Towards a sustainable diet combining economic, environmental and nutritional objectives

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Abstract

Foods consumed and dietary patterns are strong determinants of health status. Diet and nutrition have a key role in health promotion and maintenance during the entire lifetime, but what we choose to eat and drink greatly affects the environmental impact on ecosystems as well as monetary resources. Some studies suggest that a healthy diet with a low environmental impact is not necessarily more expensive. This paper aims to identify a healthy, greener and cheaper diet based on current consumption patterns. Dietary information was collected from 104 young adults in the last year of high school in Parma (Italy). Diet was monitored with 7-day dietary records. Subsequently, food items were decoded to obtain nutritional, economic and environmental impact data. An optimization tool based on mathematical programming (Multi-Objective Linear Programming) was used to identify sustainable diet. Three different 7-day diets were identified, based on nutrition recommendations for the healthy Italian adult population, characterized by different targets and optimizing different impacts: first the diet at the lowest cost (Minimum Cost Diet – MCD), then the Environmentally Sustainable Diet (ESD) obtained by minimizing the three environmental indicators (CO_2e emissions, H_2O consumption and amount of land to regenerate the resources – m^2). Finally, the Sustainable Diet (SD) was identified by integrating environmental and economic sustainability objectives. Lastly, suggestions and recommendations for communication campaigns and other interventions to achieve sustainable diet are suggested.

Keywords:

Sustainable diet; Diet cost; Nutrients; Greenhouse gases; CO2e emissions; Ecological impact.

Introduction

Foods consumed and dietary patterns are strong determinants of health status during our entire lifetime, and what we choose to eat and drink also has environmental impact on ecosystems and affects monetary resources (WHO, 2008; Duchin, 2005). The agricultural and food sector is responsible for more than 25% of all greenhouse gas (GHGs) emissions, contributing to fresh and marine water pollution, and using about a half of ice-free land area on Earth as cropland and pasture (Tilman and Clark, 2014). Animal origin food production causes greater environmental impacts than fruit and vegetable production, and most plant-based foods can have protective effects against the major chronic diseases (De Marco *et al.*, 2014). Moreover, some studies suggest that a healthy diet with a low environmental impact is not necessarily more expensive (Conforti and D'Amicis, 2000; Barilla Center for Food and Nutrition, 2011b; Germani *et al.*, 2014). Population growth, agriculture intensification, lifestyle changes, poverty, and food security are also part of this picture leading to the necessity to re-define food systems and dietary patterns from environmental and health perspectives (Johnston *et al.*, 2014; Hallström *et al.*, 2015).

It is generally acknowledged that what a person chooses to eat makes a difference from an environmental perspective (van Dooren *et al.*, 2014; Vieux *et al.*, 2012). For instance, Marlow and colleagues (2009) have estimated that a non-vegetarian diet requires 2.9 times more water, 2.5 times more primary energy, 13 times more fertilizer, and 1.4 times more pesticides than the vegetarian diet. It has been estimated that Mediterranean, pescetarian and vegetarian diets may reduce by 30%, 45% and 55% respectively per capita emissions from food production, as compared to projected 2050 income-dependent diet (Tilman and Clark, 2014). These diets might therefore be considered more sustainable than others. One of the first formalizations of the concept of sustainable diet was introduced in the seminal work by Gussow and Clancy (1986), who looked at foods from the nutritional point of view and also considering their impact on natural resources. More recently, the FAO provided a new definition which takes into account the role of dietary patterns on sustainable development and the elimination of poverty and food insecurity: "Sustainable diets are those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources" (FAO, 2010, p. 7).

The positive impacts of sustainable diets are related to public health (e.g., reduced diet-related chronic disease, etc.), environmental sustainability (e.g., mitigation of water and land use, reduction of GHG emissions, etc.), economic sustainability (e.g., employment and trade opportunities, etc.), social inequalities (e.g., closing gaps in health, incomes and food affordability in developed and developing countries, etc.), and other possible benefits (e.g., psychological and physical well-being, animal welfare, cultural and social diversity, etc.) (Johnston *et al*., 2014). The multidimensional character of sustainable diets is given by factors and effects that are closely interconnected and interdependent, so that modifying one or more components of a diet might have different and unintended effects across these categories. For instance, although reducing beef consumption might improve environmental quality and public health, it could negatively affect the economic stability of beef producers and related food systems. Public authorities aiming at stimulating sustainable consumption need to consider these links carefully.

Affordability, income distribution and costs related to food products are further important determinants influencing food choices. The sudden price increases of food commodities on world markets after 2008 led to increased concern over the ability of the world food economy to adequately feed billions of people (FAO, 2011). At the same time, the globalization of the food system has contributed to the spread of cheaper foods high in energy but low in important nutrients in developed and developing countries (Johnston *et al.*, 2014). This means that unless sustainable options become more affordable, people will continue to disregard environmental considerations when making food purchases. Moreover, it was suggested that inequities exist in the affordability of the health and sustainable food basket and the typical basket at the household level, with the most disadvantaged neighbourhoods and lowest income households spending proportionately more on sustainable food (Barosh *et al.*, 2014). Other studies have demonstrated that total expenditure on a healthy (Conforti and D'Amicis, 2000) and environmental sustainable diet (Barilla Center for Food and Nutrition, 2011b) would in fact be lower than the actual current expenditure.

Health, affordability and environment are the three key components of food consumption which need to be balanced for there to be a sustainable diet in line with health recommendations. Literature suggests that these three dimensions of the sustainable diet might be represented as and accommodated in optimization problems. One potentially useful class of operational research tools is mathematical programming (Stigler, 1945; Dantzig, 1948; Paris, 1991). Mathematical programming, linear programming in particular, has long been used to identify adequately healthy, environmentally friendly and affordable human diets. The Nobel Prize winning economist George Stigler formulated one of the first linear programming problems on the minimum cost of diet for the American population in 1945. Subsequently, various researchers tried to optimize human diet using optimization techniques. Briend *et al.* (2003) suggested the application of linear programming to support paediatricians in identifying complementary foods to provide children of 6-24 months of age with additional energy and nutrients. Macdiarmid *et al.* (2012) developed a linear programming model able to identify a diet which would be environmentally resource saving, acceptable and economically reasonable for the United Kingdom population. Their study shows the potential of mathematical programming as a tool to make the use of food resources for global warming mitigation efficient without increasing the food expenditure for consumers. These authors impose a series of constraints, beyond the macro and micro-nutrient constraints, to reach a realistic solution for the different scenarios through lower and upper weight food limits. The issue of realistic palatable and varied diet was also tackled by Wilson *et al.* (2013) through linear programming, where the objective was to suggest for New Zealand consumers a healthy, cheap and environmentally sustainable food basket. They indicated that results from an optimization model can be used to design planning policy instruments to promote the consumption of healthy and environmental sustainable foods. Communication campaigns, labelling and economic instruments such as taxation can be used to orient the public to a more aware and sustainable diet.

This study aims to identify a healthy, greener and cheaper diet based on current consumption patterns. We considered the dietary patterns of a sample of 104 young adults attending high school, and assessed their nutritional, environmental and economic impacts. This target group was selected in the light of current concerns about low dietary quality of young adults and consequent possible dietary deficiencies (Turconi *et al.*, 2008). In this framework, we performed an optimization analysis using a linear programming model to produce nutritionally correct 7-day diets that minimize the environmental impact (ecological sustainability) and the cost paid by consumers (economic sustainability), considering at the same time palatability and viability constraints. The resulting dietary scenarios should be in line with recommendations for a healthy diet (SINU, 2012). The results will be useful to inform food policy makers about the health, economic and environmental impact of the current dietary patterns of young Italians, and to suggest possible interventions to achieve a more sustainable diet.

Material and Methods

Data collection

Dietary information was collected from students attending eight different final year classes in high schools in Parma (Italy). The schools were selected in order to include participants with different socio-economic backgrounds. One-hundred twenty participants were recruited but 16 were eliminated because of data missing from the dietary record. The final sample included 104 young adults (38 male; 66 female), age 18-20 years, BMI 21.8 ± 3.3 Kg/m^2 (mean ± standard deviation). Their diet was monitored with 7-day weighed dietary records (Dall'Asta *et al.*, 2012). Participants were asked to weigh all food and drinks consumed and to use standard household measures (e.g. table spoon, tea spoon, cup) to estimate the amount where weighing was not possible. A food diary database with a list of 544 food items was created. Food items included in dietary records were used to create a nutritional database, linked to the food code of the European Institute of Oncology (EIO) database (Gnagnarella *et al.*, 2008). The following nutritional values were selected from the database: energy, proteins, total carbohydrates, sugars, lipids, saturated fats, sodium (mandatory nutrition declaration - Regulation (EU) No 1169/2011 of the European Parliament and of the Council of the European Union) and dietary fibre, of keen interest for the majority of consumers. The EIO code was used to generate an economic database and an environmental database.

The environmental impact was calculated taking into account the three indexes most representative of the agri-food system: carbon footprint (CO_2e emissions), water footprint (H_2O consumption) and ecological footprint (m^2 land needed to regenerate the resources) (Germani *et al*., 2014). These three indexes were retrieved from the database set up by BCFN (Barilla Center for Food and Nutrition) and used for the construction of the Double Pyramid (Barilla Center for Food and Nutrition, 2011a). The environmental impact was evaluated for a period of 7 days per person for each dietary model, taking into account both quantities and frequency of consumption for the different food items.

In May and June 2014, four outlets were surveyed in the Province of Parma (Northern Italy). The food items in the survey instrument represented the aggregate list of the foods indicated by the participants 7-day dietary records. From this list, it was possible to infer the outlets of large retailers most frequented by the participants. The survey instrument was used to record availability, price, weight, unit of measurement and price per unit weight for each food item. If the item was normally available (stocked), the actual price/brand of each food item was documented. If the brand of a food item was not available in the outlet, the median price of other brands of that item was calculated from price data reported in the same outlet. The recorded price of each available food item was converted into price per unit weight (€/g in case of solid foods and €/litre in the case of liquid foods), and then the price per required weight for the diet was calculated. The total cost of each diet was calculated by summing up the cost per required weight of each food item in the diet, calculated per person per week. The total cost per food item does not consider the energy cost due to the cooking operations.

The mathematical programming model

The information about the food consumption collected by the food diaries (except for ingredients) and the data on the nutritional intakes, environmental impacts and food prices were used to build a mathematical programming model aiming at optimizing diet according to three objectives. These objectives were to identify i) the diet at the minimum cost, 2) the diet with minimum environmental impact, and iii) the diet that minimizes both consumer expenditure and environmental impact.

The modelling followed the approach proposed by Stigler (1945), where he adopted a linear programming model to identify a combination of foods able to satisfy the nutrient requirements of a moderately active man of 70 Kg at minimum cost. Unlike Stigler's model, we include in the model nutrient requirement constraints, as well as restrictions on the consumption frequency of each food. This is to prevent the model showing too small a number of food items and to promote diversification in food consumption. The information about the daily and weekly consumption frequency for each category of products can be found in LARN (Levels of Absorption Reference of Nutrients and Energies for the Italian population) guidelines (SINU, 2012). Five classes of constraints are identified: 1) nutritional constraints; 2) food portion constraints; 3) food consumption frequency constraints; 4) food association constraints; 5) food alternative constraints. We now give details of each constraint using analytical formulation where necessary. All these constraints were incorporated into the optimization model.

The nutritional constraints were drawn up taking into account daily energy requirements distinguishing between men and women, and mapping the different sources of energy. Daily energy requirement was defined according to the lifestyle and sports activity of the young adult population investigated. The model incorporates restrictions on energy and macronutrients according to LARN recommendations, as shown in Table 1.

The information in Table 1 can be represented algebraically as follows:

$$\sum_i \sum_j food_{i,j} a_{i,k} \geq low_k \quad \forall k \tag{1}$$

$$\sum_i \sum_j food_{i,j} a_{i,k} \leq upp_k \quad \forall k \tag{2}$$

where $food_{i,j}$ indicates the food item $i(i=1,2,...,I)$ belonging to each food category $j(j=1,2,...,J)$ considered in the study, $a_{i,k}$ the coefficients of energy and macronutrients $k(k=1,2,...,K)$ per gram of food i; while the left hand side parameters low_k and upp_k identify the lower and upper level of nutrients respectively.

Table 1: Energy intakes and macronutrient restrictions imposed in the mathematical programming model

Constraints	Unit	Men		Women	
		Lower	Upper	Lower	Upper
Energy intake	kJ/day	≥ 11715 -10%	≤ 11715 +10%	≥ 8786 - 10%	≤ 8786 + 10%
Carbohydrates	g/day	≥ 350	≤ 455	≥ 262.5	≤ 341.25
Proteins	g/day	≥ 70	≤ 105	≥ 52.5	≤ 7.75
Fats	g/day	≥ 77.84	≤ 108.92	≥ 58.38	≤ 81.69
Sodium	g/day	≥ 1.5	≤ 2.0	≥ 1.5	≤ 2.0
Cholesterol	g/day	≥ 0	≤ 0.3	≥ 0	≤ 0.3
Saturated fatty acid	g/day	≥ 0	≤ 31.1	≥ 0	≤ 23.3
Simple sugars	g/day	≥ 0	≤ 46.67	≥ 0	≤ 35
Fibre	g/day	≥ 25		≥ 25	

The Italian Society of Human Nutrition (SINU) establishes the standard consumption quantity for each food category, i.e. the recommended daily amount or portion for a healthy diet (SINU, 2012). This information is considered as an adding restriction in the mathematical programming model. In other terms:

$$\sum_i food_{i,j} \leq port_j(1+0.10) \; \forall j \tag{3}$$

where $port_j$ identifies the portion associated with each food category. To give the model some flexibility, the right hand side of constraint (3) allows for 10% tolerance of the standard portion.

The SINU guidelines show the range of minimum and maximum frequency of each portion of food category, which is implemented by the model as follows:

$$\frac{\sum_i food_{i,j}}{port_j} \geq freqmi_j \ \ \forall j \qquad (4)$$

$$\frac{\sum_i food_{i,j}}{port_j} \leq freqma_j \ \ \forall j \qquad (5)$$

where $freqmi_j$ and $freqma_j$ indicate the minimum and maximum frequency of each food category j.

Using constraints (1)-(5), the model selects the foods that minimize an objective function taking into account costs and environmental impacts. In other words, it depicts both economic and environmental competition between food items in the final food basket. In reality, not all foods can be considered pure substitutes of others, but in certain cases and for certain consumption occasions, some foods are complementary with other foods. An example is biscuits as a complement with coffee or tea. To make the results more realistic, we formulated a specific constraint to model an association between groups of complementary foods.

At the same time, it is unlikely for some foods to be eaten at the same meal. For instance, it is not usual to eat both beef and fish. In modelling consumption behaviour to reflect real world eating habits, the model incorporates an "alternative" constraint avoiding the combination of certain food items in the same meal.

The optimization strategy was led by six objectives:

- The minimization of the total cost of weekly food consumption;
- The minimization of carbon dioxide emission from weekly food consumption;
- The minimization of water consumption for a weekly food basket;
- The minimization of the ecological footprint for a weekly food basket;
- The simultaneous minimization of the three environmental objectives (*min* CO_2e, *min* H_2O and *min* ecological footprint);

- The simultaneous minimization of the economic (weekly expenditure) and environmental objectives.

According to these objectives, six optimization models were developed to identify six different food diets. The first one aims to identify the lowest cost diet through the following objective function:

$$\min_{food_{i,j}\geq 0} MCD = \sum_i \sum_j food_{i,j} c_i \tag{6}$$

where the minimum cost diet (MCD) is determined by identifying the combination of food items $food_{i,j}$ that minimizes the total expenditure taking account of the cost of each item c_i.

The objective functions for the models that minimize environmental impact can be formulated as follows:

$$\min_{food_{i,j}\geq 0} MEM = \sum_i \sum_j food_{i,j} em_i \tag{7}$$

$$\min_{food_{i,j}\geq 0} MWA = \sum_i \sum_j food_{i,j} wa_i \tag{8}$$

$$\min_{food_{i,j}\geq 0} MEC = \sum_i \sum_j food_{i,j} ec_i \tag{9}$$

The objective functions (7)-(9) minimize carbon dioxide emission (*MEM*), water consumption (*MWA*) and ecological footprint (*MEC*) respectively, with food item specific impact em_i (CO_2e emissions), wa_i (H_2O consumption) and ec_i (ecological footprint).

The simultaneous minimization of the three environmental impacts requires a more complex objective function, which needs to include three different objectives to optimize. To avoid possible bias due to the weight of the absolute value of each item specific impact, we used multiobjective target programming; this optimizes on the basis of relative differences rather than absolute impact values. These differences are calculated considering as benchmark (or target value) the results obtained from the models specified using objective functions (7)-(9). In analytical terms, the integrated environmental objective function can be defined as:

$$\min_{food_{i,j}\geq 0} ESD = \frac{\left(\sum_i \sum_j food_{i,j} em_i\right) - MEM}{MEM} + \frac{\left(\sum_i \sum_j food_{i,j} wa_i\right) - MWA}{MWA} + \frac{\left(\sum_i \sum_j food_{i,j} ec_i\right) - MEC}{MEC} \tag{10}$$

The objective function of the environmentally sustainable diet (ESD) model is the sum of the relative differences of each specific environmental impact and the corresponding target value. The implicit assumption is that each environmental impact has the same weight in the minimization process.

In the case of the simultaneous minimization of the economic and environmental objective, following the multiobjective target approach, the objective function can be defined as:

$$\min_{food_{i,j}\geq 0} SD = \frac{1}{2}\left\{\frac{\left(\sum_i\sum_j food_{i,j}em_i\right)-MEM}{MEM}+\frac{\left(\sum_i\sum_j food_{i,j}wa_i\right)-MWA}{MWA}+\frac{\left(\sum_i\sum_j food_{i,j}ec_i\right)-MEC}{MEC}\right\} + \frac{1}{2}\left\{\frac{\left(\sum_i\sum_j food_{i,j}c_i\right)-MCD}{MCD}\right\} \quad (11)$$

Equation (11) identifies the objective function of the sustainable diet (SD), where the total environmental component has the same weight as the economic component.

Results

For the sake of simplicity, we present the results for three diets characterized by different targets and optimizing different impacts: first the lowest cost diet (Minimum Cost Diet – MCD) identified by objective function (6), then the Environmentally Sustainable Diet (ESD) obtained by minimizing the three environmental indicators (CO_2e emissions, H_2O consumption and amount of soil and water to regenerate the resources) identified by function (10). Finally, the Sustainable Diet (SD) integrating environmental and economic sustainability objectives identified by objective function (11). The resulting food basket for each dietary pattern is shown in Table 2[1].

The results provided by the optimization models reveal a lower food quantity consumed in the current diet (5,503 g/person/week) compared to the three optimal diets (from 8,148 to 10,389

[1] Individual food items were grouped into 9 food categories: 1) fruits and vegetables, 2) dairy (e.g. milk, cheese, yogurt), 3) meat, 4) fish/seafood, 5) bread and substitutes (e.g. pizza), 6) pasta and rice, 7) legumes, 8) sweets (e.g. cakes, biscuits, croissants), and 9) other (e.g. olive oil, eggs).

g/person/week). The CD (Current Diet) of the young adults surveyed is rich in meat but very poor in fruits and vegetables, which indicates low fibre consumption. Fruit and vegetable consumption (less than 180 g/day) is lower than the WHO recommended amount (400 g/day). In all three optimizations of diet, meat consumption disappears due to high economic and environmental costs, and is substituted by an increase in fruits and vegetables, legumes and dairy foods. In the MCD, the food category of bread and substitutes decreases significantly because of the high unitary cost. On the other hand, the environmental (ESD) and sustainable (SD) diets require a greater incidence of this category. The frequency constraints contribute to boosting the consumption of fruits and vegetables, and in MCD, ESD and SD models these increase by more than 200% compared to CD.

A detailed analysis of MCD food items shows that the reduction in the consumption of bread and substitutes compared to the CD is mainly due to the reduction in the consumption of pizza, which is popular with young people, but expensive compared to other foods. The increase in fruits and vegetables is explained by the low intake recorded in the CD, and the process of substitution of calories from meat. The fruits and vegetable category includes dried fruit in all diets configured, particularly the SD, because it is rich in calories and relatively inexpensive given its nutritional content, and also has low environmental impact.

Table 2: Food quantity (g/person/week) in the Current Diet (CD), Minimum Cost Diet (MCD), Environmentally Sustainable Diet (ESD) and Sustainable Diet (SD).

	CD		**MCD**		**ESD**		**SD**	
Food item	**g**	***%***	**g**	***%***	**g**	***%***	**g**	***%***
Fruit & Vegetables	1,256	*22.8*	5,148	*63.2*	4,234	*41.3*	4,359	*42.0*
Dairy	649	*11.8*	1,145	*14.1*	1,135	*11.1*	1,112	*10.7*
Meat	705	*12.8*	0	*0.0*	0	*0.0*	0	*0.0*
Fish/seafood	135	*2.5*	0	*0.0*	0	*0.0*	0	*0.0*
Bread and substitutes	1,028	*18.7*	481	*5.9*	3,065	*29.9*	3,132	*30.2*
Pasta and rice	890	*16.2*	920	*11.3*	907	*8.9*	920	*8.9*
Legumes	21	*0.4*	152	*1.9*	407	*4.0*	329	*3.2*
Sweets	503	*9.1*	233	*2.9*	375	*3.7*	417	*4.0*
Other	316	*5.7*	70	*0.9*	120	*1.2*	120	*1.2*
Total grams	**5,503**	***100.0***	**8,148**	***100.0***	**10,242**	***100.0***	**10,389**	***100.0***

In terms of food energy intake, Table 3 shows that the sample consumes on average a lower level of calories in their CD (41,981 KJ/person/week) than in the optimal diets. The optimization and the nutrients constraints in the model lead to an increase of energy intake in the MCD of 61%, in ESD of 95% and in SD of 87%. Current dietary habits of the young adults investigated are in fact inadequate and poor. Their main sources of energy are bread and substitutes (28%), pasta and rice (20%), sweets (19%) and meat (13%). And although the CD is varied, our model suggests that it is seriously insufficient to sustain the intellectual and physical activity. The strong increase in the quantity (grams per week) of dairy products consumed by the young adults in the envisaged optimal diets does not find an equivalent dynamic in the food energy intake. This means that the internal composition of the dairy products changes when the diet is optimized. In particular, milk and yogurt are preferred to the other dairy foods (see Appendix I).

Table 3: Food energy intake (kJ/person/week) in the Current Diet (CD), Minimum Cost Diet (MCD), Environmentally Sustainable Diet (ESD) and Sustainable Diet (SD).

	CD		**MCD**		**ESD**		**SD**	
Food item	**kJ**	*%*	**kJ**	*%*	**kJ**	*%*	**kJ**	*%*
Fruit & Vegetables	2,583	*6.2*	34,995	*51.5*	27,324	*33.4*	25,513	*32.4*
Dairy	2,358	*5.6*	2,549	*3.8*	3,514	*4.3*	2,904	*3.7*
Meat	5,463	*13.0*	0	*0.0*	0	*0.0*	0	*0.0*
Fish/seafood	725	*1.7*	0	*0.0*	0	*0.0*	0	*0.0*
Bread and substitutes	11,920	*28.4*	4,140	*6.1*	12,473	*15.3*	12,712	*16.2*
Pasta and rice	8,398	*20.0*	17,010	*25.0*	21,757	*26.6*	21,850	*27.8*
Legumes	122	*0.3*	2,040	*3.0*	7,004	*8.6*	5,526	*7.0*
Sweets	7,880	*18.8*	4,545	*6.7*	6,531	*8.0*	7,077	*9.0*
Other	2,533	*6.0*	2,637	*3.9*	3,110	*3.8*	3,110	*4.0*
Total kJ	**41,981**	***100.0***	**67,915**	***100.0***	**81,714**	***100.0***	**78,693**	***100.0***

The optimization models also show the environmental impact of the three diets. Figure 1 shows the CO_2e emissions of the food basket in the four different diets. For each new diet configured, there is a reduction in CO_2e emissions larger than 50% compared to the current diet. This is mainly a result of replacing meat with legumes and other food items with a lower impact in terms of CO_2e. Within “pasta and rice”, pasta has an important role in CO_2e mitigation. The SD is the model with lowest CO_2e emissions, indicating that the multiobjective programming including the objective cost function is able to better optimize the CO_2e emission component than the ESD.

A similar result is obtained for water consumption, where the SD model provides the best solution, i.e. the combination of food items that minimizes water use (Figure 2). In terms of water use, Figure 2 shows also how the minimization of the total food expenditure (MCD model) determines a displacement of meat by an important quantity of the “fruits and vegetables” category that incorporates more than 8,000 litres per week of water against 1,000 litres per week in the observed diet (CD). The best solution in terms of food expenditure entails a reduction of efficiency in water consumption.

The SD shows better results for CO_2e and water than the ESD because of different distribution of the differences with regard to the specific environmental targets. The ESD model gives a result nearer to target value for the ecological footprint, while the SD model gives the result nearest to target value for the first two environmental factors. Figure 3 demonstrates this achievement with an ecological footprint level higher in the SD than in the ESD model.

Figure 1: CO_2e emissions (KgCO_2e/person/week) of the Current Diet (CD), Minimum Cost Diet (MCD), Environmentally Sustainable Diet (ESD) and Sustainable Diet (SD).

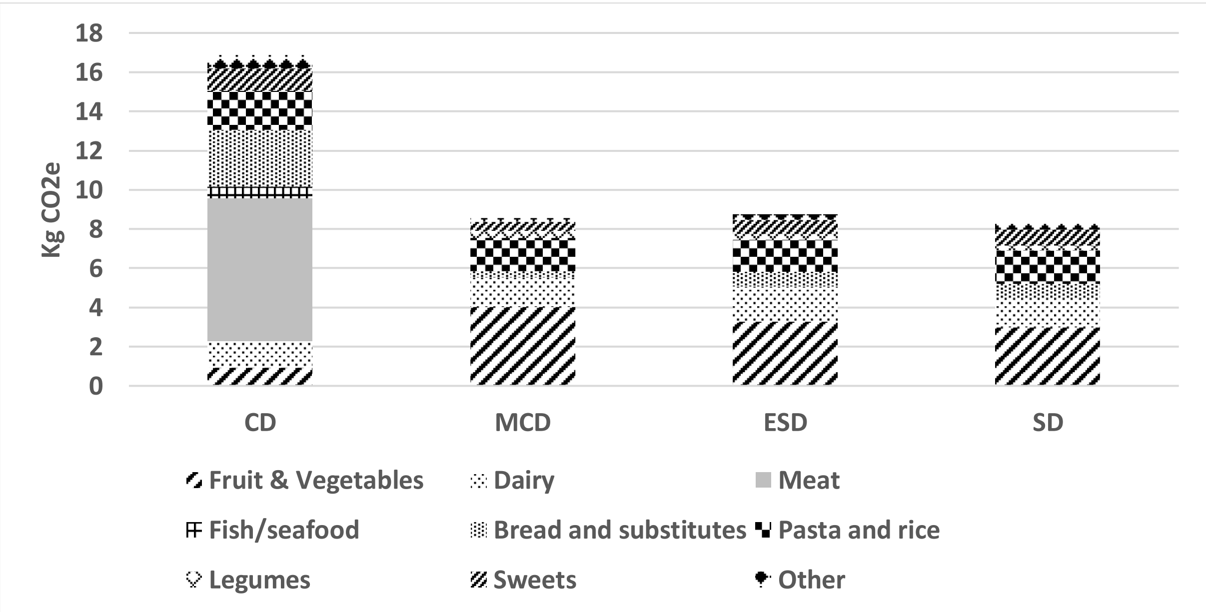

Figure 2: H_2O (litres/person/week) consumption of the Current Diet (CD), Minimum Cost Diet (MCD), Environmentally Sustainable Diet (ESD) and Sustainable Diet (SD).

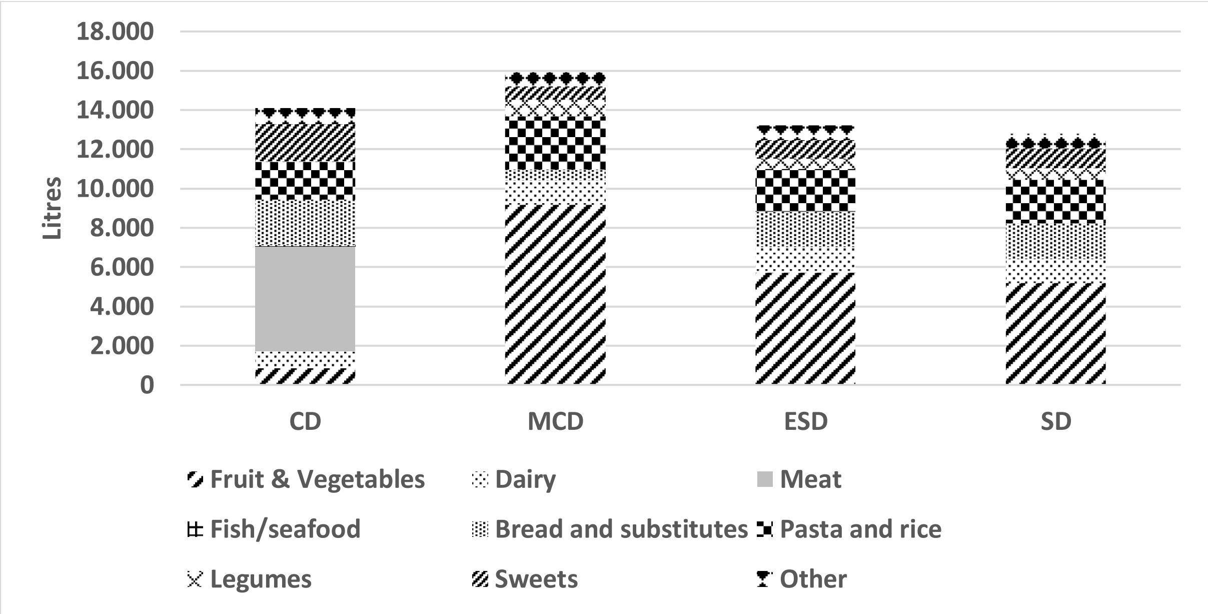

Figure 3: Land needed to regenerate the resources (m^2/person/week) of the Current Diet (CD), Minimum Cost Diet (MCD), Environmentally Sustainable Diet (ESD) and Sustainable Diet (SD).

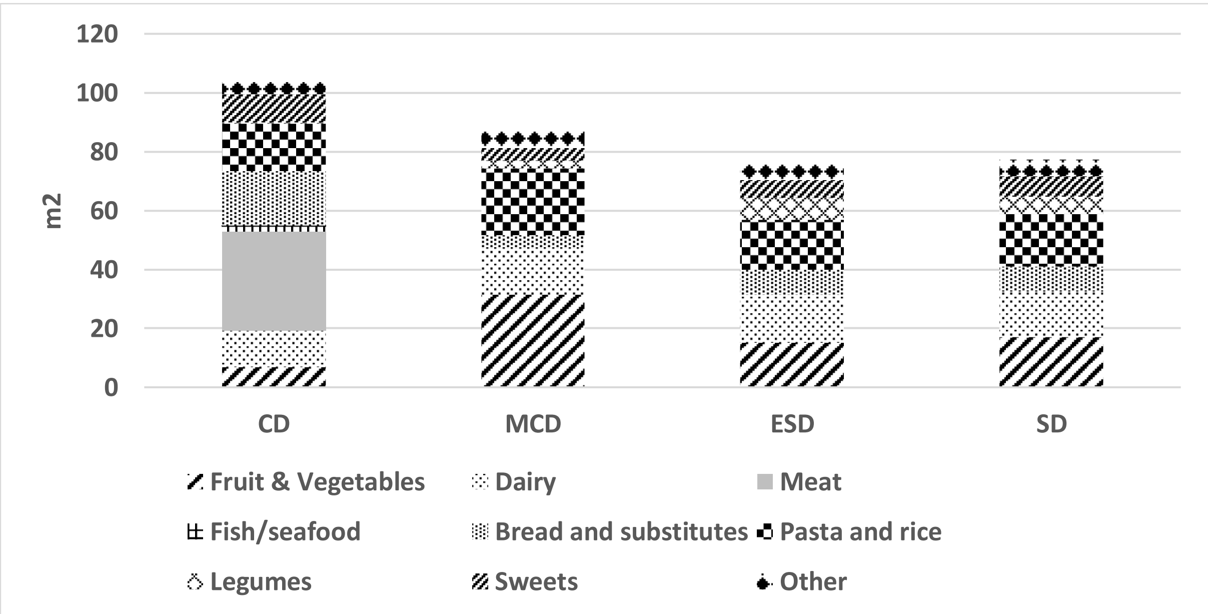

Table 4 shows that the individual weekly cost of the current diet is € 41.6, with a high incidence of bread and substitutes (26.7%), meat (26.2%), sweets (11%), and pasta and rice (10.3%). Fruit and vegetables account only for a limited share (9%) of the total budget. The optimal economic solution (MCD) costs € 31.1 /person/week allowing consumers to save more than € 10 per week, or -25% compared to the CD. Percentages spent on different items in the MCD were 74.6% for fruit and vegetables, 8% for pasta and rice, and 6.3% for dairy products.

The Environmentally Sustainable Diet (ESD) costs € 7.4 more per week (+17.8%) than the CD (i.e., overall budget € 49 /person/week). Fruit and vegetables (59.9%), bread and substitutes (10.8%) and dairy products (8%) are the food categories with highest cost incidence. This implies that the market prices do not incorporate an incentive to consume foods with low negative environmental externality.

Table 4: Weekly cost (€/person/week) of the Current Diet (CD), Minimum Cost Diet (MCD), Environmentally Sustainable Diet (ESD) and Sustainable Diet (SD).

	CD		**MCD**		**ESD**		**SD**	
Food item	**€**	*%*	**€**	*%*	**€**	*%*	**€**	*%*
Fruit & Vegetables	3.73	*9.0*	23.19	*74.6*	29.38	*59.9*	23.24	*57.4*
Dairy	2.11	*5.1*	1.95	*6.3*	3.91	*8.0*	2.23	*5.5*
Meat	10.92	*26.2*	0.00	*0.0*	0.00	*0.0*	0.00	*0.0*
Fish/seafood	2.05	*4.9*	0.00	*0.0*	0.00	*0.0*	0.00	*0.0*
Bread and substitutes	11.09	*26.7*	0.92	*3.0*	5.28	*10.8*	5.39	*13.3*
Pasta and rice	4.28	*10.3*	2.48	*8.0*	3.66	*7.5*	3.55	*8.8*
Legumes	0.07	*0.2*	0.48	*1.6*	3.85	*7.8*	2.93	*7.2*
Sweets	4.57	*11.0*	1.43	*4.6*	2.19	*4.5*	2.39	*5.9*
Other	2.79	*6.7*	0.63	*2.0*	0.77	*1.6*	0.77	*1.9*
Total € per week	**41.62**	***100.0***	**31.07**	***100.0***	**49.04**	***100.0***	**40.48**	***100.0***

Source: our elaborations.

In order to investigate the cost and affordability of a healthy and environmentally sustainable diet, we also estimated the cost of the sustainable diet (SD), which is not considerably different from the cost of the current diet. There thus appear to be no significant differences between the total budget for the SD and the total budget for current diet, which indicates that the SD is economically affordable for the young adults surveyed. However, there is a substantial difference in the allocation of budget across the different food categories. In particular, the weekly budget spent on fruit and vegetables in the CD is almost € 20 lower than in the SD model.

Discussion and Conclusions

This paper presented integrated solutions analyzing the quantitative linkages between nutrition, environmental and economic impacts of the dietary patterns of a sample of young Italian adults. Several mathematical programming model configurations were used to design diets at minimum cost, at lowest environmental impact and at the lowest integrated impact (economic and environmental) for consumers. Mathematical programming has the capacity to consistently reproduce the nutritional constraints to guarantee a healthy diet under different (economic and/or environmental) objectives.

The current diet of the young adults investigated consists of food products rich in animal proteins and extremely poor in fibre. The model suggests that there need to be radical changes for the young adults to have an affordable and environmentally sustainable diet. In particular, the model suggests that there needs to be the complete substitution of meat and fish with vegetal proteins (legumes), dairy products and bread, and a significant increase in fruit and vegetable consumption to achieve a nutrient adequate intake. However, from a purely nutritional point of view, there are no strong evidence to exclude the consumption of animal products (meat and fish) in a healthy adult population. In particular, consumption of fish once or twice a week is recommended in order to consume sufficient polyunsaturated fatty acids (WHO, 2003). However, polyunsaturated fatty acids could be readily obtained also from plant foods, such as nuts. The evidence favouring nut consumption for reduction in CVD deaths, cancer deaths and all-cause mortality, is getting strong (Banel *et al.*, 2009; Grosso *et al.*, 2015). Indeed, plant-based diets could be a healthy choice, favouring a balanced intake of macro- and micro-nutrient intake, as well as a more sustainable scenario. Despite this, if meat and fish were excluded from diet, a detailed assessment of micronutrient would be required.

The sustainable diet, according to our model, may lead to a 51% cut in CO_2e emissions, 9% reduction in H_2O consumption and 26% less land needed to regenerate the resources compared to the current diet. Hallström *et al.* (2015), having considered the environmental impact of dietary changes in 14 studies, have suggested that vegan and vegetarian diets (i.e. removing meat products) have the lowest GHG emissions, with up to 53% reduction compared to reference scenarios. Moreover, since the possibility of reducing the area of land required to feed humans depends largely on the amount of meat consumed, our results are similar to many already appearing in the literature (Hallström *et al.*, 2015). Our results also suggest that the sustainable diet – where the environmental pressures and food expenditure are simultaneously minimized (SD) – is not more expensive than the current diet, therefore fully affordable for the population under study. This confirms other findings that a healthier and more eco-friendly diet is not necessarily more expensive (Conforti and D'Amicis, 2000; Barilla Center for Food and Nutrition, 2011b; Germani *et al.*, 2014).

Given these results, one can reasonably ask how we might motivate sustainable dietary patterns among young adults. Policy-makers know that consumer behaviour change would be central to any policy process aiming at integrating nutrition and sustainability (Lang and Barling, 2013). Policies aiming at stimulating healthy eating are usually divided into two broad categories: those aimed at supporting informed choice by consumers, mostly through the provision of information or education, and those aiming at changing the market environment, by influencing food prices or availability. Most measures adopted in the EU are those intended to promote informed choice, mostly through public information campaigns and nutrition education in schools (Capacci *et al.*, 2012). Because they have large audiences, television cooking shows have also been suggested as a way of enhancing cooking skills among young people. This has been tried on limited scale in the UK (Wilson *et al.*, 2013). The development and dissemination of guidelines promoting sustainable diets is also necessary and currently takes place in some countries, like the US (HHS/USDA, 2015), Germany (German Council for Sustainable Development, 2008), France (ADEME, 2015), the UK (NCC/SDC, 2006) and Australia (NHMRC, 2013). The progressive abandonment of the healthy Mediterranean diet pattern induced by socioeconomic changes (Dernini *et al.*, 2013) is another issue that Mediterranean countries must necessarily consider in the future.

Measures aiming at modifying the food "environment" have mostly been focused on directly providing healthy foods in schools (e.g. fruits). Increasing the price of foods and beverages high in fat, sugar and salt content through taxation is a potential policy measure which should discourage over-consumption (Cornelsen *et al.*, 2015). In recent years, a number of countries have introduced health-related food taxes. Hungary and Mexico have taxes on foods high in salt, sugar or fat content, Finland has a tax on sweets, ice-cream and soft drinks, and France and the US California city of Berkeley have taxed sugar-sweetened beverages (Cornelsen and Carreido, 2015). Denmark introduced the world's first tax on saturated fat in 2011, but although it showed short run effects on consumption (Jensen and Smed, 2013) the tax was removed after only 15 months for lack of political support (Vallgårda *et al*., 2015). Subsidies or voucher programs, which have also been developed in some countries to assist low income families (Wilson *et al*., 2013), may be more socially acceptable than taxes. It has been suggested that the combination of taxes on unhealthy food with a subsidy on more healthy food can be more economically neutral (i.e. not regressive) with respect to poverty than simply imposing taxes on foods high in fat or sugar (Madden, 2015). Fiscal measures could thus be an effective tool for shifting current dietary patterns towards more sustainable ones. These regulatory tools might properly address and promote a nutritional adequate and environmental friendly diet such as that identified by the purely environmental minimization model (ESD).

A further issue raised by this study is the need for an integrated and comprehensive database of data on nutrition and the environmental and socio-economic impact of dietary change. Other authors also stress the need to improve metrics and measurement mechanisms in order to understand how dietary behaviours might improve human and environmental health, without affecting affordability of food, and to disseminate these findings to consumers (see, e.g., Johnston *et al*., 2014). The development of integrated databases and indicators might also help policymakers to understand the potential tradeoffs for making investments in promoting such diets, while addressing any potential negative consequences, and providing adequate incentives to the supply chains (Menozzi *et al.*, 2015).

Some limitations of the study should be highlighted. First of all, the nutritional constraints do not take into account micronutrients, such as vitamins, that define a diet consisting of more varied foods than those in the present setting. Secondly, the model does not implement the cultural and traditional factors which can strongly affect food choices, and this affects the level of realism of our findings. For example, the total elimination of meat and seafood from the diet would be unacceptable in some population for cultural reasons for both consumers and producers. The adoption of a plant-based diet could be difficult for many people, since it requires significant changes in dietary patterns (Van Dooren *et al.*, 2014). Therefore, cultural acceptability of diet is a crucial factor for the definition and the implementation of a sustainable diet, according to the FAO's definition (FAO, 2010). Nevertheless, our study reported and based simulations on registered consumption data, and current consumption patterns have the advantage of being more realistic than hypothetical dietary scenarios (Hallström *et al.*, 2015). Third, in this study, we considered three environmental impacts (carbon footprint, water footprint and ecological footprint) identified in international literature. Unfortunately, it was not possible to make these measurements territorial or food chain specific because of the absence of studies on local foods (e.g. life cycle analysis). As noted by other authors, geographical variability of input data may lead to variability of results (Hallström *et al.*, 2015). Data related more precisely and specifically to the Italian food system might have produced different results. Similarly, beside food prices, other socio-economic components such as poverty indices, income distributions, etc., could be possibly included in the further analyses. Fourth, the fact that lower amounts of food in grams are reportedly consumed in the current diet compared to the three optimal diets may suggest that a certain level of underreporting of self-reported dietary records occurred in the sample. Furthermore, another important limitation of the study is the absence of an appraisal of food waste embedded in the dietary pattern, and for some foods (e.g. fruit and vegetables) this might be very important in terms of resource consumption. Finally, the results cannot be safely generalized to the whole Italian population given the small size and the nature of the sample. The application of the model to large random samples representative of the Italian adolescent population is a useful avenue for future research.

Despite these limitations, this study provides useful findings for recommendations on the sustainability of current diets. The models suggested that substituting animal-based products with vegetable proteins may lead to a substantial reduction in CO_2e emission and resource depletion, at the same cost for consumers. This demonstrates that the food choices based on environmental and health objectives are not necessarily more expensive. This study, moreover, shows that evidence-based policy recommendations for improving the sustainability of current diets require the thorough and efficient integration of nutritional, environmental and economic information and data.

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Appendix 1 – Model's results per specific food item

Food item	Grams/person/week				kJ/person/week				kg CO2e /person/week				liters H2O/person/week				M2/person/week			
	CD	***%***	**SD**	***%***	**CD**	***%***	**SD**	***%***	**CD**	***%***	**SD**	***%***	**CD**	***%***	**SD**	***%***	**CD**	***%***	**SD**	***%***
Vegetables	375.3	*6.8*	1,207.9	*11.6*	593	*1.4*	1,811	*2.3*	0.3	*1.8*	0.8	*10.3*	210	*1.5*	960	*7.5*	1.4	*1.3*	1.9	*2.4*
Legumes	20.6	*0.4*	328.8	*3.2*	122	*0.3*	5,526	*7.0*	0.0	*0.1*	0.3	*3.1*	38	*0.3*	566	*4.4*	0.4	*0.4*	5.8	*7.5*
Fruits	874.0	*15.9*	2,693.6	*25.9*	1,801	*4.3*	13,312	*16.9*	0.6	*3.6*	1.6	*19.0*	593	*4.2*	3,242	*25.3*	5.5	*5.3*	7.7	*10.0*
Dried fruits	6.9	*0.1*	457.3	*4.4*	189	*0.4*	10,391	*13.2*	0.0	*0.1*	0.6	*6.8*	59	*0.4*	979	*7.6*	0.1	*0.1*	7.5	*9.7*
Milk/Yogurt	585.2	*10.6*	1,112.3	*10.7*	1,523	*3.6*	2,904	*3.7*	0.8	*5.0*	1.5	*17.9*	645	*4.6*	1,218	*9.5*	8.1	*7.8*	15.4	*19.9*
Cheese	63.5	*1.2*	0.0	*0.0*	835	*2.0*	0	*0.0*	0.5	*3.2*	0.0	*0.0*	202	*1.4*	0	*0.0*	4.1	*4.0*	0.0	*0.0*
Butter	4.5	*0.1*	0.0	*0.0*	35	*0.1*	0	*0.0*	0.0	*0.1*	0.0	*0.0*	8	*0.1*	0	*0.0*	0.1	*0.1*	0.0	*0.0*
Red meat	504.9	*9.2*	0.0	*0.0*	4,180	*10.0*	0	*0.0*	5.8	*34.2*	0.0	*0.0*	4,494	*31.9*	0	*0.0*	27.2	*26.2*	0.0	*0.0*
White meat	200.5	*3.6*	0.0	*0.0*	1,283	*3.1*	0	*0.0*	1.5	*8.8*	0.0	*0.0*	866	*6.1*	0	*0.0*	6.5	*6.3*	0.0	*0.0*
Fish/Seafood	135.5	*2.5*	0.0	*0.0*	725	*1.7*	0	*0.0*	0.6	*3.4*	0.0	*0.0*	43	*0.3*	0	*0.0*	2.0	*2.0*	0.0	*0.0*
Bread	452.8	*8.2*	3,132.4	*30.2*	4,460	*10.6*	12,712	*16.2*	0.4	*2.2*	0.7	*9.0*	578	*4.1*	1,829	*14.3*	3.5	*3.3*	8.6	*11.1*
Bread subs.	66.7	*1.2*	0.0	*0.0*	1,193	*2.8*	0	*0.0*	0.1	*0.6*	0.0	*0.0*	69	*0.5*	0	*0.0*	0.6	*0.6*	0.0	*0.0*
Pizza	508.8	*9.2*	0.0	*0.0*	6,267	*14.9*	0	*0.0*	2.4	*14.3*	0.0	*0.0*	1,691	*12.0*	0	*0.0*	14.4	*13.9*	0.0	*0.0*
Pasta and rice	889.8	*16.2*	920.0	*8.9*	8,398	*20.0*	21,850	*27.8*	2.0	*11.8*	1.7	*20.6*	1,919	*13.6*	2,226	*17.4*	16.1	*15.5*	17.8	*23.1*
Biscuits/cakes	352.8	*6.4*	416.7	*4.0*	5,825	*13.9*	7,077	*9.0*	0.8	*4.8*	0.8	*10.1*	1,026	*7.3*	1,028	*8.0*	5.3	*5.1*	6.9	*8.9*
Other sweets	150.0	*2.7*	0.0	*0.0*	2,054	*4.9*	0	*0.0*	0.3	*1.9*	0.0	*0.0*	841	*6.0*	0	*0.0*	4.2	*4.0*	0.0	*0.0*
Eggs	51.9	*0.9*	50.0	*0.5*	324	*0.8*	472	*0.6*	0.1	*0.7*	0.1	*1.0*	170	*1.2*	123	*1.0*	0.8	*0.7*	0.7	*0.9*
Olive oil	40.8	*0.7*	70.0	*0.7*	1,535	*3.7*	2,638	*3.4*	0.1	*0.7*	0.2	*2.2*	418	*3.0*	626	*4.9*	3.3	*3.2*	4.9	*6.4*
Wine/Beer	173.1	*3.1*	0.0	*0.0*	375	*0.9*	0	*0.0*	0.4	*2.2*	0.0	*0.0*	201	*1.4*	0	*0.0*	0.1	*0.1*	0.0	*0.0*
Alcoholic beverages	45.4	*0.8*	0.0	*0.0*	263	*0.6*	0	*0.0*	0.1	*0.5*	0.0	*0.0*	24	*0.2*	0	*0.0*	0.1	*0.1*	0.0	*0.0*
Total	**5,503.1**	***100.0***	**10,389.0**	***100.0***	**41,981**	***100.0***	**78,693**	***100.0***	**16.9**	***100.0***	**8.3**	***100.0***	**14,094**	***100.0***	**12,795**	***100.0***	**103.7**	***100.0***	**77.2**	***100.0***