport Experiment III: Total Wet Meat Yield by Temperature and Water Flow

This experiment was conducted by Oregon State University Marine Science Center during the period October 11 to December 15, 1973. The experiment was a 3 x 4 factorial design (3 temperatures and 4 water flows in all possible combinations). The temperatures used were 11, 15 and 20°C. The water flow rates used were 4, 8, 16 and 32 milliliters per oyster per minute. Each treatment received 25 oysters, randomly selected from the same population. Then at the end of the experimental period, all oysters from each treatment were shucked and weighed. Growth was expressed as the average weight of 25 oysters in each treatment. The average yield of shucked meat for each treatment is shown in Table 14.

Table 14. Newport Experiment III: October 11-December 15, 1973 Temperature-Water Flow Treatments and Average Yields (gram) in Wet Meat

Temperature (°C)	Water flow (ml[a/])			
	4	8	16	32
11	0.082	0.091	0.111	0.121
15	0.079	0.118	0.135	0.154
20	0.087	0.097	0.148	0.157

[a/] Milliliters/oyster/minute

Newport Experiment IV: Total Weight Gain by Temperature and Water Flow

This experiment was a 3 x 4 factorial design using the same conditions and the same samples as in experiment III. Weight gains were determined by measuring the shell length of all 25 oysters in each treatment at the beginning and at the end of the experiment. Weight gains were expressed as the difference between the initial and final mean weights for each treatment. The total weight gains for each treatment are shown in Table 14.

Table 15. Newport Experiment IV: October 11-December 15, 1973. Temperature-Water Flow Treatments and Average Gains (gram) in Total Weight a/

Temperature (°C)	Water flow (ml b/)			
	4	8	16	32
11	0.021	0.038	0.081	0.132
15	0.027	0.086	0.150	0.204
20	0.032	0.054	0.102	0.290

a/ Total weight is inclusive of shell

b/ Milliliters/oyster/minute

Newport Experiment V: Total Weight Gain by Temperature and Water Flow

This experiment was conducted in the same fashion as in experiment IV, but the water flows used were 4, 16, 28 and 40 milliliters per oyster per minute. Weight gains were expressed as the difference between the initial and final mean weights for each treatment. The average total weight gains for each treatment are shown in Table 16.

Table 16. Newport Experiment V: May 16-July 15, 1974. Temperature-Water Flow Treatments and Average Gain (gram) in Total Weight [a/]

Temperature (°C)	Water flow (ml[b/])			
	4	16	28	40
11	1.21	3.09	4.16	4.31
15	1.31	3.53	4.50	5.77
20	1.08	1.77	3.72	6.17

[a/] Difference in gain between experiment IV and V was due to a difference in food availability by season (i.e., experiment IV was in winter, whereas experiment V was in summer)

[b/] Milliliters/oyster/minute

Newport Experiment VI: Total Weight Gain by Temperature and Organic Carbon Supply

The experimental conditions were the same as experiment V, but water flow was replaced as a variable by organic carbon count. During the sixth experiment, the organic carbon content of a given quantity of sea water was monitored for a 24-hour period once a week. Since, during summer time, organic carbon supplies from non-sea sources were negligible,[10/] the estimation of growth relation-

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[10/] Sources of organic carbon could be dissolved organic carbon, seaweeds, plankton (phyto and zoo) and so on.

ships between temperature and organic carbon was attempted, assuming that oysters would take any organic matter in the sea water and utilize it for growth. From the experiment conducted by the School of Oceanography at Oregon State University, the amount of organic carbon and the algae equivalency were estimated.[11]

Table 17. Newport Experiment VI: May 16-July 15, 1974. Temperature-Organic Carbon (Algae, <u>Isochrysis sp.</u>) Treatments and Average Gains (grams) in Total Weight

Temperature (°C) / µg[a]	5.56	22.24	38.92	55.60
# of algae[b]	3.9×10^5	1.6×10^6	2.7×10^6	3.9×10^6
11	1.21	3.09	4.16	4.31
15	1.31	3.53	4.50	5.77
20	1.08	1.77	3.72	6.17

[a] Organic carbon (µg)/oyster/minute

[b] Number of algae/oyster/minute

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[11] The estimation of the level of algae requirement was inferred from the equation of monocultured algae, <u>Isocrysis sp.</u>, and the organic carbon content of the algae.

$$A = 70384C$$

$$R^2 = 0.989$$

where A: number of algae
C: organic carbon (µg)

Caution should be used in the interpretation of the level of algae equivalency, since the organic carbon content of algae may vary according to environmental factors and the growth stage of algae.

Production Function Specification

Since little previous study in aquaculture has been done in deriving equations with one or two inputs, the primary consideration in the selection of a production function is that the mathematical characteristics or restrictions of the function must fit the biological relationships involved. The requirements of the production function are that (1) it must allow decreasing productivity to each unit of input, since the higher the stage of growth the greater the amount of energy needed to maintain an organism, (2) the capacity to increase output by an increase in the application level of one input is limited by the levels of other inputs, and (3) as oysters increase in size the changes in body composition are expected to cause changes in substitution rates between inputs. Heady et al., (1955, p. 303) listed five possible equations to explain the production relationships between crops and fertilizer application.

$$Y = a + bF + cF^2 \tag{12}$$

$$Y = m - ar^F \tag{13}$$

$$Y = aF^b \tag{14}$$

$$Y = a + bF + c\sqrt{F} \tag{15}$$

$$Y = a + bF + cF^2 + d\sqrt{F} \tag{16}$$

The production function of the types (13) and (14) do not fulfill all of the mathematical requirements stated above. A major disadvantage of the Cobb-Douglas type function is that if b (power) is greater than zero, the equation will imply a continually increasing yield with respect to that input. It would reach neither a maximum nor a limiting output, if inputs were increased proportionally. Such an implication is inconsistent with biological phenomena. That is, even if all inputs are increased by the same proportion, high temperature, for example, will kill oysters by heat exhaustion.

A simple parabolic function of the form, (12), where a minus sign before C would denote a diminishing marginal rate of returns, does not impose the restrictions common to the power function or the exponential function. It allows both a declining and a negative marginal productivity.

A variation of the quadratic form, used in most of the fertilizer application studies (Heady et al., 1955; Brown et al.; 1956; Baum et al., 1956) took the form of (15). This form allows for a diminishing marginal rate of return. The equations (15) and (16) produce a curve which turns down more slowly than the equation (12). The function increases more rapidly at the beginning of the factor application (if $C < 0$), which might somewhat better describe the biological properties of organisms.

Regression Results

Tables 14, 15, 16 and 17 show that on the average, water flow yields a greater growth response than temperature, and that the interaction between temperatures and water flows results in higher yields. The equations, which were statistically acceptable, were used in deriving the "best fit" production function. The results of the statistical analysis are shown in Tables 18, 20, 22 and 24.

A square root transformation of input interaction and a square transformation of temperature were fitted to the 12 observations of experiment III included in Table 14. The resulting curvilinear equation is equation (17).

A square and square root transformation of the temperature of the quadratic equation (18) was fitted to the data of experiment IV. A square transformation of input interaction and fourth power transformation of temperature was fitted to the data of experiments V and VI (eqs. 19 and 20). These specifications of the regression equations gave the best fit because they explained more of the variations; each of the regression coefficients showed a significant contribution to the explanation of the dependent variable.[12/] The

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[12/] Criterion used in selecting production functions were t value of each coefficient and R^2 of each equation, in addition to the specification described in the preceding section.

transformed equations allow (1) diminishing marginal rates of return (eq. 17 and 18), (2) diminishing marginal rates of substitution, and (3) changes in substitution rates at a ratio line (eq. 17, 18, 19 and 20).

These are as follows:

$$(17) \quad Y_m = 0.0046696T - 0.0033235W + 0.010931\sqrt{TW} - 0.00024191T^2$$

$$(18) \quad Gt = -0.4917 - 0.0022987W + 0.1823\sqrt{T} + 0.00057373TW - 0.00085433T^2$$

$$(19) \quad Gt = 0.15245T + 0.008941W + 0.000004266T^2W^2 - 0.000015534T^4$$

$$(20) \quad Gt = 0.15245T + 0.049598C + 0.0000022081T^2C_2 - 0.000015534T^4$$

where

Y_m = predicted growth in grams of meat (eq. 17)

Gt = predicted gain in grams of total weight (eqs. 18, 19 and 20)

T = temperature level (°C)

W = water flow rate (milliliters/oyster/minute)

TW = interaction between temperature and water flow

C = organic carbon (μg/oyster/minute) (eq. 20)

TC = interaction between temperature and organic carbon (eq. 20)

The t values of the regression coefficients are shown in Tables 18, 20, 22 and 24. The t values indicate the statistical significance of the contribution of the independent variables, hypothesizing that the coefficients of each of the independent variables are not equal to zero against the null hypothesis that coefficients in the independent variable were equal to zero.

The constant terms were dropped from equations (17), (19) and (20). The constant terms in those equations were found to be not significant (at 30 percent significance level). By dropping the constant, the equation would gain a degree of freedom, and therefore improve the t values.[13/] It is also reasonable to assume that, if temperature and water flow were equal to zero, oysters at best would gain no weight.

[13/] J. Neter and W. Wasserman (1974, p. 159) state that "When it is known that $\beta_o = 0$, one could still use the general model (e.g., $y = \beta_o + \beta_1 x_i + e_i$), anticipating that b_o will differ from zero only by a small sampling error. However, it is more efficient to incorporate the knowledge $\beta_o = 0$ into the model, thereby gaining a degree of freedom and simplifying the calculations...." (However) "The model (e.g. $y = \beta_1 x_i + e_i$) should be evaluated for aptness. Even though it is known that the regression function must go through the origin, the function might not be linear other than in the observed area."

Predicted yields and gains per oyster (as shown in Tables 19, 21 and 23) are the average yields from the derived equations. The tables show that diminishing marginal rates of return eventually take place as temperature increases with a given low water flow rate (e.g., 4 milliliters/oyster/minute).

The marginal physical products at high temperatures (e.g., 20°C), given a low water flow, are in fact negative, indicating that at a higher temperature, oysters require more energy just to maintain their bodies. With a limited food supply, growth slows down, since little can be used for growth. However, as contrasted with experiments III and IV, diminishing marginal rates of returns did not take place for water flow in the experiments V and VI, indicating that in the presence of higher temperature and the abundant food supply, oysters grow at increasing rate within the observed experimental area. The differences in marginal physical product between experiments III and IV indicate that the processes of formation of the shell and the meat may be quite different, i.e., shell growth may occur relatively faster than that of meat.

Statistical Results

The equations derived from the experiments, the regression coefficients, predicted yields and gains for those equations are shown below:

Newport Experiment III: Total Wet Meat Yield (gram) by Temperature and Water Flow

(17) $Y_m = 0.0046696T - 0.0033235W + 0.010931\sqrt{TW} - 0.00024191T^2$

$R^2 = 0.933$

Table 18. Newport Experiment III: Regression Coefficients and t Values for the Total Wet Meat Yield (gram) Function

Independent variables	Regression coefficients	t Values	Significance levels (%) a/
T	0.46696×10^{-2}	3.3038	2
W	-0.33235×10^{-2}	-2.5771	5
$\sqrt{TW}$	0.10931×10^{-1}	4.2481	1
T^2	0.24191×10^{-3}	-4.9731	1

a/ Probability of obtaining as large or a larger value of t by chance, given the hypothesis that the variables do not affect yield.

Table 19. Newport Experiment III: Predicted Yield (gram) Per Oyster for Various Temperatures and Water Flows

Temperature	Water flow (ml a/)				
(°C)	4	8	16	24	32
11	0.08111	0.0978	0.1137	0.1197	0.1201
13	0.0851	0.1044	0.1240	0.1327	0.1362
15	0.0869	0.1085	0.1315	0.1430	0.1485
17	0.0860	0.1100	0.1362	0.1513	0.1577
20	0.0807	0.1079	0.1385	0.1560	0.1664

a/ Milliliters/oyster/minute

Newport Experiment IV: Total Weight Gains (grams) by Temperature and Water Flow

$$(18)\quad Gt = -0.4917 - 0.0022987W + 0.1823\sqrt{T} + 0.00057373TW - 0.00085433T^2$$

$$R^2 = 0.960$$

Table 20. Newport Experiment IV: Regression Coefficients and t Values for the Total Weight Gain (gram) Function

Independent variables	Regression coefficients	t Values	Significance levels (%) a/
W	-0.22987×10^{-2}	-0.9776	50
$\sqrt{T}$	0.18230	1.8025	20
TW	0.57373×10^{-3}	3.8475	1
T^2	-0.85433×10^{-3}	-2.0708	10

a/ Probability of obtaining as large or a larger value of t by chance, given the hypothesis that the variables do not affect yield.

Table 21. Newport Experiment IV: Predicted Gain (gram) Per Oyster for Various Temperatures and Water Flows

Temperature (°C)	Water flow (ml a/)				
	4	8	16	24	32
11	0.0255	0.0415	0.0736	0.1057	0.1378
13	0.0418	0.0626	0.1039	0.1451	0.1864
15	0.0472	0.0724	0.1229	0.1770	0.2274
17	0.0429	0.0727	0.1323	0.1920	0.2516
20	0.0185	0.0552	0.1286	0.2021	0.2755

a/ Milliliters/oyster/minute

Newport Experiment V: Total Weight Gain (grams) by Temperature and Water

$$(19) \quad Gt = 0.15245T + 0.068941W + 0.000004266T^2W^2$$
$$-0.000015534T^4$$
$$R^2 = 0.939$$

Table 22. Newport Experiment V: Regression Coefficients and t Values for the Total Weight Gain (gram) Function

Independent variables	Regression coefficients	t Values	Significance levels (%) a/
T	0.15245	3.8231	1
W	0.68941×10^{-1}	3.1034	2
T^2W^2	0.42660×10^{-5}	2.2678	5
T^4	-0.15534×10^{-4}	-3.0141	2

a/ Probability of obtaining as large or a larger value of t by chance, given the hypothesis that the variables do not affect yield.

Table 23. Newport Experiment V and VI: Predicted Gain (gram) Per Oyster for Various Temperature and Water Flow

Temperature (°C)							
	ml a/	4	8	16	24	32	40
	c·(μg) b/	5.56	11.12	22.24	33.36	44.48	55.60
	algae c/	3.9×10^5	7.8×10^5	1.6×10^6	2.3×10^6	3.1×10^6	3.9×10^6
11		1.734	2.034	2.685	3.401	4.184	5.033
13		1.825	2.087	2.826	3.763	4.483	5.224
15		1.791	2.113	2.849	3.708	4.689	5.794
17		1.590	1.925	2.713	3.759	4.763	6.025
20		0.863	1.224	2.103	3.201	4.517	6.052

a/ Water flow, milliliters/oyster/minute

b/ Organic carbon(μg)/oyster/minute

c/ Algae equivalency/oyster/minute

Newport Experiment VI: Total Weight Gain (grams) by Temperature and Organic Carbon

$$(20)\quad Gt = 0.15245T + 0.049598C + 0.0000022081T^2C^2 - 0.000015534T^4$$

$$R^2 = 0.939$$

Table 24. Newport Experiment VI: Regression Coefficients and t Values for Total Weight Gain (gram) Function

Independent variables	Regression coefficients	t Values	Significance levels (%) a/
T	0.15245	3.8231	1
C	0.49598×10^{-1}	3.1034	2
T^2C^2	0.22081×10^{-5}	2.3678	5
T^4	-0.15534×10^{-4}	-3.0141	2

a/ Probability of obtaining as large or larger value of t by chance, given the hypothesis that the variables do not affect yield.

Yield Isoquants

The isoquants were derived from the predicting equations, (17, 18, 19 and 20). The isoquants show the various combinations of the two pairs of inputs, temperature and water flow, or temperature and organic carbon, that can be used to obtain a particular yield.

The different slopes of the isoquants show the change in the temperature required to maintain a given yield when a higher water flow is applied and vice versa. That is, the slope of the isoquants indicates the rate of substitution between the two inputs.[14/]

[14/] Input combinations have been expressed in terms of substitution rates. In the biochemical processes of an organism one input may not substitute for another; however, a given output may be attained with several combinations of inputs. This may be the case in oyster production, since temperature can never replace the nutrients that oysters need for growth. However, it may be true that at lower temperatures potential nutrients cannot be utilized due to slow digestive process. Temperature and nutrients can be looked upon as substitutes for each other in attaining a given yield even though physiological substitution does not actually take place. The fact that similar yield increases can be attained with different combinations of inputs causes them to serve as substitutes in the decision-making process.

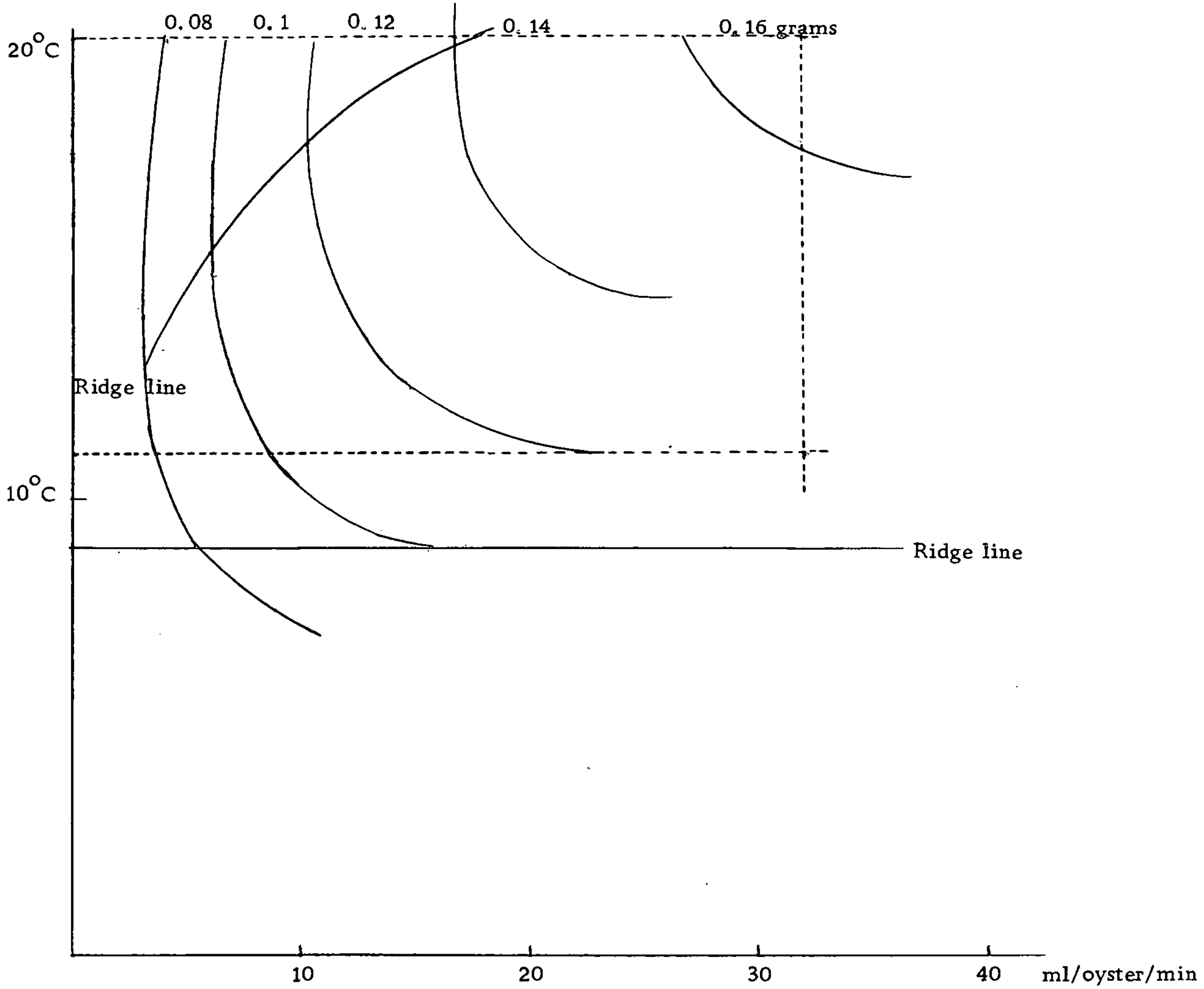

Figure 12. Newport experiment III: Isoquants which illustrate temperature, water flow combinations at specified oyster yields (gram) (dashed horizontal and vertical lines are limit of temperature and water flow in experiment).

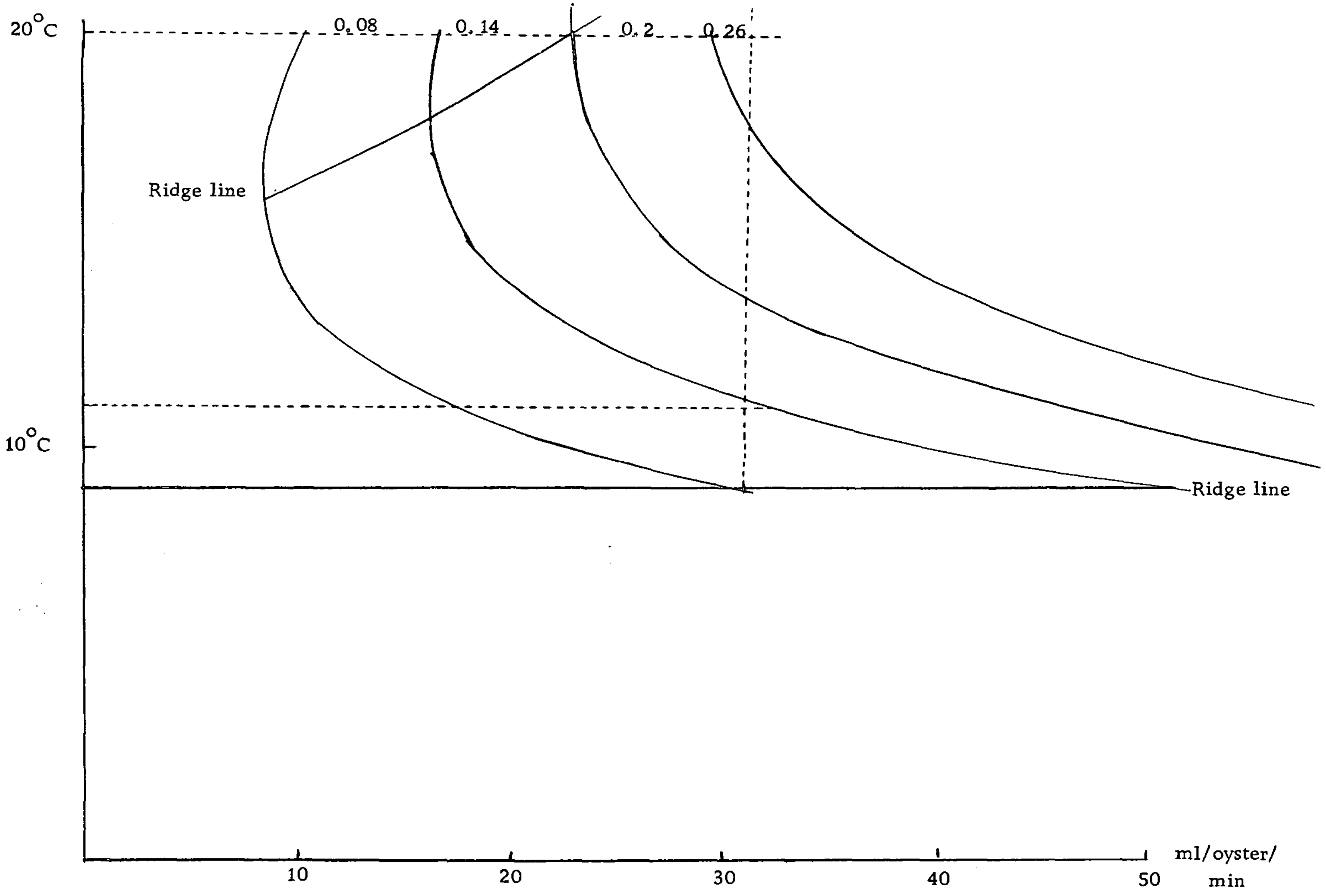

Figure 13. Newport experiment IV: Isoquants which illustrate temperature, water flow combinations at specified oyster gains (gram) (dashed horizontal and vertical lines are limit of temperature and water flow in experiment).

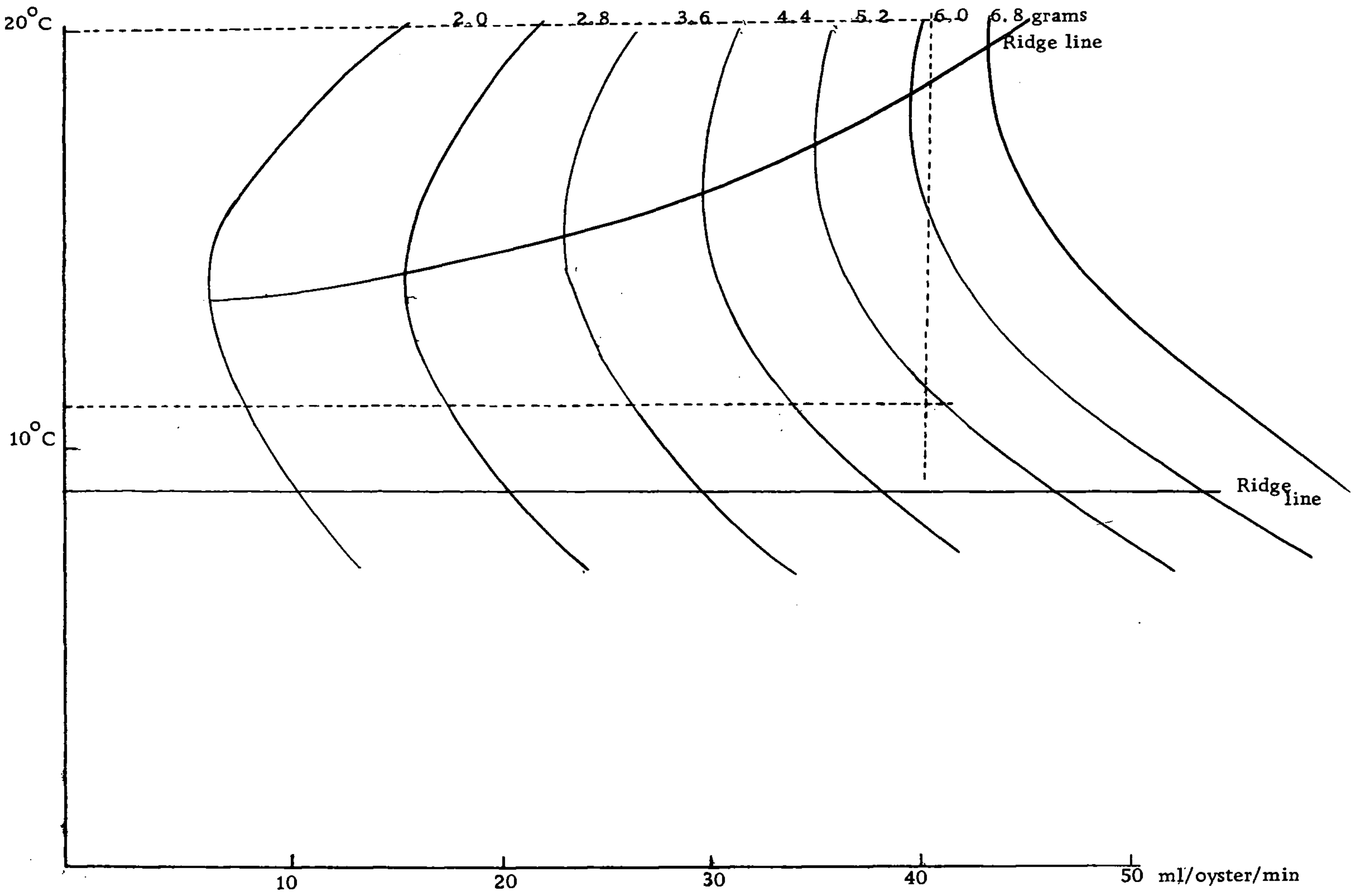

Figure 14. Newport experiment V: isoquants which illustrate temperature, water flow combinations at specified oyster gains (gram) (dashed horizontal and vertical lines are limit of temperature and water flow in experiment)

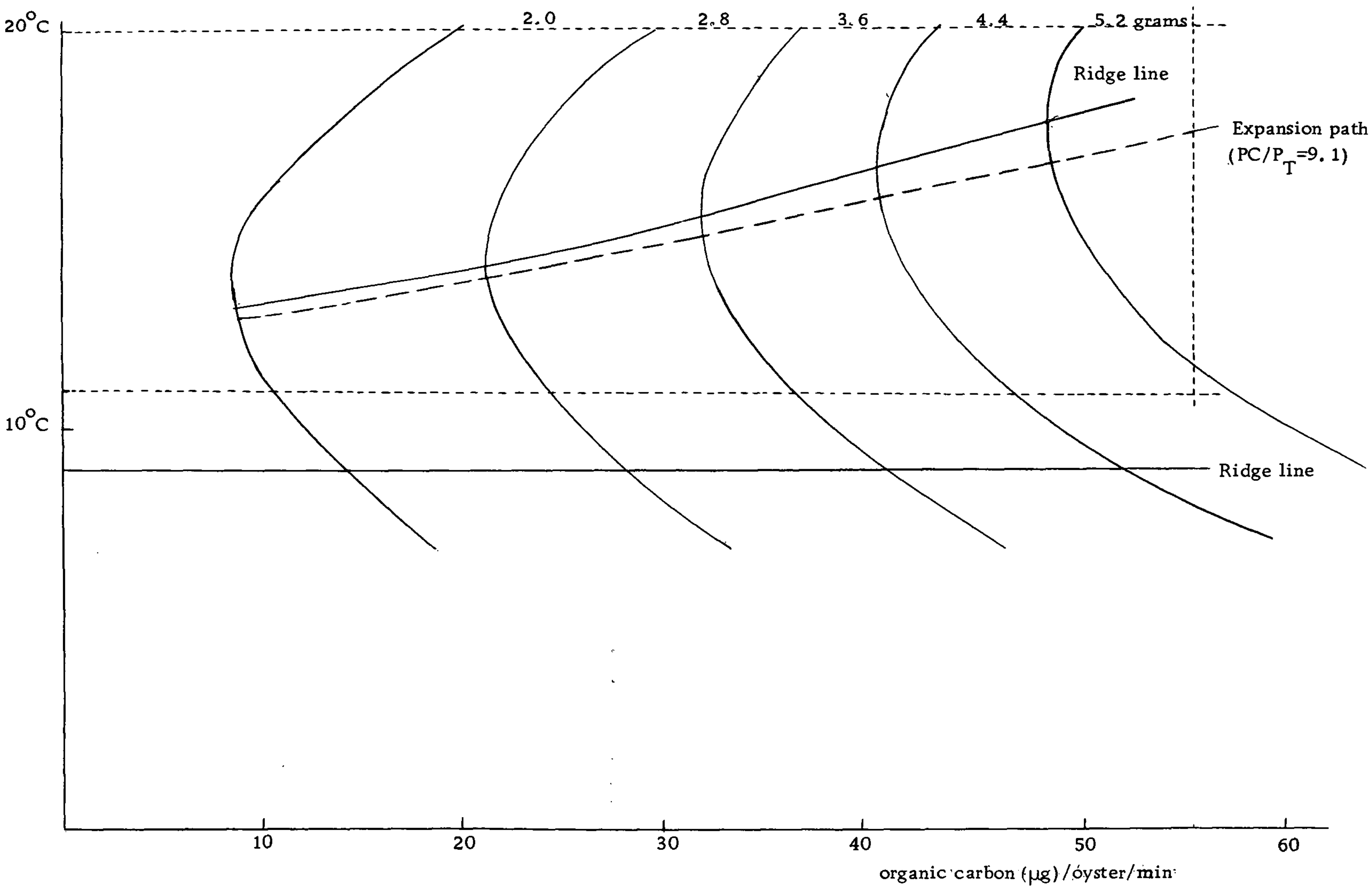

Figure 15. Newport experiment VI: Isoquants which illustrate temperature, organic carbon combinations at specified oyster gains (gram.) (dashed horizontal and vertical lines are limit of temperature and organic carbon supply in experiment).

IV. ECONOMIC RELATIONSHIPS

The results such as those derived in the preceding section provide the basis for specifying the least-cost combinations of heating, water flow and organic carbon for oysters. The least-cost input combinations can be determined by equating the marginal rate of substitution with the inverse price ratio of the inputs. Thus, where the need is to have the least average cost over entire production periods, equating substitution rates from the production function to the inverse price ratios will accomplish this, since the least-cost combination of inputs may be different at each level of oyster growth.

The optimum application of one input depends upon the level of other inputs as explained in the Methodology section in Chapter II. From the equations (17, 18, 19 and 20), partial derivatives with respect to water, temperature and feeding were derived ($\partial Gt/\partial W$, $\partial Gt/\partial T$ and $\partial Gt/\partial F$). For example, with an oyster price of 0.034 cent per gram and heating costs of 1.4×10^{-5} cent for one milliliter per minute, the partial derivative of equation (18) for oyster gain with respect to temperature at a specific quantity is shown below:

$$(21)\ \partial Gt/\partial T = 0.09115/\sqrt{T} + 0.00057373W - 0.00170866T$$

From the above price ratio, the optimum application of one input, the other being fixed, is given below:

$$(22)\quad 0.09115/\sqrt{T} + 0.00057373W - 0.00170866T = 1.4\text{x}10^{-5}/0.034$$

Selection of the optimum quantity of a single input is only a partial solution to the problem when two or more inputs were employed. In the case of multiple inputs, the optimum rate of application is found by equating the partial derivatives of each variable input to the inverse of the input-output price ratio when the other inputs are fixed.

Previous analyses were based upon changing a single input, others being fixed, and upon least-cost combinations at specified yields. However, the optimum input applications were based upon varying levels of inputs and outputs. In these cases, a simultaneous solution must be used for determination of the optimum (1) combination of inputs, and (2) levels of application.

These optima are attained when the partial derivatives for both inputs are equal to the input price/oyster price ratios. Hence, with a series of prices for oysters and for inputs, quoted in Chapter II, the equation (20) becomes (23), (24), (25), and (26). These are shown below:

(23) $\partial Gt/\partial T = 0.15245 + 0.0000044162TC^2 - 0.000062135T^3$

(24) $\partial Gt/\partial C = 0.049598 + 0.0000044162T^2C$

(25) $0.15245 + 0.0000044162TC^2 = 0.000062135T^3 = 1.4x10^{-5}/0.034$

(26) $0.049598 + 0.0000044162T^2C = 2.1x10^{-5}/0.034$

From the simultaneous solution of these equations, the optimum solution for given sets of price ratios of oysters and inputs are shown in Table 25.[15/] The expansion path for a specific level of production with a given price ratio is shown in Figure 15.

The same procedures can be applied for the equations for experiments III, IV and V. However, as explained in Chapter II, heating costs are about 30 times greater than the costs of water flow. This results in a very low price ratio.

The least-cost level of inputs are below zero heating range for experiments IV and V.[16/] The isoquants do not give a relevant solution, since the solutions for temperature were in the dormant

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[15/] Here we assume that there are no heat losses from the system and that there are no costs incurred for maintaining temperature. Temperature is only raised at the beginning of operation. The present value of algae production costs are assumed to be the same over the 60 day period.

[16/] Zero heating range means that the temperature is at or below the average annual temperature of sea water which is 11.44°C at the O.S.U. Marine Science Center, Newport, Oregon.

Table 25. Optimum Temperature and Organic Carbon Application at Various Prices of Inputs and Output for Experiment VI

Given			Resulting				
Oyster prices (¢/gram)	Imput costs		Optimum input level		Gains (grams)	Total revenue (¢)	Total feeding cost (¢)
	Heating (¢/ml/°C)	Organic carbon (¢/μg)	Temperature (°C)	Organic carbon (μg/oyster/min)			
0.034	1.4×10^{-5}	2.1 x 10	16.3	41.3	4.48	0.15	75.7
	1.2×10^{-5}	2.1 x 10	16.3	41.3	4.48	0.15	75.5
0.243	1.4 x 10	2.1 x 10	16.1	41.1	4.41	1.03	74.6
	1.2 x 10	2.1 x 10	16.1	41.1	4.41	1.03	74.6

range and, biologically, in stage III for water flow, assuming that the extrapolations outside of the observed experimental area are accurate.

Tables 26 and 27 illustrate the maximum heating costs for which it would be feasible to produce in stage II at various costs of water flow. Marginal rates of substitution and price ratios for heating and water flow can be found in experiment III. However, the mathematical solution for experiment III was not only outside of the observed experimental area but also the optimum temperature is too high (i.e., 28°C) for oyster production. (Oysters may die from heat exhaustion.)

Two systems of feeding organic carbon to oysters may be applied: (1) organic carbon (in the form of algae) is produced artificially and fed to the oysters by a recycled water system, or (2) fresh sea water containing natural algae is heated and fed to the oysters. The cost of producing organic carbon fed to the oysters is about 2, 000 to 3, 000 times greater in method (1) compared to method (2). However, the costs of heating the sea water under method (2) are such that method (2) becomes 3-4 times more expensive than method (1). Solution for least-cost combinations of organic carbon (in the form of algae) and temperature gives expansion path very close to upper ridge line. This is in spite of the expansion path being congruent with lower ridge line when

Table 26. Maximum Feasible Heating Costs Per Unit (1°C/ml) to Produce in Stage II, Given the Price of Water Flow and Oyster Gain, Experiment IV [a]

Water flow costs (¢/ml)	0.08 Gram (gain level) Maximum feasible heating costs (¢/ml/°C)
7×10^{-8}	7×10^{-7}
3.7×10^{-8}	3.7×10^{-7}

Water flow costs (¢/ml)	0.26 Gram (gain level) Maximum feasible heating costs (¢/ml/°C)
7×10^{-8}	3.5×10^{-7}
3.7×10^{-8}	1.9×10^{-7}

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[a] Equalizing price ratio to marginal rate of substitution at the average annual temperature of sea water at the O. S. U. Marine Science Center.

Table 27. Maximum Feasible Heating Costs Per Unit (1°C/ml) to Produce in Stage II, Given the Price of Water Flow and Oyster Gain, Experiment V

Water flow costs (¢/ml)	2.0 Grams (gain level) Maximum feasible heating costs (¢/ml/°C)
7×10^{-8}	5.8×10^{-8}
3.7×10	3.1×10^{-8}

Water flow costs (¢/ml)	5.6 Grams (gain level) Maximum feasible heating costs (¢/ml/°C)
7×10^{-8}	7.0×10^{-8}
3.7×10^{-8}	3.7×10^{-8}

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[a] Equalizing price ratio to marginal rate of substitution at the average annual temperature of sea water at the O. S. U. Marine Science Center.

finding least-cost combination of water flow and temperature.

If heat losses from the recycled system were negligible or very low, the high algae production costs would eventually pay off. However, the total costs with respect to algae production alone still exceed the total revenue incurred by oyster sales as shown in Table 25.

As indicated in Chapter II oysters tend to become dormant when the environmental temperature is below 9°C. The ridge line (which is defined as the locus of points where one input's marginal physical product is equal to zero) for water flow occurs around 9°C.

Figure 11 shows that the isoquants become further apart at higher output levels, indicating diminishing marginal rates of return. However, Figures 13 and 14 show increasing marginal rates of returns within the observed area. This phenomenon reflects the difference in food availability in the sea by season. At low water flow rates, the isoquants indicate little substitutability between two inputs. As one input increases with the other input being fixed, production gets into the third stage very quickly. However, as water flow increases, the ridge line expands upward.

Production should not take place at low water flow rates (e.g., 4-16 milliliters/oyster/minute), since production occurs in stage III, and, in fact, returns to increased temperature become negative.

If oysters were raised under controlled conditions, with a reduction in the time required for maturity, the temperature level would have to be higher than that of the natural environment. If higher temperatures were used, higher water flow would have to be implemented to be within the economic region (stage II).

Normally, the optimizing solution for economic analysis will occur between the ridge lines. However, optimizing solution for the economic analysis in this case occurs between the upper ridge line and annual average sea water temperature (11.44°C) for experiments III, IV and V. The annual average sea water temperature can be considered as being equal to zero in economic scale. The input is heat and at 11.44°C no heat is being added.

Figure 16 (A and B) shows relevant biological relationship and economic relationship. The ridge lines aa' and bb' were derived from the production function. The bb' ridge line represents dormancy as discussed in Chapter II. The area between the lines cc' and zero axis in B of Figure 16 is the only relevant range for economic analysis for this particular case. Below 11.44°C heat must be removed (negative input). However, for the purpose of illustration heat added is measured in terms of resulting temperature of water (°C).

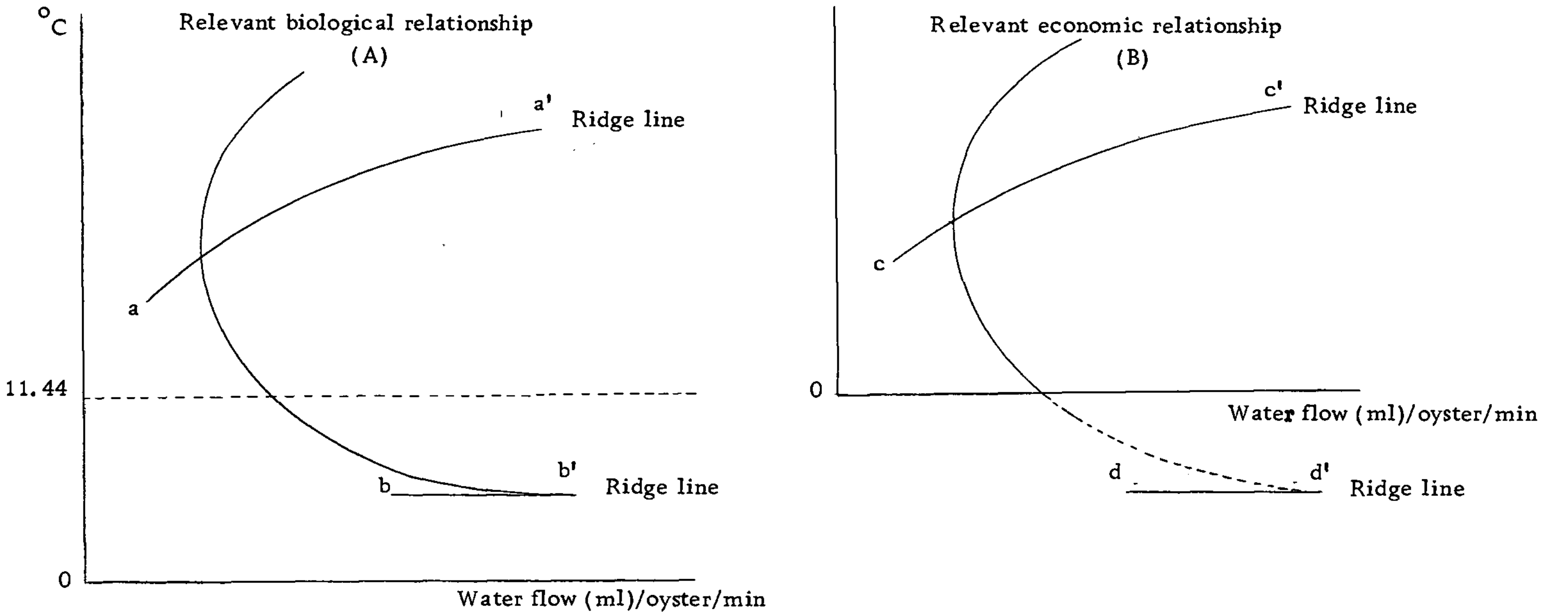

Figure 16. Relevant biological relationship and economic relationship with average annual sea water temperature at 11.44°C

Although the experiments were conducted in the same period and conditions, there were differences in isoquants between experiments III and IV. However, they could be explained as follows: (1) the production function (18) is the gain function vis-à-vis the production function (17) which is the yield function where equal initial weight of oysters is assumed, and (2) the formation of shell and meat may be a different process and shell formation may require less nutrients (mostly inorganic substances) than that of meat (mostly organic substances).

V. SUMMARY AND CONCLUSIONS

Efforts in this study were directed towards:

(1) gaining insights into the recent trend of the oyster industry in North America,

(2) identifying the problems of the industry that may be solved by oyster production under controlled conditions,

(3) biological literature reviews to determine the critical controllable variables for the production function estimates,

(4) the estimation of relationships among the identified variables and production from the experimental data,

(5) the estimation of costs associated with these controllable variables, and

(6) the economic feasibility of oyster production under controlled conditions with respect to these controllable variables..

The U.S. oyster industry has numerous problems, and its production has been declining for 20 years. The major problems of the industry identified in this study were as follows:

(A) the random fluctuations in natural seed supply on which the industry is heavily dependent,

(B) natural disasters and predators, particularly on the East Coast,

(C) pollution,

(D) oyster disease (e.g., MSX),

(E) limited changes in technology,

(F) stringent regulation regarding the use of common property,

(G) an increasing demand for alternate use of common property, and

(H) increasing competition from foreign countries.

Among identified problems, oyster production under controlled conditions could overcome (A), (B), (C), (D) and (E), and possibly (F) and (G).

The following variables were identified as biologicially critical in order to achieve production under controlled environmental conditions:

W = water flow (milliliters/oyster/minute)

F = feeding [organic carbon (μg)/oyster/minute]

T = temperature (^{o}C)

0_2 = dissolved oxygen (micromilliliters/oyster/minute)

P = pH

S = salinity (ppt)

A general oyster production function was of the form:

$$Y = f\ (W,\ T,\ F,\ 0_2,\ P,\ S,\ X_1,\ \ldots,\ Xn)$$

where

Y = yield
Xi = unspecified factors affecting oyster growth

However, the relative significance of dissolved oxygen, pH and salinity were found to be less critical in terms of costs. Thus, the framework of oyster production could be expressed as follows:

$$Y = f\,(W,\ T,\ F \mid 0_2,\ P,\ S,\ X_1,\ \ldots,\ Xn)$$

But if food were supplied through sea water, the food supply would be a function of water flow. Therefore, the production function would be of the form for the once-through-sea water system:

$$Y = f[g\,(w),\ T \mid 0_2,\ P,\ S,\ X_1,\ \ldots,\ X_n]$$

Or, if food were supplied by artificial feeding and water were recycled (assuming water and dissolved oxygen requirements are minimum at a given temperature), then the equation would be of the form:

$$Y = f\,(F,\ T \mid W,\ 0_2,\ P,\ S,\ X_1,\ \ldots,\ X_n)$$

These models developed above were fitted to the data obtained from the experiments conducted by the Department of Fisheries and Wildlife, Oregon State University, at Newport, over a 2-year period from 1973 to 1974. The experiments were designed (1) to investigate the effects on salmon and oyster production of the application of effluent from a (possible) nuclear power plant in the Pacific Northwest, (2) to investigate the seasonal changes in growth patterns due to changes in natural food supply, and (3) to identify what constitutes the biologically optimum water flow and temperature without artificial feeding.

The four models, examined in Chapter III, estimated parameters involved in predicting the total yields and gains. The equations were of the form:

$$(1)\quad Ym = 0.0046696T + 0.0033235W + 0.01093\sqrt{TW} - 0.00024191T^2$$
$$R^2 = 0.933$$

$$(2)\quad Gt = -0.4917 - 0.0022987W + 0.1823\sqrt{T} + 0.00057373TW - 0.00085433T^2$$
$$R^2 = 0.960$$

$$(3)\quad Gt = 0.15245T + 0.068941W + 0.000004266T^2W^2 - 0.000015534T^4$$
$$R^2 = 0.939$$

$$(4)\quad Gt = 0.15245T + 0.049598C + 0.000002208T^2C^2 - 0.000015534T^4$$
$$R^2 = 0.939$$

where

Ym = predicted growth in grams of meat

Gt = predicted gain in grams of total weight

T = temperature (°C)

W = water flow (milliliters/oyster/minute)

TW = interaction between temperature and water flow

C = organic carbon (μg)/oyster/minute

TC = interaction between temperature and organic carbon

The coefficients of determination were significant for experiments III, V and VI. Interaction between these inputs was also important in increasing growth. However, the absence of either input prevents the growth of oysters.

The gain responses in the summer are superior to the winter, reflecting the difference in food availability in sea by season. With the basic physiological relationships estimated for the experiments, an economic analysis could be made.

The original hypothesis was designed to test whether oyster production under controlled conditions is economically feasible. The results of the analysis indicate that the costs of heating and algae must be near zero to make production under controlled conditions economically feasible, with current and forecasted (1976) prices of oyster. This conclusion is based upon the production function estimate of the observed experimental area. However, there may exist economies of size beyond the experimental area, particularly for experiments V and VI in which oysters grew at an increasing rate. In order to take these facts into consideration, the electricity charge was calculated, at least to hold 100 tons of oysters (assuming each oyster weighs 30 grams and 40 ml/oyster/

minute). The results show that much of the economies of scale could not be obtained with respect to heating and pumping costs. However, economies of scale may be obtained for algae production. The cost calculation of algae production was based upon the batch system, but if continuous culture were employed, economies of scale might be attained.

If it were economically feasible under a once-through-seawater system, the combination of these two inputs (i.e., temperature and water flow) should be changed by season because of differences in production function due mainly to the different food availability by season.

Future research will be able to improve the biological basis for economic analysis; however, the basic procedures and critical variables identified in the analysis can be applied to the new data.

The weaknesses of the analysis principally stem from the lack of reliability of the biological experiments. Since inputs--except temperature and water flow--were not controlled, substitution among controlled and uncontrolled variables may have occurred. An identification of the exact impact of each variable was not made.

There were only three different temperatures and four water flows. These small-scale factorial experiments did not yield sufficient data, but impeded the use of less complicated production functions (due mainly to multicollinearity problems). Therefore, the use of polynominal estimating functions (fourth power) for experiments V and VI may not reflect true relationships between output gains and input levels, particularly outside of the observed area.[17/]

General recommendations for future studies concerned with oyster culture under controlled conditions can be summarized as follows:

(1) increase different levels of temperature and water flow for factorial experiments. This will increase the estimating equations' precision, and, as a result, will minimize multicollinearity problems between transformations (e.g., T, T^2 and $\sqrt{T}$).

(2) concentrate biological observations in the relevant economic region (stage II) particularly at temperature levels above 15°C, water flow levels above 30 milliliters per oyster per minute and organic carbon levels above 40 μg per oyster per minute,

(3) control, or at least monitor, critical variables in incoming and outgoing water,

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[17/] J. Neter and W. Wasserman (1974, p. 276) state that "Polynomial models with the independent variable present in high powers than the third are not often employed. The interpretation of the coefficients becomes difficult for such models, and they may be highly erratic for even small extrapolations."

(4) control experiments by artificial feeding so that effects of other unknown variables will be minimized in determining the effect of feeding, and

(5) experiments should be conducted on the different stages of growth, since the input requirements may change as oysters reach a certain stage, and a different production function may be required for different stages of growth (or if a once-through-sea-water system were economically feasible, different combinations of inputs should be employed by season as well), and--even if it is less practical to often change feeding rates--as long as the revenues incurred by changing feeding rates exceed the costs, that is the least-cost method of production as well as giving a biologically more accurate production function estimate.

BIBLIOGRAPHY

Amenia, I. Ecological Studies of Japanese Oyster, with Special Reference to the Salinity of their Habitats. J. Coll. Agr. Univ. Tokyo. 9: 333. 1928.

American Cyanamid Company. New Engineering Approaches for the Production of Connecticut Oysters: A Problem Analysis, Vol. 1 and 2. American Cyanamid Company, Connecticut. 1968. 308 p.

Bardach, J. E. and J. H. Ryther. The Status and Potential of Aquaculture. Amer. Inst. of Biol. Scie. 1968. 225 p.

Bardach, J. E., J. H. Ryther and W. O. McLanncy. Aquaculture. New York, John,Wiley and Sons. 1972. 868 p.

Barrett, E. M. The California Oyster Industry. Res. Agen. of Calif., Dept. of Fish and Game. Fish Bull. 123: 1-103. 1963.

Baum, E. L., E. O. Heady, J. T. Pesek and C. G. Hildreth. Economic and Technical Analysis of Fertilizer Innovations and Resource Use. Ames, Iowa. The Iowa State College. 1956. 398 p.

Baum, E. L., E. O. Heady and J. Blackmore. Methodological Procedures in the Economic Analysis of Fertilizer Use Data. Ames, Iowa. The Iowa State College. 1956. 217 p.

Bell, F. W. The Factors Behind the Different Rates of U. S. Fisheries. Div. of Econ. Res. Working Paper #13. 1969. 10 p.

Bilas, R. A. Microeconomic Theory, 2nd ed. New York, McGraw-Hill. 1971. 362 p.

Brown, W. G., E. O. Heady, J. T. Pesek and J. A. Stritzil. Production Functions, Isoquants, Isoclines and Economic Optima in Corn Fertilization for Experiments with Two and Three Variable Nutrients. Ames, 1956. 25 p. (Iowa. Agri. Exp. Stat. Res. Bull. 441)

Butler, P. A. Reaction of Some Estuarine Mollusks to Environmental Factors. U. S. D. H. E. W. Working Paper #999. 25 p.

Burke, B. H., B. Glenne and B. W. Adams. The Nearshore Physical Oceanographic Environment. Corvallis, 1971. Ref. 71-45. 127 p. (Oregon. Dept. Oceanog., Oregon State University)

Chew, K. K. The Growth of a Population of Pacific Oysters (Crassostrea gigas) when Transplanted to Three Different Areas in the State of Washington. Doctoral Dissertation. Seattle, University of Washington, 1963. 192 p.

Claus, G. and C. Alder. Optimal Conditions for Oysters Grown in Closed Environments. Paper presented at Marine Technological Society Meeting. Washington, D. C. 1970. 8 p.

Current Fishery Statistics of the U. S. No. 6333. Dept. of Comm. 1973.

Davis, H. C. Survival and Growth of Larvae of the European Oyster, Ostrea edulis at Lowered Salinities. Biol. Bull. 122 (1): 33-9. 1962.

Dean, D. The Experimental Feeding of Oysters. Doctoral Dissertation. New Brunswick, Rutgers University. 1957. 108 p.

Emadi, H. Effect of Heated Oceanwater on the Growth of Three Species Oysters: Pacific, C. gigas, European, O. edulis, and Native, O. lurida. 1972. 11 p.

Engle, J. B. The Mollscan Shellfish Industry-Current Status and Trend. Proc. of the Nat. Shellf. Assoc. 56: 13-21. 1966.

Feng, S. Y. Paper presented at the Shellfish Culture Conference, Selden, New York. 1968.

Ferguson, C. E. Microeconomic Theory. Illinois, Richard D. Irwin. 1972. 565 p.

Fishery Statistics of the U. S., 1950-1972, U. S. D. C. 1950-72.

Furfari, S. A. Depuration Plant Design. U. S. D. H. E. W. Publ. Health Serv. 1966. 119 p.

Galtoff P. S. The American Oyster, Crossostrea virginica Gmelin. U.S. Fish. Wildl. Serv. Fish Bull. 64: 1-480. 1964.

Heaven, D. Aspects of Biodeposition by Oyster and other Invertebrate Filter Feeders. Limnol. Oceanogr. 11(4): 178-88. 1966.

Heady, E. O., J. T. Pesek and W. G. Brown, Crop Response Surfaces and Economic Optima in Fertilizer Use. Ames, 1955. p. 292-332. (Iowa. Iowa State College. Agri. Exp. Stat. Res. Bull. 424)

Henderson, J. M. and R. E. Quandt. Microeconomic Theory. New York, McGraw-Hill. 1971. 431 p.

Imai, T. (ed.) Kanzenyoshoku (in Japanese). Tokyo, Koseisha-Koseikaku. 1971. 454 p.

Imai, T. and S. Sakai. Study of Breeding of Japanese Oyster, *Crassoshea gigas.* Tohoku Univ. J. Agri. Res. 12: 125-71. 1961.

Johnston, W. E. and P. C. Allen. Technology Assessment and the Direction of Future Research: Use of Computerized Budgeting for Lobster Aquaculture. Contri. Paper for Annual Meeting of the American Agricultural Economic Asso., College Station, Texas, August 1974.

Kmenta, J. Elements of Econometrics. New York, The Macmillan Co. 1971. 655 p.

Korringa, P. Recent Advances in Oyster Biology. Quart. Rev. Biol. 27:339-65. 1952.

Langmo, D. and K. Im. Unpublished Research on Economic Feasibility on Oyster Seed Hatchery. Corvallis, Dept. of Agri. Econ. 1974.

Loosanoff, V. L. and H. C. Davis. Spawning of Oysters at Low Temperatures. Science III: 521-2. 1950.

________________ Requirements for Maturation of Gonads of Northern Oysters. Biol. Bull. 103(1): 80-96. 1952.

Matthiessen, G. C. and R. C. Toner, Possible Methods of Improving the Shellfish Industry of Martha's Vineyard, Duke's County, Mass. Mass., 1966. 138 p. (The Marine Research Foundation).

Matthiessen, G. C. A Review of Oyster Culture and the Oyster Industry in North America. Woods Hole, 1970. 52 p. (Woods Hole Oceanogr. Inst. Contri. No. 2528).

Medawar, P. B. Size and Age. In: Legros Clark and P. B. Medawar (eds.) Essay in Growth and Form. London, Oxford Press. 1945. p. 157-187.

Menzel, R. W. Reports on Commercial-Scale Oyster Planting Experiments in Bayou Bas Bleu and Bay Ste. Elaine Oil Field. Texas A&M Res. Proj. 9. 1952. 146 p.

Mori, M. Studies on Oyster Mass Mortalities in Matsushima Bay. IV. Sexual Maturity and Changes on Physiological Activities and Glucose Contents. Tohoku J. Agri. Res. 25: 49-63. 1965.

Neter, J. and W. Wasserman. Applied Linear Statistical Models. Illinois, Richard D. Irwin. 1974. 800 p.

Oregon. University. Dept. of Fish. and Wildl., Corvallis, Oregon. Use of Heated Sea Water for Farming Oysters and Salmon. 1974. 40 p.

Pereyra, W. T. Growth of the Pacific Oyster (*Crassostrea gigas* Thunberg) in Various Exposure Situations, with Considerations of the Experimental and Methodological Difficulties Encountered. Master's Thesis. Seattle, University of Washington. 1961. 87 p.

Quayle, D. B. The Seasonal Growth of the Pacific Oyster (*Ostrea gigas*) in Ladysmith Harbor. Ann. Rept. Br. Columbia. Dept. Fish. 1951. p. 85-90.

________________ Pacific Oyster Culture in British Columbia. Fish. Res. Bd. Can. 169: 1-92. 1969.

Seno, H., J. Hori and D. Kusabe. Effects of Temperature and Salinity on the Development of the Eggs of the Common Japanese Oyster, *Ostrea gigas* Thunberg. J. Fish. Inst. Tokyo. 22: 1-41. 1965.

Sokoloski, A. A. The Role of Imports in the U.S. Oyster Market. College Park, 1970. 4 p. (University of Maryland, Extension Service)

Sparks, A. K., and K. K. Chew. Preliminary Report on Growth and Survival of the Pacific Oyster in Washington Waters. Proc. Nat. Shellf. Assoc. 50: 125-32. 1961.

Tarr, M. A., M. I. Carr and R. E. Westly. Final Report of Investigations for the Lummi Aquaculture Project. Dept. Fish., Res. Div., Washington State, p. 46. 1971.

Tenore, K. R., J. C. Goldman and J. P Clarner. The Food Chain Dynamics of the Oyster, Clam, and Mussel in an Aquaculture Food Chain. J. Exp. Biol. Ecol. 12: 157-65. 1973.

Wallace, D. H. Industry's Appraisal of the Future of the Oyster Industry. Proc. of the Gulf Carib. Fish. Inst. Miami. p. 135-38. 1961.

Warren, C. E. and G. E. Davis. Laboratory Studies on the Feeding, Bioenergetics, and Growth of Fish. In: S. D. Gerking (ed.) Biological Basis of Freshwater Fish Production. Oxford, Blackwell Scientific Publ. 1967. p. 175-214.

Windham, D. M. Economic Aspects of the Oyster. Proc. of the Oyster Culture Workshop. Sapelo Island, 1968. p. 41-9. (Georgia. Mar. Fish. Div. Georgia Contri. Ser. Numb. 6)

Woelke, C. E. Introduction of the Kumamoto Oyster, *Ostrea (Cressostrea) gigas*, to the Pacific Coast. Washington State Dept. Fish., Fish. Res. Paper. 1(3): 41-50. 1955.

Wolfe, J. W. Professor, Oregon State University, Dept. of Agri. Engr., Personal Communication. Corvallis, Oregon. August 15, 1974.

APPENDIX I

COST CALCULATIONS

Heating Costs

Heating cost calculations were based upon General Lincoln People's Utility District, Rate Schedule No. 200. The basic unit of water flow is milliliters per oyster per minute, and caloric requirement for raising one milliliter sea water by one degree centigrade was calculated.[1] The calorie was converted into a common unit, Kwh (Kilowatt-hour) which is the basis of electricity charge. The conversion equations were as follows:

(1) Kwh = 859, 184 calories

(2) $859,184 \times \frac{1.00}{1.05} \times \text{efficiencies} =$ milliliters of sea water that can be raised by one degree centigrade by 1 Kwh

where 1.00 = the specific gravity of pure water

1.05 = the specific gravity of sea water

efficiency = heat exchanger efficiency, expressed as decimal, 0.9 (Johnston and Allen, 1974, p. 25).

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[1] One calorie is the amount of heat required to raise the temperature of one gram of water by one degree. The specific gravity of sea water is about 1.05, therefore sea water requires more energy than fresh water to increase its temperature by 1°C.

Water Flow Costs

Without applying some detailed engineering systems analysis, it is difficult to estimate hydrographical values of piping and pumping efficiencies. In order to estimate the cost of pumping per milliliter of water, the brake horsepower was calculated. The formula necessary for the estimation is of the form:

$$(3)\ \text{BHP} = \frac{Q \times \text{TDH}}{75 \times \text{efficiency}}$$

where Q = liters per second (one liter equals 1000 milliliters)

TDH = total dynamic head in meters (which refers to the vertical lift of sea water from the average tide[2/])

efficiency = pumping and motor efficiency

75 = conversion factor

The conversion between the brake horsepower and kilowatt is shown below:

$$(4)\ \text{Kw} = 1.34\ \text{BHP}$$

Under given conditions shown below, the unit costs of inputs were calculated as follows:

$$\text{BHP} = \frac{Q \times \text{TDH}}{75 \times \text{efficiency}}$$

TDH = 5 meters, OSU Marine Science Center mean tide

[2/] The precise estimation of the horsepower needed for piping and pumping requires the estimation of the degree of friction of the water with the friction losses are negligible due to sufficiently large pipes.

efficiency 1 pumping 0.75
2 motor 0.85 [3]

Table 1. Pumping Costs and Heating Costs as a Function of Water Flow, and its Brake Horsepower and Kilowatt-hour Requirements

Liters/ second	BHP	Liters/ hour	Kwh	Water flow costs (¢/ml)	Heating costs (¢/ml/°C)
100	10.46	36×10^{4}	479.74	7.0×10^{-8}	2.3×10^{-6}
500	52.29	18×10^{5}	2,398.66	4.7×10^{-8}	1.5×10^{-6}
1000	104.58	36×10^{5}	4,797.32	4.0×10^{-8}	1.3×10^{-6}
2000	209.16	72×10^{5}	9,594.39	3.7×10^{-8}	1.2×10^{-6}

Algae Costs

Costs of algae production used in the analysis were obtained from the study on the oyster seed hatchery. The study reveals that the costs of producing one tank of algae is $20.17, including associated variable costs. One tank contains about 500 gallons, which is equal to 1,893 liters. Then μg of organic carbon per liter was calculated, and the equivalency was converted into 1,893 liters.

(5) 1 liter of full bloomed algae, *Isocrythis sp.* [4]

= 50 mg-organic carbon
= 50,000 μg-organic carbon

(6) $20.17/50,000 \times 1,893 = 2.1 \times 10^{-5}$ ¢/μg

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[3] J. W. Wolfe, Professor, Oregon State University, Dept. of Agric. Engrg., Personal Communication, Corvallis, Oregon. August 15, 1974.

[4] Caution should be used in the interpretation of these figures. The organic carbon contents of phytoplankton vary by environment, stage of growth, density and so forth, as well as species.

APPENDIX II

MARGINAL PHYSICAL PRODUCT FOR VARIOUS COMBINATIONS OF TEMPERATURE AND WATER FLOW

Table 1. Newport Experiment III: Marginal Physical Product for Various Combinations of Temperature and Water Flow

Water flow (ml/oyster/min)	Marginal physical product for temperature (°C)				
	11	13	15	17	20
4	0.0026	0.0014	0.0002	-0.0009	-0.0026
8	0.0040	0.0026	0.0014	0.0002	-0.0016
16	0.0059	0.0044	0.0030	0.0017	-0.0001
24	0.0074	0.0058	0.0043	0.0029	0.0010
32	0.0087	0.0069	0.0054	0.0039	0.0019

Temperature (°C)	Marginal physical product for water flow (ml/oyster/min)				
	4	8	16	24	32
11	0.0057	0.0031	0.0012	0.0004	0.0001
13	0.0065	0.0036	0.0016	0.0007	0.0002
15	0.0073	0.0042	0.0020	0.0010	0.0004
17	0.0079	0.0046	0.0023	0.0013	0 0007
20	0.0089	0.0053	0.0028	0.0017	0.0010

Table 3. Newport Experiment V: Marginal Physical Product for Various Combinations of Temperature and Water Flow

Water flow (ml/oyster/min)	Marginal physical product for temperature (°C)				
	11	13	15	17	20
4	0.0712	0.0177	-0.0552	-0.0150	-0.3419
8	0.0758	0.0230	-0.0491	-0.1435	-0.3337
16	0.0938	0.0443	-0.0245	-0.1157	-0.3010
24	0.1239	0.0798	0.1646	-0.0693	-0.2463
32	0.1659	0.1295	0.0738	-0.0043	-0.1699
40	0.2199	0.1934	0.1475	0.0793	-0.0716

Temperature (°C)	Marginal physical product for water flow (ml/oyster/min)					
	4	8	16	24	32	40
11	0.0731	0.0772	0.0855	0.0937	0.1020	0.1102
13	0.0747	0.0805	0.0920	0.1035	0.1151	0.1266
15	0.0766	0.0843	0.0997	0.1150	0.1304	0.1457
17	0.0788	0.0887	0.1084	0.1281	0.1478	0.1676
20	0.0826	0.0962	0.1235	0.1508	0.1782	0.2055

Table 2. Newport Experiment IV: Marginal Physical Product for Various Combinations of Temperature and Water Flow

Water flow (ml/oyster/min)	Marginal physical product for temperature (°C)				
	11	13	15	17	20
4	0.0110	0.0054	0.0002	-0.0046	-0.0115
8	0.0132	0.0077	0.0025	-0.0024	-0.0092
16	0.0179	0.0122	0.0071	0.0022	-0.0046
24	0.0225	0.0168	0.0117	0.0068	-0.00002
32	0.0270	0.0214	0.0163	0.0114	0.0046

Temperature (°C)	Marginal physical product for water flows (ml/oyster/min)				
	4	8	16	24	32
11	0.0040	0.0040	0.0040	0.0040	0.0040
13	0.0046	0.0046	0.0046	0.0046	0.0046
15	0.0063	0.0063	0.0063	0.0063	0.0063
17	0.0075	0.0075	0.0075	0.0075	0.0075
20	0.0092	0.0092	0.0092	0.0092	0.0092

Table 4. Newport Experiment VI: Marginal Physical Product for Various Combinations of Temperature and Organic Carbon

Organic carbon (μg) corresponding number of algae	Marginal physical product for temperature(°C)				
	11	13	15	17	20
5.56 (3.9x10^5)	0.0712	0.0177	-0.0552	-0.0150	-0.3419
11.12 (7.8x10^5)	0.0758	0.0230	-0.0491	-0.1435	-0.3337
22.24 (1.6x10^6)	0.0938	0.0443	-0.0245	-0.1157	-0.3010
33.36 (2.3x10^6)	0.1239	0.0798	0.1646	-0.00693	-0.2463
44.48 (3.1x10^6)	0.1659	0.1295	0.0738	-0.0043	-0.1699
55.60 (3.9x10^6)	0.2199	0.1934	0.1475	0.0793	-0.0716

Temperature (°C)	Marginal physical product for organic carbon (μg) and corresponding number of algae					
	5.56 (3.9x10^5)	11.12 (7.8x10^5)	22.24 (1.6x10^6)	33.36 (2.3x10^6)	44.48 (3.1x10^6)	55.60 (3.9x10^6)
11	0.0731	0.0772	0.0855	0.0937	0.1020	0.1102
13	0.0747	0.0805	0.0920	0.1035	0.1151	0.1266
15	0.0766	0.0843	0.0997	0.1150	0.1304	0.1457
17	0.0788	0.0887	0.1084	0.1281	0.1478	0.1676
20	0.0826	0.0962	0.1235	0.1508	0.1782	0.2055

ISOQUANT COMBINATIONS OF TEMPERATURE AND WATER FLOW FOR PRODUCING SPECIFIED YIELDS AND GAINS AND CORRESPONDING MARGINAL RATES OF SUBSTITUTION

Table 5. Newport Experiment III. Isoquant Combinations of Temperature and Water Flow for Producing Specified Yields and Corresponding Marginal Rates of Substitution

Temperature (°C)	0.08 gram (yield level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	3.81	2.38
13	3.27	6.94
15	3.15	-86.83
17	3.30	-7.83
20	3.92	-3.50

Temperature (°C)	0.10 gram (yield level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	8.74	0.69
13	6.86	1.84
15	6.18	5.84
17	6.07	-19.31
20	6.35	-3.33

Table 5. Newport Experiment III. Isoquant Combinations of Temperature and Water Flow for Producing Specified Yields and Corresponding Marginal Rates of Substitution --Continued

Temperature (°C)	0.12 gram (yield level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	24.81	0.05
13	13.75	0.52
15	11.28	1.44
17	10.42	5.29
20	10.56	-4.08

Temperature (°C)	0.14 gram (yield level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	No solution (imaginary number)	
13	No solution (imaginary number)	
15	21.37	0.34
17	17.74	1.05
20	16.51	-48.77

Temperature (°C)	0.16 gram (yield level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	No solution (imaginary number)	
13	No solution (imaginary number)	
15	No solution (imaginary number)	
17	36.23	0.16
20	26.64	1.17

Table 6. Newport Experiment IV: Isoquant Combinations of Temperature and Water Flow for Producing Specified Gains and Corresponding Marginal Rates of Substitution

Temperature (°C)	0.08 gram (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	17.56	0.21
13	11.39	0.54
15	9.18	1.99
17	9.00	-4.20
20	10.70	-1.20

Temperature (°C)	0.14 gram (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	32.51	0.15
13	23.02	0.32
15	18.69	0.73
17	17.03	2.63
20	17.24	-2.35

Temperature (°C)	0.2 gram (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	47.47	0.11
13	34.65	0.22
15	28.20	0.45
17	25.08	1.00
20	23.78	-61.94

Temperature (°C)	0.26 gram (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	62.42	0.09
13	46.28	0.17
15	37.72	0.32
17	33.13	0.62
20	30.85	2.35

Table 7. Newport Experiment V: Isoquant Combinations of Temperature and Water Flow for Producing Specified Gains and Corresponding Marginal Rates of Substitution

Temperature (°C)	2.0 grams (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	7.56	0.99
13	6.29	3.61
15	6.63	-1.44
17	8.84	-0.57
20	15.15	-0.35

Temperature (°C)	2.8 grams (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	17.34	0.99
13	15.72	2.22
15	15.50	-3.76
17	16.80	-0.98
20	21.27	-0.55

Temperature (°C)	3.6 grams (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	26.09	0.99
13	23.92	1.67
15	23.06	12.69
17	23.53	-2.06
20	26.57	-0.84

Table 7. Newport Experiment V: Isoquant Combinations of Temperature and Water Flow for Producing Specified Gains and Corresponding Marginal Rates of Substitution--Continued

Temperature (°C)	4.4 grams (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	34.09	1.00
13	31.28	1.43
15	29.74	3.26
17	29.49	-7.31
20	31.34	-0.20

Temperature (°C)	5.2 grams (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	41.50	1.00
13	38.01	1.30
15	35.81	2.18
17	34.89	10.34
20	35.70	-2.25

Temperature (°C)	6.0 grams (gain level)	
	Water flow (ml/oyster/min)	MRS of temperature for water flow
11	48.44	1.00
13	44.25	1.23
15	41.40	1.78
17	39.85	3.86
20	39.75	-4.51

Table 8. Newport Experiment VI: Isoquant Combinations of Temperature and Organic Carbon for Producing Specified Gains and Corresponding Marginal Rates of Substitution

Temperature (°C)	2.0 grams (gain level)	
	Organic carbon (µg/oyster/min)	MRS of temperature for organic carbon
11	10.50	0.73
13	8.74	2.74
15	9.22	-1.14
17	12.29	-0.46
20	21.06	-0.18

Temperature (°C)	2.8 grams (gain level)	
	Organic carbon (µg/oyster/min)	MRS of temperature for organic carbon
11	24.10	0.63
13	21.85	1.49
15	21.55	-2.79
17	23.35	-0.72
20	29.55	-0.38

Temperature (°C)	3.6 grams (gain level)	
	Organic carbon (µg/oyster/min)	MRS of temperature for organic carbon
11	36.27	0.51
13	33.25	0.91
15	32.05	6.26
17	32.72	-1.31
20	36.93	-0.52

Table 8. Newport Experiment VII: Isoquant Combinations of Temperature and Organic Carbon for Producing Specified Gains and Corresponding Marginal Rates of Substitution--Continued

Temperature (°C)	4.4 grams (gain level)	
	Organic carbon (μg/oyster/min)	MRS of temperature for organic carbon
11	47.39	0.41
13	43.48	0.64
15	41.34	0.89
17	41.00	4.53
20	43.56	-0.74

Temperature (°C)	5.2 grams (gain level)	
	Organic carbon (μg/oyster/min)	MRS of temperature for organic carbon
11	57.70	0.34
13	52.83	0.49
15	49.78	0.88
17	48.49	3.78
20	49.63	-1.14