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Substitute Foods--a Practical Alternative?

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Substitute foods – a practical alternative?

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Any practicable alternative food for human use must be highly acceptable to the consumer and must also fulfil man's nutritional requirements. Substitute foods can consist of two types: synthetic, and reformed or modified.

Synthetic proteins are unlikely to be produced by chemical techniques but biochemical techniques are currently being developed which allow the production of protein from inorganic nitrogen sources by the use of single cells. While much of the work is geared to the provision of animal food some are looking directly to human food. The requirements for these are reviewed and problem areas identified. Synthetic fats can be made and the chemical production and biochemical degradation is considered. There is unlikely to be a requirement for synthetic carbohydrates.

Reformed or modified food has been of long standing use and recent developments in texturizing soya meal and in spinning vegetable proteins are discussed together with limitations of their use.

Suggestions are made as to what might occur during the 1980s based on the opinions expressed by over forty members of the food industry (both scientific and commercial) in the course of a Delphi exercise predicting future trends in the food industry.

This paper, which of necessity can only be a broad survey, will be confined to considering the situation in this country and in developed countries generally, and will not be particularly concerned with the situation in developing countries. It must be recognized that if one is to produce foods which will be accepted by the highly sophisticated market in this country they must be highly acceptable products. One cannot envisage a situation where less palatable foods will ever be accepted in considerable amounts, for the population of this country really lives to eat rather than eats to live.

Substitute foods can consist of either of two types. The first and more theoretical situation is that of the truly synthetic food, that is food produced from materials which are not normally regarded as foodstuffs. The other class of substitute foods is the reformed or modified foods and these can be distinguished because the material which is used is already accepted as a normal foodstuff but by the application of technology the acceptability of this material is increased. We must consider proteins, fats and carbohydrates as the basic food components.

Proteins are essentially sources of amino acids and there is no difficulty about producing amino acids by either biochemical or chemical techniques. Of the two alternatives the biochemical methods appear to offer the most promise and table 1 lists those which have been produced commercially (K. Yamada 1973, personal communication).

It will be noted that much of the production is in Japan in which country the most significant advances have been made. It is certain, however, that humans will not accept a solution or a paste of synthetic amino acids as a regular source of these materials in place of, for instance, meat; and if they are to become accepted as part of the human diet in other than trace amounts as supplements for foods which are deficient in one or more of the essential amino acids, it is necessary to polymerize them to generate a polymer which is capable of having a reasonable texture which will provide the enjoyment which is necessary. In theory it is possible to synthesize a food protein in which the amino acid sequence is known by normal protein synthetic methods, which usually require the addition of single amino acids. This process usually involves blocking one of the functional groups of the amino acid, converting the second functional group into a reactive state so that it may be coupled to the peptide already synthesized. This is followed by the removal of the protective agent of the amino acid and further processing to add an additional amino acid. Theoretically it is possible to build up any sequence of amino acids; in practice it is extremely difficult, and in terms of human food it is certain that this approach will not be adopted. There appears to be no special attribute possessed by a particular sequence of amino acids when considered as foodstuffs, so that in theory one could envisage a random polymerization process starting with the appropriate mix of amino acids, and while this is more likely than the building up of individual proteins it again is unlikely to provide a suitable route for human food.

Table 1. Production of amino acids by microbiological methods

	world production (tonnes per annum)	Japanese production (% of world)
L-Ala	12	85
DL-Ala	200	50
L-Glu	220000	45
L-ILe	15	100
Gly	6500	45
L-Lys-HCl	20000	100
L-Met	80	100
DL-Met	50000	40
L-Pro	10	100
L-Thr	20	100
L-Try	20	100
L-Val	20	100

The biochemical techniques of producing synthetic protein are much more promising and are currently being developed through the pilot plant stage into larger scale production using the method of culturing single cells. The basic concept in all the processes is that a carbon source is used as a substrate for the growth of an organism which, with a suitable inorganic nitrogen source which can be prepared synthetically, produces a useful protein. The differences in the various processes are primarily geared to variations in the carbon source and this in its turn leads to variations in the organism used. Table 2 shows the desirable properties of micro-organisms used for the production of single cell protein which were recognized several years ago (Enebo 1970).

Table 3 summarizes some aspects of the work on alternative substrates (Tannenbaum 1971). With methane, bacteria appear to be unlikely to be successful. Gas oil is unlikely to find acceptance for human food because of the possible contamination with polycyclic hydrocarbons. In this way light oils look more satisfactory while again solvent extraction may be required before use. Alcohols are simply produced by catalytic reaction of methane, and while the work at present appears to be concentrated on the development of animal feeds, there is a potential development for use as food. Cellulose, however, is unlikely to extend beyond the feed use and this is particularly aggravated by the necessity in many cases of using mixed cultures with the resultant increased problems of the control of the individual cells. The use of fungi on starch is well advanced for human food outlets and sugars provide a similar possible carbon source for these organisms. The use of fungi is particularly interesting here because the organism itself provides a considerable amount of the texture which is required in food, as distinct from the yeast or bacteria which essentially provide powders requiring further processing before they can be accepted by humans. The use of carbon dioxide with algae is very restricted and is unlikely to become significant in this country. The problems associated with the use of starch and sugars are different from those with hydrocarbons. Table 4 shows that very much higher quantities of substrate are required but lower amounts of oxygen. This arises as a result of the different oxidation state of the carbon. The decreased utilization of oxygen, of course, eliminates many of the cooling problems associated with the use of hydrocarbons.

Table 5 gives the three sets of factors which will influence the development of single cell proteins (Mateles & Tannenbaum 1968). We have the economic and technological factors, the nutritional factors and finally the food technological factors, and for any process to be acceptable solutions have to be found to all the problems associated with any of these factors.

One major criticism of single cell proteins has been of their possible high content of nucleic acids (Anonymous 1972). In general the nucleic acid content of single cell proteins is much

Table 2. Desirable properties of micro-organisms used for production of s.c.p.

composition of the organism

high-protein content
essential amino acids
non-toxic
highly digestible
good taste
high content of other nutrients than protein
fat and carbohydrate content of high quality

other essential properties

rapid growth on simple media in submerged culture
efficient energy utilization
tolerance towards toxic compounds in the medium
tolerance towards mechanical strains during the culture process
resistance to contamination
simple separation
easy protein extraction

Table 3. S.c.p. processes in various stages of development

substrate	organism	comments
methane	bacteria	low productivity
gas oil	yeast or bacteria	more likely to be used for feed than for food
n-paraffins	yeast or bacteria	may require solvent extraction
alcohols	yeast or bacteria	potential use for food
cellulose	yeast or bacteria	potential use for feed; requires hydrolysis
starch	fungi	potential use for food
sugars	any	economic problems
carbon dioxide	algae	interesting in certain locations

Table 4. Material balance for production of s.c.p. by hydrocarbon and carbohydrate fermentation processes

	input		output
process	substrate	oxygen	cells
hydrocarbon (CH_2)	100	200	100
carbohydrate (CHO)	200	67	100

higher than that of a majority of other foods. Yeast may have a content of about 8%, certain bacteria may contain up to 20% of RNA, contrasting with levels of 2.6% for liver, 4.1% for fish roe. However, the significance of these concentrations is quite different for man and other primates than for other mammals. The objection to an excessive dietary intake of nucleic acids is that the final metabolic properties of the purines contained in them is, for primates, uric acid and some toxicologists consider this might result over a long period in the formation of kidney

TABLE 5. FACTORS INFLUENCING S.C.P. PROCESS SELECTION

economic and technical	*nutritional*	*food technological*
yield of protein	amino acid pattern	flavour
cost of substrate and nutrients	protein digestibility	texture
productivity	protein content	colour
sterilization costs	extraneous material	solubility
recovery costs		flexibility

stones in some cases and it would aggravate arthritic tendencies in certain others. Fortunately, there are several methods available for reducing the RNA content of most single cell proteins and these would certainly be applied to those materials designed for human consumption. In the case of fungi which are specifically geared for human consumption the RNA content is sufficiently low as to not present the metabolic problem. It is, therefore, technically feasible to produce synthetic protein which could theoretically be used as human foods, but to take the step from the dry and relatively unpalatable powder which is produced by many of the processes to a food which humans will consume on a regular basis under normal conditions, demands a very high input of food technology. This in itself will increase the cost of these materials.

Synthetic fat was developed by the Germans before and during World War II for human consumption (Imhausen 1949). This was initially produced by the Ficher–Tropsch process which produced a waxy, high molecular mass hydrocarbon which was then oxidized and fatty acids were then extensively purified before being coupled with glycerol to form fats. These were used with water, salts, emulsifiers, flavour and vitamins to give margarine which was mostly consumed by the German armed forces when no digestive disturbances or ill effects were reported. Just how safe these synthetic fats would be for prolonged human consumption can be questioned (Thomas & Weitzel 1946). The differences between these fats and natural fats are that they contain equal amounts of both odd and even chained fatty acids, together with small amounts of non-saponifiable material partly composed of polycyclic hydrocarbons and variable amounts, usually 1 or 2% of dicarboxylic acid. In addition, there are large amounts, perhaps as much as 35% of alkyl substitute fatty acids (Shapira 1971). More recently it has been recognized (Frankenfeld 1968) that the Ziegler process offers considerably greater promise with a postulated reaction sequence of synthesis of ethylene from carbon monoxide, polymerization of ethylene to α-olefins, oxidative ozonolysis to monocarboxylic acids and condensation with glycerol to produce fats which should not contain branched chain or cyclic acids. Theoretically this could provide an alternative fat source.

The simplest triglyceride is triacetin and the nutritional evidence of the use of this material as a food source is variable (Shapira 1971). For instance, when it was fed to rats for 60 days as 55% of the diet, the animals only grew one half as well as those fed on lard; however, in other experiments when fed to weanling rats at lower levels, the growth observed was good. It is particularly important that the amount of branch chain acids should be restricted (Carroll 1963) since metabolic studies have shown that the glyceride ester bonds of the branch chain acids are almost resistant to pancreatic lipase, and the normal oxidation pathway of β-oxidation is also apparently hindered by the methyl groups and ω-oxidation occurred instead giving rise to dimethyladipic acid which was excreted in the urine. In other instances, such as with 2,2,17,17-tetramethylstearic acid, the fatty acid was found to be inert to both β- and ω-oxidation and is excreted in the faeces, largely as the unchanged acid, therefore, providing no nutritional value. However, in theory it is possible to contemplate the provision of fats from hydrocarbons prepared by a purely synthetic route. An alternative source of fats is from the growth of single cells along similar lines to the production of proteins, but this presents many problems, particularly those associated with fatty acids which are not part of the normal diet.

It does not seem reasonable at this time that we can contemplate the substantial production of carbohydrate materials by chemical means, and the most efficient biological means which we have at our disposal is the use of plants. Here it may be possible to devise techniques which do not require the sowing of seeds in fields and the reliance on weather to determine whether or not we will achieve foodstuffs which we require for our survival. It is possible to contemplate radically different techniques, but whether these will be achieved in the 1980s is open to doubt.

The above summarizes briefly the position of the basic food materials which we require to survive, but in addition to these we need a wide range of vitamins and trace materials. The majority of these materials have already been synthesized, and since they are only required in very small amounts, it is quite reasonable to contemplate a situation where they are provided by purely synthetic methods.

So far the possibilities which have been discussed have been theoretically possible in some instances but are in fact rather remote in many cases. There is a very different situation with reformed or modified foods. There is a lot of emotional rubbish talked about knitted steaks and such developments, designed to worry the farmer and to horrify the housewife. There is absolutely nothing different in principle in what is being carried out nowadays, from what has been carried out for many years. Bread is a reformed or modified food. Flour could, if necessary, be consumed with merely a modicum of further processing but as such it is dull and unappetizing and so, many years ago, a simple technology was developed which is in fact based on a complicated science to give a modified food which has come to be accepted as the norm. Similarly, substitute foods have been accepted; for instance, custard is a substitute for egg custard which was difficult and complicated to make. The improved product based on cornflour was much more straightforward. The classical modified food is, however, margarine. Fats were taken which were unacceptable and put through a technological process which converted them to a product which was something like butter. This was well over 100 years ago, and for a long time the development work on margarine attempted to simulate butter, but as a result of a massive research effort over many years it was recognized that margarine could be made which was superior to butter. Once this realization was achieved, many of the disadvantages present in butter were overcome so that now a considerable amount of research is being devoted to making butter like margarine. In addition, with margarine there is the ability to control the fatty acids which are included in the product, so that if it is ever demonstrated that animal fats are harmful to health there is a technology available which will provide an entirely adequate alternative which should not suffer from these nutritional defects. This development has, of course, been with us for many years and at first farmers and agriculturists were anxious about

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the effect on the sales of butter. Despite their fears the dairy farmer has survived. We now face a similar situation in the field of protein foods with the much publicized advent of meat substitutes.

Meat substitutes fall into two quite distinct classes. The first class consists of relatively crude products prepared by extruding soya meal, while the other has much more sophisticated products produced by spinning of vegetable protein fibres.

The extrusion process (Ashton, Burke & Holmes 1970; Burke 1971) involves subjecting a plasticized mix of defatted oil seed, flour, water and flavourings to high temperatures and pressures and extruding the mix through dies into a region of lower pressure, using equipment such as that in figure 1 (Flier 1968). On emergence, steam is flashed off the paste expanded and

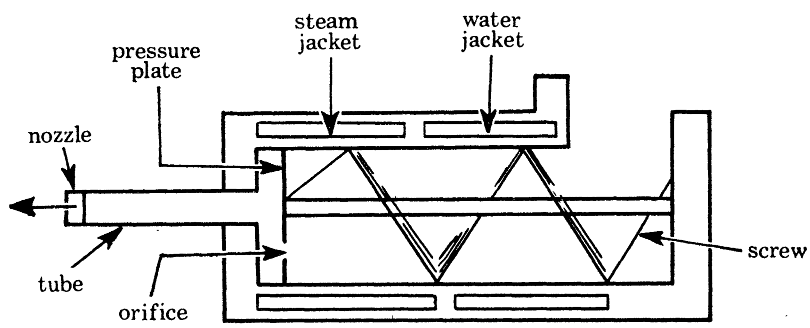

Figure 1. An extruder (Flier 1968).

a relatively dry textured product results. The dry foam consists of interconnected ribbons of varying widths and thicknesses which can be chopped to the required size and further dried for storage. On rehydration, the pieces assume an expanded gel like structure with a texture resembling that of cooked meats. This is then a relatively simple technology which is capable of producing a cheap product but which, nevertheless, provides a nutritious material which can, in certain circumstances, be used as a substitute or as an extender for meat products. One cannot envisage that this sort of simple technology will ever be capable of producing substitute steaks. Variations in the conditions of production give rise to variations in texture, and as the products become more and more accepted by the food industry, developments in technology will occur which will lead to larger varieties of these materials being available. In general, however, the texture differs considerably from meat and in particular the eating qualities vary in that the juiciness is very different. Their water retention is very similar to that of a sponge (Elson 1973).

The alternative technology is that of spinning, and this is much more complicated (Holmes 1970). The process requires the nine stages given in figure 2. Isolation of the protein is required in order to remove the insoluble material which will prevent the production of suitable sized fibres. Production of the spinning dope requires, in many cases, an alkaline degradation of the protein with a change from a globular molecule to a more fibrous molecule. This is then extruded through a spinneret and precipitated at the isoelectric point. The filaments are drawn away, stretched and heat treated; rinsed to remove the precipiting bath solution which leads to off-flavours and squeezed to remove excess water. Finally other ingredients are added, the whole mass is heat set and further processed to produce the particular products which are required. In the final product there is a surprisingly low amount of fibre; for instance, the typical formula of a beef analogue only contains 30 % fibre.

The products which can now be produced as a result of the application of a considerable amount of technology are almost indistinguishable from natural chicken or beef, but we have a situation where the technology is so complicated, and the processing so difficult, that in order to make a satisfactory chicken analogue the cost may at present match the price of natural chicken. But looking to the future, the price of meat will rise but the price of the substitute products will decrease by the application of mass production techniques and improved technology, and in this case there will be a very real place for these meat-like substitutes. It must be emphasized, however, that the use of these meat-like materials is, and will continue to be, heavily controlled by legislation which is designed to protect the consumer. This protection is so effective that it can reasonably be argued that it is inhibiting the development of the food industry and is restricting the ability of the industry to provide the consumer with what is needed.

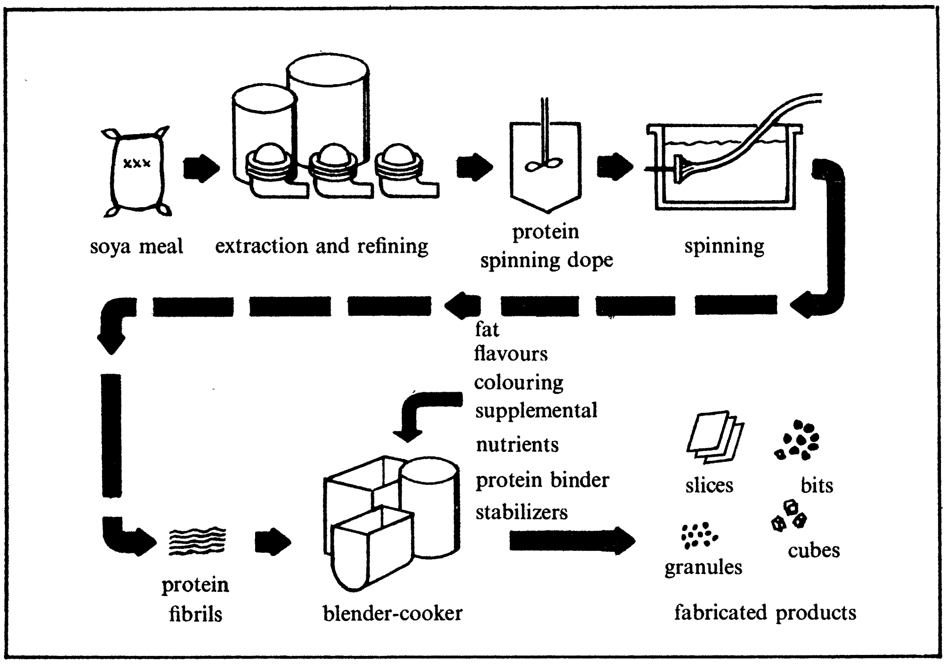

Figure 2. The spinning process for meat substitute production

So far this paper has expressed a purely personal view as to what developments will occur in the food industry. It may be of interest to know what the industry collectively thinks. A colleague of mine carried out a Delphi Exercise on trends in the food industry over the next 20 years (Steiner 1972) which involved the participation of nearly 40 senior technical and non-technical members of the food industry. It is clearly impossible in this paper to discuss the outcome of this exercise in any detail but a few of the opinions expressed may be sufficient to indicate the way the industry is thinking. Figure 3 shows the probability of new sources of ingredients becoming available on a commercial scale. From this it is seen that there is only a moderate chance of the new fats and oil sources becoming available by 1980 but there is believed to be a very much better chance that this will occur by 1990. If this assessment is correct it means that we may anticipate considerable changes in the industry during the 1980s.

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With meat or simulated meat products it is certain that new vegetable sources of protein will be available, certainly by 1990 and very probably by 1980.

Turning now to carbohydrates, there appears to be little development likely except in the interesting concept that by 1990 we will be able to process cellulose and obtain a digestible syrup.

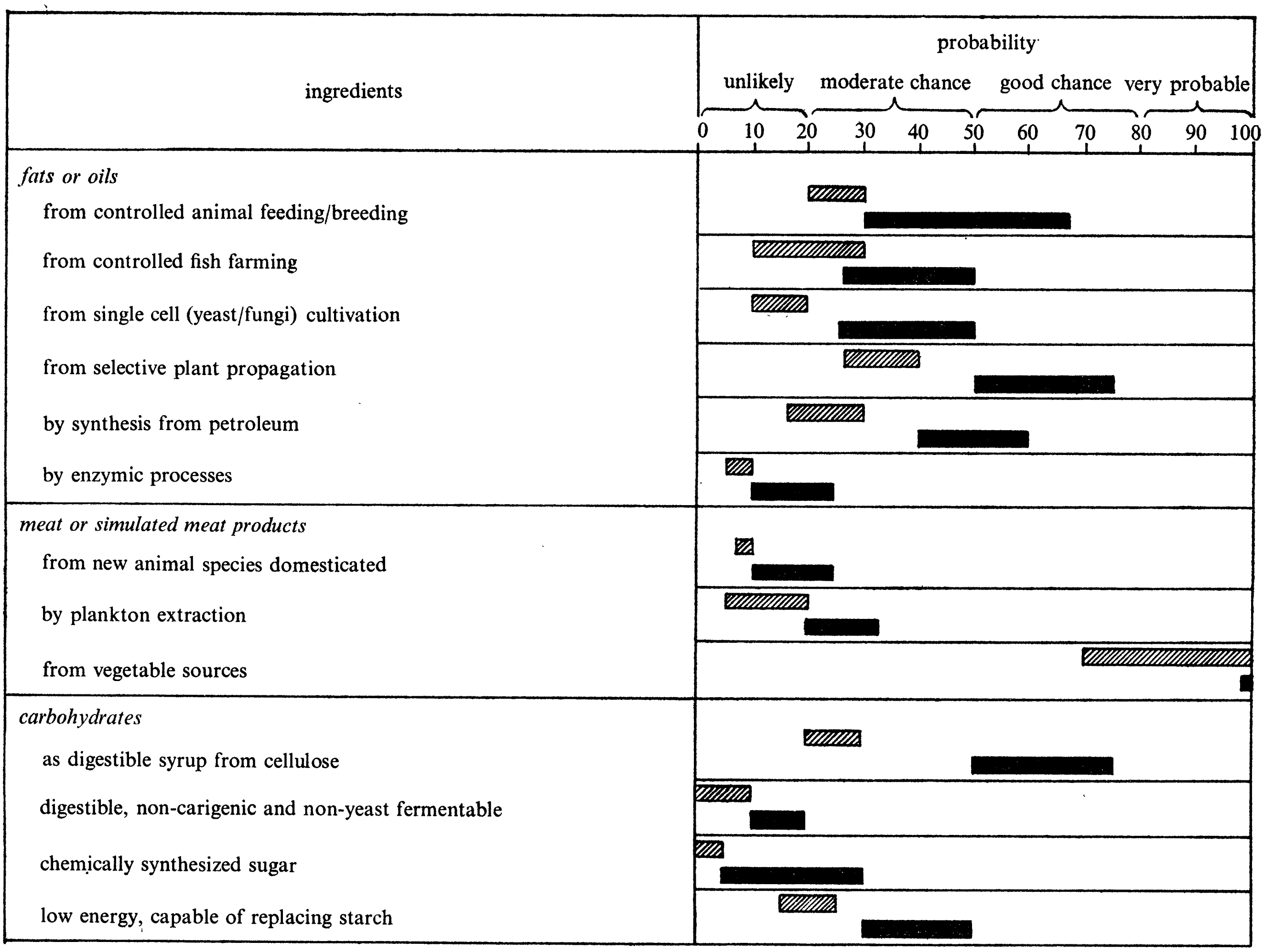

FIGURE 3. Probability of new sources of ingredients becoming available on a commercial scale. Length of line indicates inter-quartile range of replies. ▨, by 1980; ■, by 1990.

Figure 4 shows the estimated production for some major protein sources which shows two points of significance. The animal proteins are anticipated to increase relatively gently except that the production of fresh meat is anticipated to reach a plateau by 1985. This suggests that the food industry feels that the developments in production of fresh meat will mostly occur in the next decade or so and thereafter little further development will be possible. However, the indications are from this graph that vegetable protein will become a very much more important source of protein in our diet than has been the case up to now. The detailed consideration of the vegetable protein situation is given in table 6 which shows that it is believed that over the next 20 years the total production of vegetable protein will double and that a large amount of this protein which becomes available will be utilized in a textured form. Clearly in projections of this nature there is a large element of guesswork and the figures should only be taken as an indication of trends.

These changes will not just happen. They will only occur as a result of increased technological ability coupled with the need to satisfy consumer demands and table 7 gives the industry's assessment of what these demands will be. In the short term it appears that the demand for

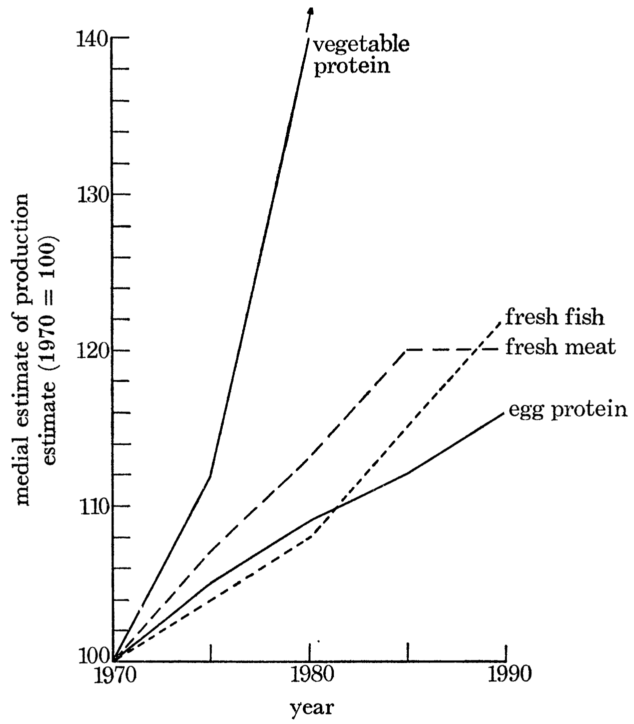

Figure 4. The estimated production for some major protein sources.

Table 6. Lower quartile, median and upper quartile of estimates of the future production index of vegetable proteins

(1970 = 100)

		by year			
protein		1975	1980	1985	1990
total vegetable protein (excluding textured)	lower quartile	110	120	135	155
	median	112	140	190	200
	upper	130	200	300	350
textured vegetable protein	lower quartile	115	150	180	220
	median	130	220	290	320
	upper	200	470	900	1000

variety in the diet, the demand for substitute foods which overcome the increasing costs of traditional foods and the queries about health risks will be the main motivating factors which lead to changes in the industry. These factors will continue to be important during the period 1980 to 1990, but the industry anticipates that during this period the increasing effort to supply nutritional needs of underdeveloped countries will itself influence food elements in this country.

It is hoped that from the brief survey which has been presented and the summary of the opinions of the industry, it will be seen that in certain fields, particularly that in protein foods,

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Table 7. Future social and legislative trends

trend	will occur during 1970–80 yes	no	will occur during 1980–90 yes	no
growing demand for variety in diet from increasing living standards	***		***	
stimulation of developments in food technology and production of substitutes due to increasing cost of traditional foods	***		***	
development of new products becoming increasingly restricted by legislation requirements	**		*	
changes in production methods stimulated by restrictions on permissible additives			**	
continually increasing effort to supply nutritional needs of underdeveloped countries			***	
reduced consumption of foods with potential health risk (e.g. cancer, obesity, heart disease) promoting new product development	***		***	

Level of significance: *, number of replies reached 1 in 10 level of significance; **, number of replies reached 1 in 100 level of significance; ***, number of replies reached 1 in 1000 level of significance.

substitutes do provide a practical alternative and that the industry believes that these changes will not only be possible but also will be required during the 1980s.

References (A. W. Holmes)

Anonymous 1972 *Br. Nutr. Foundation Bull.* **7**, 9–12.
Ashton, M. R., Burke, C. S. & Holmes, A. W. 1970 *B.F.M.I.R.A. Scientific & Technical Survey*, no. 62.
Burke, C. S. 1971 *B.F.M.I.R.A. Scientific & Technical Survey*, no. 68.
Carroll, K. K. 1963 *J. Am. Oil Chem. Soc.* **42**, 516.
Elson, C. R. 1973 *Food R.A., Technical Circular*, no. 532.
Enebo, L. 1970 *Evaluation of novel protein products*, p. 94. London: Pergamon Press.
Flier, R. J. 1968 Ralston Purina Co, Brit. Pat. 1105904.
Frankenfeld, J. W. 1968 (ed.) Study of methods for chemical synthesis of fatty acids and lipids (Esso Res. Eng. Co.), Washington D.C., Nasa. (CR–1105).
Holmes, A. W. 1970 *B.F.M.I.R.A. Symposium Proceedings*, no. 8, p. 57.
Imhausen, K. H. 1949 *Verh. dt. Ing. Z.* **91**, 463.
Mateles, R. L. & Tannenbaum, S. R. 1968 *Economic Bot.* **22**, 42.
Shapira, J. 1971 *Environ. Biol. Med.* **1**, 243.
Steiner, E. H. 1972 Trends in the food industry over the next twenty years (Delphi Exercise).
Tannenbaum, S. R. 1971 *Fd Technol.* **25**, 962.
Thomas, K. & Weitzel, G. 1946 *Dt. med. Wschr.* **71**, 18.