What is the cost of a healthy diet in terms of achieving RDAs?

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Abstract

Objective: Assessing how the Italian average food pattern would be affected in terms of consumption structure and expenditure by the adoption of nutritional prescriptions.
Design: A linear programming model with nutritional and food habits constraints was employed to generate a pattern following recommended daily allowances (RDAs) and nutritional guidelines provided for the Italian population.
Setting: Food consumption data from ISTAT Household Budget Survey of Italian population.
Subjects: Italian families investigated by the Family Budget Survey of the National Institute of Statistics.
Results: Compared to actual behaviour, the pattern generated by the model implies an increased consumption of vegetables, pasta, rice and fresh fish, and a decreased consumption of meats, bread, sugars and cakes, and especially fats and oils. At given prices, total expenditure is lower than actual expenditure.
Conclusions: Differences between actual behaviour and the generated pattern are consistent with long-term trends in food consumption. The adoption of RDAs is unlikely to result in an increased food expenditure.

Keywords
Diet cost
Linear programming
RDAs
Nutritional guidelines
Food habits
Food consumption trends

Nutritional features of food are becoming increasingly relevant determinants of consumption patterns for Italian households. Over the last decades, income growth and the consequent decreasing incidence of food expenditure compared with total consumption, have progressively diverted consumers' attention toward qualitative aspects in the choice of foods, as opposed to quantitative ones. Today this implies an increasing willingness to pay for additional safety of food products, and increasing attention toward the overall safety of consumption patterns, given a more widespread knowledge of the relation between food patterns and health status[1,2]. Health considerations, however, appear to be still significantly moulded by food tastes and habits, so that, in most population groups, consumption tends to be imbalanced compared with nutritional recommendations for most developed countries.

This paper assesses what could be the effect of the adoption of a nutritionally correct food behaviour on average food patterns and related expenditure. In other words, the basic question that has been addressed is: 'What would happen to food expenditure if Italians suddenly switched from their actual food consumption pattern to one that meets nutritional requirements as defined by nutritionists?' An answer is provided by comparing the actual average food pattern of the Italian population with one obtained through linear programming. Applications of linear programming to diet problems have frequently encountered problems in terms of solution viability. The minimum cost criterion, in fact, tends to produce solutions composed of a few foods which are particularly efficient in terms of nutrient provision. This has also been the case in the seminal work of Stigler[3] which showed how nutritional considerations tend to be absent from choice criteria, even in poorer households. In the present work, 'food habit constraints' (or 'palatability constraints') have been included in the linear programming model – similar to those employed in other studies[4,5] – in order to introduce more realistic features within the solution. The aim of this work is descriptive rather than normative, i.e. the purpose is to *describe* what the average Italian food pattern may look like and how much it would cost if the population followed RDAs, rather than to *indicate* how RDAs should be met.

The next section contains a brief description of the linear programming model as it applies to the diet problem, of the specific features of this application, and of the information base employed. The third section deals with the description and discussion of the main results obtained. Finally, the fourth section provides some concluding comments.

Methods and materials

Linear programming models provide solutions to constrained maximization and minimization problems. These can be used to build diets by minimizing food expenditure

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subject to the intake of given maximum and/or minimum levels of nutrients, given vectors of prices, vectors of maximum and minimum requirements, and a food composition matrix[6,7]. The problem is expressed as:

$$\text{Min} \sum_i p_i x_i \text{ where } i = 1, \ldots, n \quad (1)$$

$$\text{s.t. } N_j \leqslant \sum_i a_{ij} x_i \leqslant M_j \text{ where } j = 1, \ldots, m$$

$$x_i \geqslant 0$$

where i = foods, j = nutrients, p_i = price of food i, x_i = quantity of food i, a_{ij} = unit content of nutrient j in food i, s.t. = subject to, N_j = minimum allowed intake of nutrient j, and M_j = maximum allowed intake of nutrient j.

This formulation of the diet problem implies several restrictive hypotheses. First, it assumes that nutritional requirements are independent, while every nutritionist would agree that this is not the case. Second, all nutrients are considered equally important, while it is known that some of them are more important than others. Third, all sources of nutrients are considered equivalent. Despite these limitations, the model has been frequently employed, especially in the formulation of normative diets, either for poor households[3,4,8] or for specific population groups, such as the elderly or the young[9]. In order to increase the viability of solutions, most applications add extra constraints to model (1), providing limitations on the amounts of some foods entering the solution. These are derived from observed habits and behaviour, so that the solution contains foods in proportions which are common in the reference population. Food habit constraints that have been employed here are of the form:

$$\chi_{i+1} + \chi_{i+2} + \chi_{i+3} \geqslant \lambda \sum_i \chi_i \quad (2)$$

and

$$\chi_{i+1} \geqslant \theta(\chi_{i+1} + \chi_{i+2} + \chi_{i+3}) \quad (3)$$

Constraint (2) specifies given proportions in which a group of foods has to enter the solution, e.g. the total amount of meat (made of, for example, beef, pork or poultry) has to enter the solution in a given proportion compared to all other foods included. Constraint (3) specifies something similar within food groups, e.g. it requires that the amount of pork meat that enters the solution must be a given proportion of the total amount of meat. Values of λ and θ have been derived from the observed average behaviour of the Italian population, but they had to be appropriately modified to include nutritional norms.

It is worthwhile to remark that model (1) generates a food pattern which is the cheapest only under the specified constraints, so that its total cost is the minimum under those conditions. This implies that it is not the only pattern that could be chosen by consumers willing to meet RDAs. However, the idea of generating a minimum cost pattern meeting RDAs and food habit constraints rests upon the hypothesis that, on average, consumers will minimize expenditure associated with the fulfilment of habits, palatability and nutritional requirements.

Consumption data have been retrieved from unpublished files of the yearly Family Budget Survey made by the Italian National Institute of Statistics (ISTAT)[10]. The use of this source has to be considered as a limitation for the analysis, since data refer to the amounts bought by households, rather than to food intake. Data were available for 50 food items, both in terms of expenditure and physical amounts. These have been used to calculate unit values of foods, which have been used as a proxy for the price vector p_i (Table 1). The same dataset was employed to derive the λs and θs included in food habit constraints (2) and (3).

The dataset employed does not allow us to qualify the analysis for different population groups; this is a limitation too, since it is clear that the issue of the cost of a healthy diet may be more relevant for relatively poor households.* The breakdown of food quantities for different population groups is, in fact, published by ISTAT only for a few aggregates (about 10 food items are used to describe the whole diet). In the future, a more suitable database for the purpose of the present work will be provided by the Italian National Institute of Nutrition (INN) INN-CA 1995 food survey (unpublished data, 1997), whose data, in terms of expenditure and net and gross quantities, are being processed. This paper should therefore be considered as a provisional exercise, which will be expanded when more data are available.

What model (1) provides is a so-called 'total diet', i.e. a list of food amounts that, with reference to a unit time period, includes all food which are consumed. Food composition data – the a_{ij} coefficients – have been taken from Ferro-Luzzi *et al.*[12,13] and includes a list of 14 nutrients (Table 2). (The most complete food composition database available for Italy[14,15] could not be employed here, since it includes far more items than the ISTAT list. The composition data used for this work is the outcome of an *ad hoc* aggregation of data from Carnovale and Miuccio[15] and the ISTAT 50 food items list.)

Nutritional norms were established from the nutritional guidelines for the Italian population[16] and the RDAs published by SINU[17]. RDAs for nutrients have been calculated as proportions of the amount of energy included in the diet – excluding energy derived from alcohol – according to SINU[17]. The average per capita requirement (kJ person^{-1} day^{-1}) for the Italian population

*However, this may not be of great significance in Italy. A recent study tried to establish the relationship between a poverty multi-dimensional index and a similar index for nutritional imbalance, based on the distance of nutrient consumption from RDAs. The outcome showed only a weak relation between the two phenomena[11].

Table 1 Per capita consumption in Italy (1994)

Food groups	Items*	Amounts (g person^{-1} day^{-1})	Expenditure (IT £ day^{-1})	Unit values (IT £ g^{-1})
Bread and similar	Bread	160.67	498.74	3.104
	Bread-sticks, rusks, etc.	11.51	72.49	6.300
	Biscuits and cakes	36.20	319.82	8.836
	Flour	12.49	16.90	1.353
Pasta and rice	Pasta	78.97	180.99	2.292
	Prepared pasta	10.78	110.20	10.220
	Rice	25.64	76.08	2.967
Fish	Fresh and frozen fish	31.27	463.56	14.826
	Preserved fish	5.52	83.21	15.065
Meat	Veal meat	34.09	616.90	18.095
	Beef	22.98	371.34	16.159
	Pork meat	14.53	173.16	11.916
	Horse meat	0.99	15.62	15.833
	Sheep meat	1.81	26.37	14.582
	Poultry	35.57	322.82	9.075
	Rabbit, turkey, etc.	5.88	61.91	10.520
	Canned meat	0.79	12.20	15.458
	Ham and salami	22.68	449.62	19.820
Fat and oils	Lard and other animal fats	0.13	0.82	6.250
	Margarine	1.58	11.08	7.021
	Butter	6.25	57.53	9.211
	Olive oil (dl)	42.74	285.80	6.687
	Seed oil (dl)	23.01	58.13	2.526
Dairy and eggs	Milk (dl)	200.55	334.75	1.669
	Yogurt	11.80	80.91	6.855
	Cream	2.27	19.92	8.783
	Fresh cheese	24.30	332.19	13.673
	Preserved cheese	16.01	268.08	16.743
	Eggs	21.70	89.39	4.120
Vegetables and potatoes	Potatoes	71.70	74.86	1.044
	Fresh tomatoes	43.27	95.93	2.217
	Fresh and frozen pulses	16.01	59.84	3.737
	Fresh and frozen vegetables	86.60	255.09	2.946
	Canned tomatoes	29.85	52.73	1.767
	Preserved and dried pulses	9.14	32.09	3.511
	Preserved and dried vegetables	7.99	36.33	4.547
Fruits	Fresh fruits	163.23	374.99	2.297
	Citrus fruits	79.99	168.07	2.101
	Dried fruits and nuts	1.97	12.59	6.383
	Preserved fruits	0.69	4.64	6.714
Sugar and cakes	Sugar	41.59	77.00	1.851
	Jam, jelly, etc.	16.08	175.33	10.906
	Other cakes	7.76	82.36	10.614
	Ice-creams	8.32	92.98	11.178
Non-alcoholic beverages	Coffee, tea and other stimulants	14.63	205.81	14.067
	Fruit juices, syrups, etc. (dl)	9.86	23.24	2.357
	Soft drinks	39.45	53.42	1.354
Alcoholic beverages	Wine	118.36	269.26	2.275
	Beer	32.88	65.33	1.987
	Spirits	6.58	76.64	11.655
Total expenditure			7699	

Source: calculations based on unpublished data from *Indagine sui Consumi delle Famiglie* (ISTAT, Rome, 1995).
* Among available items, 'other foods' has been excluded as no quantitative and composition data were available.

was calculated with reference to an average amount of physical activity, and was weighted with sex and age. This calculation yielded a per capita requirement of 8819 kJ day^{-1}. Both a maximum and a minimum constraint have been applied to this although these limits are highly tentative, since the appropriate energy range can vary widely, even with the same age and levels of physical activity[17]. Nonetheless, the calculation yields a credible average indication – that appears to be widely shared by other studies[17] – which suggests that energy intake is slightly excessive in Italy.

Maximum and minimum constraints have also been employed in the case of energy derived from alcohol; this is not due, obviously, to the existence of a minimum RDA for alcohol, rather it is required, as the model is run, to avoid substitution between alcohol and other sources of energy. A maximum threshold of 30 g per person per day was set for alcohol, corresponding to 879 kJ. A level of 79 g of protein was adopted for the maximum RDA, corresponding to 15% of (non-alcohol) energy in the diet, while no adjustment could be included in the model for quality. Lipids were given a maximum RDA of about 70 g,

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Table 2 Per capita consumption in Italy (1994) in terms of nutrients

Nutrients	Actual consumption (*a*)	RDAs (*b*)	(*a*/*b*) * 100
Total energy (kJ)	12947.5	8819	147
Alcohol energy (kJ)	443.8	879	50
Total protein (g)	95.3	79	120
Total lipids (g)	138.6	69	202
Polyunsaturated/saturated fatty acids	0.6	0.5	116
Available carbohydrates (g)	362.2	306	118
Soluble carbohydrates (g)	108.5	74	147
Dietary fibre (g)	19.7	20	99
Cholesterol (mg)	358.0	269	133
Alcohol (g)	15.1	30	50
Calcium (mg)	876.3	800	110
Iron (g)	15.2	11.19	136
Vitamin C (mg)	116.9	65.84	178
Riboflavine (mg)	1.8	1.63	108
Tiamine (mg)	1.1	1.04	104

Source: calculations based on unpublished data from *Indagine sui Consumi delle Famiglie* (ISTAT, Rome, 1995) and ref. 17.

corresponding to 30% of energy. Moreover a constraint was introduced for the polyunsaturated/saturated fatty acids content, that requires this ratio to be higher than 0.5.

For carbohydrates, both the soluble and the available portions were considered separately, and maximum and minimum constraints were imposed for both, so that the proportion between the two is fixed. The soluble portion was fixed at 13.5% of energy, while 55% of energy was set as the maximum for simple carbohydrates. In the case of dietary fibre only a minimum constraint was imposed at 20 g person^{-1} day^{-1}, since this is the goal indicated by the nutritional guidelines[16]. Minimum constraints only were also imposed for calcium (800 mg), vitamin C (66 mg), thiamine (1 mg) and riboflavine (1.6 mg). The amounts of these nutrients generated by the model always fell within acceptable ranges; for this reason it was decided to eliminate maximum constraints in order to facilitate the running of the model.

A maximum constraint was imposed in the case of cholesterol, assuming a reference value of 269 mg person^{-1} day^{-1}. Minimum and maximum constraints were also imposed for iron – assuming a range of 11–20 mg person^{-1} day^{-1}. In this case, the maximum constraint was needed since the model tends to generate patterns with excessive amounts of iron.

Finally, for those nutrients for which only one reference value was available, but both maximum and minimum constraints apply – energy, proteins, lipids and carbohydrates – a range of ±3.5% centred on the reference value was used as 7% is the average variability of RDAs according to sex and age classes.* In this way the model took into account the range of possible variability of RDAs due to the demographic structure.

*This means that, for example, the maximum constraint for energy specifies a value of $+8819+(8819*0.035)=9127.7$, while the minimum constraint specifies a value of $8819-(8819*0.035)=8510.3$.

Results and discussion

The comparison of effective consumption (in terms of nutrients) with RDAs for the Italian population shows that major imbalances in average behaviour are mainly due to an excessive intake of energy – excluding the portion derived form alcohol – followed by an excess of proteins, lipids, cholesterol and carbohydrates (mainly soluble). Other nutrients appear to be within the RDA range, with the exception of dietary fibre, which is slightly below the minimum (Table 2).

The model was first run with only the constraints on maximum and minimum nutrient requirements, i.e. by ignoring food habit constraints on the diet. As expected, the outcome is a very poor diet (Table 3), including only eight items and corresponding to an expenditure level which is about one-third of the effective food expenditure. This diet represents a sort of pure 'cost of subsistence' in Stigler's terms[3], i.e. it indicates the cost of meeting nutritional requirements without any consideration of taste and habit.

Given the form of food habit constraints, a full food habits structure of observed behaviour was first defined by considering 11 constraints of type (1) for each food group (as reported in Tables 1 and 3), and 39 constraints of type (2) for $k-1$ items within each of the 11 groups of k items. Values of λ and θ are those observed in effective behaviour, that is, from Table 1. As expected, such a diet is inconsistent with RDAs (Table 2). At the same time, nutritional prescriptions are not only made of RDAs: they include more general indications of the food from which these RDAs have to be achieved. These indications are reported in the simplified form of *Guidelines for a Healthy Italian Nutrition*[16] and were used, together with the results of Table 2, to introduce modifications to the food habit constraints, by following the qualitative criterion of modifying to the lowest possible extent the observed values of λ and θ, in order to obtain a solution reflecting, as far as possible, effective tastes and habits.

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Table 3 Pattern obtained as a solution of the linear programming model (g person^{-1} day^{-1})

Food groups	Items	Without food habit contraints (*a*)	With food habit contraints (*b*)	(*b*) as % of actual consumption
Bread and similar	Bread		74.87	46.6
	Bread-sticks, rusks, etc.		11.23	97.6
	Biscuits and cakes		16.89	46.7
	Flour	283.78		0.0
Pasta and rice	Pasta		133.14	168.6
	Prepared pasta			0.0
	Rice		37.99	148.1
Fish	Fresh and frozen fish		34.33	109.8
	Preserved fish			0.0
Meat	Veal meat		24.44	71.7
	Beef		16.46	71.6
	Pork meat		10.37	71.4
	Horse meat		1.30	131.5
	Sheep meat		1.30	71.7
	Poultry		25.43	71.5
	Rabbit, turkey, etc.		4.19	71.2
	Canned meat			0.0
	Ham and salami		16.26	71.7
Fat and oils	Lard and other animal fats			0.0
	Margarine		0.33	20.8
	Butter		1.33	21.2
	Olive oil (dl)		9.05	21.2
	Seed oil (dl)	33.47	4.90	21.3
Dairy and eggs	Milk (dl)	608.25	192.42	95.9
	Yoghurt		11.29	95.6
	Cream			0.0
	Fresh cheese		23.10	95.1
	Preserved cheese		15.23	95.1
	Eggs	42.96	20.48	94.4
Vegetables and potatoes	Potatoes		104.48	145.7
	Fresh tomatoes	204.40	63.23	146.1
	Fresh and frozen pulses	130.95	23.52	146.9
	Fresh and frozen vegetables		137.25	158.5
	Canned tomatoes		43.57	145.9
	Preserved and dried pulses		13.49	147.6
	Preserved and dried vegetables			0.0
Fruits	Fresh fruits		152.30	93.3
	Citrus fruits		74.54	93.2
	Dried fruits and nuts		2.52	127.9
	Preserved fruits			0.0
Sugar and cakes	Sugar	15.37	19.36	46.6
	Jam, jelly, etc.		7.48	46.5
	Other cakes			0.0
	Ice-creams		7.48	90.0
Non-alcoholic beverages	Coffee, tea and other stimulants		13.58	92.8
	Fruit juices, syrups, etc. (dl)			0.0
	Soft drinks		45.71	115.9
Alcoholic beverages	Wine	140.78	131.09	110.8
	Beer		34.43	104.7
	Spirits			0.0
Total expenditure (IT £ person^{-1} day^{-1})		2830	6168	80.1

Source: calculations based on unpublished data from *Indagine sui Consumi delle Famiglie* (ISTAT, Rome, 1995) and ref. 17.

Constraints of type (3) were left equal to those observed in the actual behaviour of the population, so that the quantitative proportions among foods within the major food groups are the same as in observed consumption. Constraints of type (2) were modified as follows:

1 The constraint on fats and oils was considered with an arbitrary coefficient of $\lambda/4$ instead of λ, since effective lipid intake appears to be significantly higher than the RDA (Table 2). A general recommendation of the INN[16] is for a reduction of fat and oil consumption. Within this group the preference for olive oil – which is also recommended by INN[16] – is provided by the related type (3) constraint.

2 The constraints for the three groups of bread and cereals, pasta and rice and sugar and cakes, have been considered with a coefficient of $\lambda/2$ instead of λ, since both carbohydrate and protein intakes were higher than the RDAs (Table 2).

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With these modifications in the food habits structure, the model provides a solution that is far more realistic than one yielded by the RDAs alone (Table 3). Compared to effective behaviour, 11 food items are excluded from the solution (flour, prepared pasta, dry fish, canned meat, lard, cream, dried vegetables and fruit, other cakes, fruit juices and spirits) which are, with the exception of filled pasta and fruit juices, less important in terms of quantity within each respective group. Compared to actual consumption, the pattern obtained shows an increase in consumption of vegetables, pasta, rice and fresh fish, and a decrease in consumption of meats, bread, sugar and cakes, and especially of fats and oils.

As already mentioned, the food pattern obtained through linear programming is not intended as a normative tool; rather it attempts to provide a stylized description of what the average Italian diet would look like if the population moved toward nutritional prescriptions, while maintaining where possible current tastes and habits. Given this, it is useful to compare the differences between the generated pattern and actual behaviour with trends in Italian average consumption, in order to yield a qualitative assessment of the credibility of the generated pattern itself (Table 4).

For more than one food group, differences with the observed behaviour appear to be consistent with long-term changes in average consumption. This is the case, for example for meat, where consumption has been declining over a 10-year period, and for which provisional models indicate a further reduction over the next few years[9]. The consumption of sugar, oils and fat, which are significantly reduced in the generated pattern, has also been declining over this 10-year period. In the case of vegetables and fresh fish, the long-term trend toward an increased consumption appears to be consistent with the indication provided by the generated diet. On the other hand, the indications provided by the generated pattern for fruit, pasta and non-alcoholic beverages are not consistent with the long-term trends of consumption. For the first two items this result is probably due to the strict application of RDAs on carbohydrates, while, for non-alcoholic beverages, the generated pattern does not take into account mineral water, which has been one of the major determinants of the long-term growth of consumption of these products.

Finally, the expenditure necessary to acquire the food pattern generated by the model is about 20% lower than the effective average food expenditure. This result is obtained assuming fixed prices, that is, it does not take into account the changes in prices that may follow the change in demand for the items considered. A switch toward a more healthy diet – according to the direction prescribed by RDAs – would correspond to a change in consumer preferences. Economic studies have shown that the demand for food items is relatively price-insensitive in Italy, as is normal in a high-income country[18,19]. This means that the price change for food items would be primarily determined by supply elasticity. At the same time, it is possible that qualitative changes may occur within the food items as they are defined by ISTAT data. Due to health considerations, consumers may decide to buy smaller amounts of some goods, while switching from lower to higher quality. This could, in turn, change expenditure patterns. All such changes, however, are not detectable with the linear programming model employed, which, in this respect, deals with consumption and not with demand.

Conclusions

The main insights provided by this work can be grouped into three areas. First, the solution of the linear programming exercise supports the idea that consumers normally choose foods rather than nutrients; the minimum cost of the mere acquisition of RDAs – or even of the amounts of nutrient intake observed in effective consumption – accounts for a very small share of effective expenditure. That is, most food expenditure pays for tastes and habits in consumption in the Italian case. Food habit constraints were included in the model for this reason. It is

Table 4 Comparison between trends in food patterns and the difference between model solution and actual behaviour

Food groups	Per capita consumption in 1993–94 (100 = 1983–84)	Pattern generated through linear programming (100 = per capita consumption in 1993–94)
Bread	87	47
Pasta	92	148
Fish	178	110
Meat	83	72
Fat and oils	86	21
Dairy and eggs	100	95
Vegetables	105	146
Fruits	110	93
Sugar and cakes	82	47
Non-alcoholic beverages	384	93
Alcoholic beverages	74	105

Source: calculations based on refs 10, 12 and 17.

useful to recall that their modifications – necessary to make them accommodate RDAs – though arbitrary, have been set according to both nutritionists' prescriptions on foods and to the criterion of minimizing changes in the structure of effective consumption, as represented by the values of λ and θ.

Second, the pattern generated by including both RDAs and food habit constraints in the models shows several features which were consistent with consumption trends of some major food groups. This can be considered a confirmation that the generated pattern is a credible description of what a healthier average diet may look like in Italy. By turning the argument upside down, the consistency of the generated pattern with the effective trend in behaviour allows one to argue that, to some extent, consumption by Italians has been moving toward a more healthy pattern over the last years. This result is, at the same time, consistent with the indication of nutritional surveys, which have shown that, compared to the 1980s, there was a reduction in excessive intake of macronutrients in the mid 1990s (INN, unpublished data, 1997).

Third, given the indications provided by the generated pattern, it seems likely that a trend toward a healthier average diet in Italy does not imply per se an increase in food expenditure. Even though the model does not take into account price changes that may follow the move toward a more healthy diet, major uncertainties in terms of total expenditure seem to be more likely to be due to qualitative changes within the food items considered which may result in an increase of unit prices.

Finally, it is useful to remember that costs associated with an imbalanced average food pattern lend themselves to more far-reaching considerations which go beyond private consumption. Epidemiological studies on the association between food intake and health status have shown that even a small decrease in the risk of contracting food-related diseases – arising from a more healthy average pattern – may significantly affect both health care expenditure and labour productivity (see, for example, ref. 12). This provides motivation for increased efforts in the area of nutritional policies aimed at consumer education on the one hand, and on the other, food production standards.

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