TRansition paths to sUstainable
legume-based systems in Europe

A Combined Environmental and Nutri-Economic Assessment of Diets

Work Package: 5

Deliverable (D): 5.6 (D34)

Lead Author: Michael Williams, Trinity College Dublin

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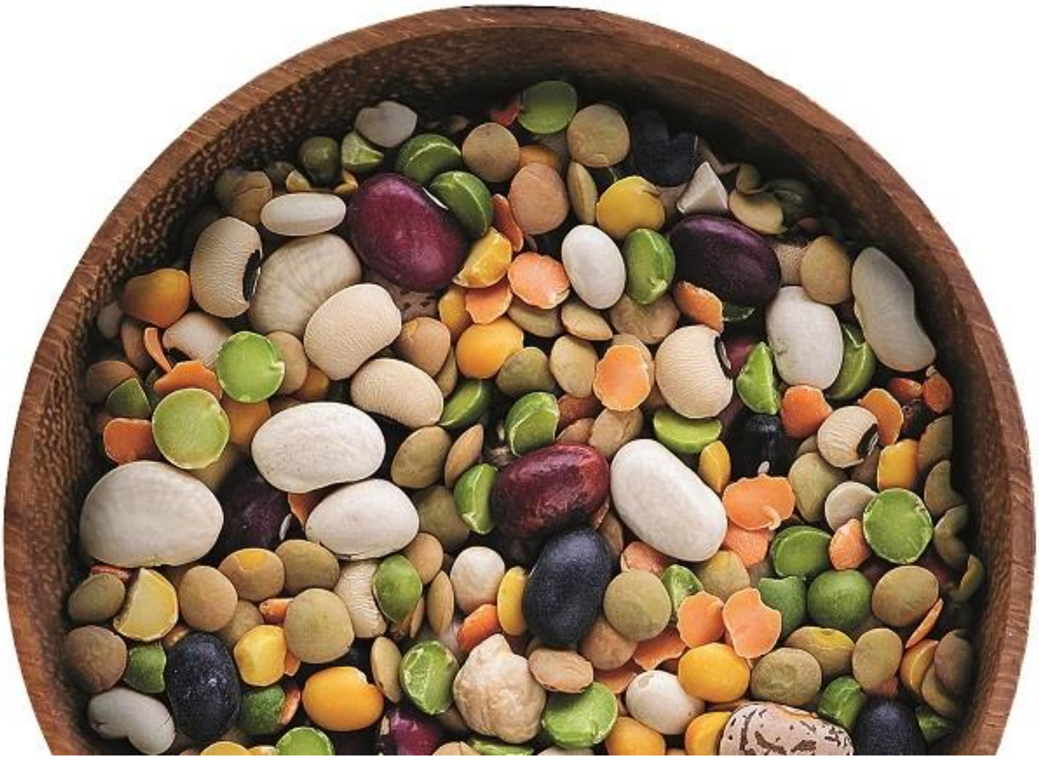

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  This report follows on from Deliverable 5.5 – The Environmental Assessment of Diets (Williams *et al*., 2020) and provides a combined environmental and nutri-economic analysis of both the 'Irish Diet' and EAT-Lancet Commission 'Reference (planetary healthy) Diet' (Willett *et al*., 2019), where food items, categories and diet have been costed - not only in terms of price to the consumer, but also in terms of nutrition and environmental burden.

- **Co-authors**

- Michael Williams, Bethan O'Driscoll, Sophie Saget (Trinity College Dublin)
- Pietro Iannetta (James Hutton Institute)
- David Styles (University of Bangor)

- **Contributors**

- Damian Bienkowski (James Hutton Institute)
  Henrik Maaß (University of Hohenheim)

- **Key words**

- Legume; EAT-Lancet Commission; Irish Diet; Global Warming Potential; Eutrophication Potential; Nutrient Density; Cost.

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Executive summary

This report is a continuation from TRUE Project Deliverable 5.5, The Environmental Assessment of Diets (Williams *et al.,* 2020), and specifically addresses the question of cost per unit energy/nutrient density/environmental impact attributes as a means of assessing the sustainability of food items and dietary choice. The Irish Diet is used as an example of how increasing the intake of low impact sustainable foods can significantly lower per capita per day costs, increase nutritional quality and reduce environmental burdens.

Fifty-three food items representative of Food and Agriculture Organisation (FAO) agency of the United Nations (UN), food balance data and the 18 EAT-Lancet Reference ('planetery healthy') Diet food categories were assessed for cost, energy and nutrient density. High energy density does not coincide with high nutritional content. Using a nutrient density index, which includes a measure of twelve nutrients of benefit and three to limit (Drewnowski, 2010), animal fats, vegetable oils and sweeteners, occupy the lowest range of nutritional rich food (NRF) index scores (NRF<24), with poultry, fish, soy and vegetable categories scoring the highest (NRF>160). Legumes, whole grains, tree nuts, red meat and dairy occupy the mid-range of NRF values (55 to 140), with legumes having nutritional density scores above the 2nd quartile. **(section 3.1.1)**

In terms of energy intake, prices for the 53 food items studied range from as little as 6 cents (euro) per 100 kcals for animal fats to over 1 euro per 100 kcals for fish. Foods with mid-range energy densities, in particular red meat and fish, represent some of the highest-cost foods (>60 cents per 100 kcals), with legumes costing considerably less (<26 cents per 100 kcals). More extreme differences appear between sources of animal and plant protein, when food categories are scored in terms of price per nutrient density unit (NRF12:3). Except for tree nuts, plant protein sources occupy a price range below the median value. **(section 3.1.2)**

The environmental burden per nutrient density unit as a useful attribute in Life Cycle Analysis was first proposed by van Dooren (2016) and adapted for use with the EAT-Lancet Commission reference diet in a complementary report to this study (Williams *et al*., 2020).

In this report both Global Warming Potentials (GWP) per NRF unit, and Eutrophication Potential (EP) per NRF unit are plotted against the cost per 100 kcals for the 53 individual food items used in the previous analyses. Food items that occupy the area intercepted by both median lines are considered the most suitable with respect to sustainable diets, while those food items placed outside the intercept of the 3rd quartile values, are the least suitable. Ideal sustainable foods are those occupying the area intercepted by the 1st quartile values.

Food items which represent an ideal basis for sustainable, nutritional and cost-effective diets are legumes, cereals, starchy vegetables and fruit – the least suitable being lamb, pork and farmed salmon. **(section 3.2.3)**

Converting the National Adult Nutrition Survey (Ireland) (NANS) dietary intake statistics of Flynn *et al*. (2011) to kcals and cost per day, then the Irish Diet maybe described as one rich in cereals, dairy, red meat and convenience foods (miscellaneous savoury and sweet dishes). The top 70% of the daily calorific intake is made up of cereals, dairy, red meat, savoury and dessert dishes. With less than 5% of the total daily total made up of legumes, non-starchy vegetables and fruit. Alcohol consumption represents 7% of the daily energy intake, equal to that from potatoes, and is over 8× the daily energy intake from legumes. Taking into consideration the major sustainable food groups outlined in section 3.2.3, then these constitute 47% of the daily total energy intake, dominated by inclusion of cereals and dairy (34.5% combined).

In terms of proportional costs, 25% of the daily cost per capita of € 5.6 is spent on alcohol, equal to the combined daily cost of the sustainable food items highlighted in section 3.2.3 (24.5%), but only representing 7% of daily energy intake. Meat and savoury dishes combined, constitute approximately 30.5% of the daily cost, with sugars, sweeteners and sweet dishes constituting 10% of the total. **(section 3.3.1)**

Using FAO food balance statistics offers a similar diet profile but at a higher calorific intake and cost. Comparing the Irish Diet with the EAT-Lancet Reference Diet highlights the considerable savings in cost possible – up to €4 euros a day dependant on which data set is used. As with data presented in Williams *et al*. (2020), adoption of the Reference Diet would also involve reductions in diet associated emissions of CO_2e and gPO_4^{3-}e release to the environment by 57 and 48 % respectively. **(section 3.3.2)**

1. Introduction

1.1. Work Package 5 (Environment) objectives

The aim of WP5 in the TRUE project is to provide coordinated life cycle assessments (LCA) based analysis of the environmental impact of legume production and processing coupled with a nutri-economic analysis of legume-enriched diets for feed and food. This WP will answer the following overarching questions.

- What is the environmental footprint of animal feed and food produced from legumes, considering nutrient cycling and break-crop effects in legume-rotations across major EU agri-climatic zones?
- What are the optimum legume-enriched diets/food choices for improving health, that decrease the environmental footprint – including indirect effects incurred during supply chain transitions - and reduce direct costs to the consumer?

The specific objectives of this WP are summaries as follows.

- Produce a practical report outlining the LCA methodologies to be used in TRUE.
- Assess using attributional LCA the environmental footprints of legume products, and benchmark against conventional alternatives.
- Assess the European diet in terms of environmental burden and nutrient quality. By constructing a suitable nutrient density functional unit for the attributional LCA, food choices will be scored according to both decreasing environmental impact and increasing health.
- Assess how increasing the proportion of legumes and legume products in the European diet may increase the beneficial nutrient content of diet/food choice but decrease their environmental impact, accounting for rotation and land use effects associated with supply chain transitions.
- Calculate the combined environmental, health and purchase costs of diet/food choices and assess if increasing the proportion of legumes and legume products in these may increase the affordability and environmental sustainability of healthier diets. *This report*

1.2. Purpose of this report

This report follows on from Deliverable 5.5, The Environmental Assessment of Diets (Williams *et al*., 2020) and provides a combined environmental and nutri-economic analysis of both the Irish and EAT-Lancet Commission Reference Diet (Willett *et al*., 2019), where food items, categories and diet have been costed - not only in terms of price to the consumer, but also in terms of nutrition and environmental burden. The Irish Diet has been chosen as an example of a particularly unhealthy diet (Flynn *et al*., 2011; Friel *et al*., 2003, WHO, 2013), while the EAT-Lancet Commission diet has been chosen as an ideal comparison, aimed to provide healthy nutrition *and* significantly reduce the environmental footprint of food production (Willett*, et al*., 2019). Three sources of diet information have been used: FAO food balance data which essentially refers to the availability of food per capita per day, the NANS data undertaken by the Irish Universities Nutrition Alliance (IUNA) between 2008 and 2010 (Flynn *et al.*, 2011), and the EAT-Lancet Commission Reference Diet of Willett *et al*. (2019).

In addition to the cost assessment of diet and dietary choice, an environmental/nutri-economic assessment of FAO food groups has also been carried out, based in part on the approach of Primavesi *et al*. (2015). Food items are assessed, not in terms of kilocalories, but in terms of nutrient density, this index of nutrition being related to the environmental footprint of food production by means of the environmental burden per nutrient density unit, described by Williams *et al*. (2020). Scoring this attribute in terms of cost per 100 kcals, allows a more informed dietary choice, and selection of nutritious food items which are both low in cost and both GWP and EP. Using an extensive dataset of farmgate GWP and EP values from peer-reviewed literature and Irish food commodity prices available online, this study highlights the cost effectiveness and environmental sustainability of increasing the proportion of plant protein over animal protein in diets.

1.3. Context for a combined environmental and nutri-economic assessment of diets

Globally, “sustainable intensification” of agriculture, to deliver more output from less input, is imperative if projected demand for food is to be met from a finite land area, minimising further encroachment onto areas of high nature value and terrestrial carbon (C) storage (Godfray *et al.*, 2010). Major challenges to the sustainability and resilience of EU food production include: (i) dependence on non-renewable resource use including for energy, water, fertilisers, animal feed and food; (ii) low nutrient use efficiency (NUE) and associated nutrient pollution; (iii) high levels of greenhouse gas emissions; and (iv) soil degradation (Poore and Nemecek, 2018), with intensive production having severe impacts on ecosystems and global stability (Geiger *et al*., 2010; Sparks and Lorsbach, 2017; Levers *et al*., 2018).

Discourse on global food systems should also consider health benefits – or lack thereof – of diets and food choice (Tilman *et al*., 2002, 2011; Foley *et al*., 2011). The World Summit of Food Security in Rome in 1996, set a target of halving the global population of undernourished people based on 1990-92 figures of 824 million, but by 2010 this figure had increased by over 10 million. Present day numbers are approximately 820 million, (FAO, 2018). In contrast, over 2 billion people consume unhealthy, high-calorie diets leading to an ‘epidemic’ of obesity and other diet related non-communicable illnesses with an extra 1 million deaths, and 12 million life-years of illness each annually (Burkert *et al*., 2013). There has been a doubling in the incidence of diabetes in recent time (WHO, 2016), and a projected increase of 90% in the occurrence of diet related colon cancers in people aged 20-34 (Bailey *et al*., 2015).

Interestingly, social divisions between healthy and non-healthy diets are not limited to income. Since, per capita consumption of animal fat and protein increases with increasing GDP (da Silva *et al*., 2009; Gerbens-Leenes *et al*., 2010; Williams *et al*., 2020). However, according to FAO, the definition of a healthy and sustainable diet encompasses environmental, health and cost aspects, defining it as one that has a low environmental impact and adequate nutrition, in addition to being *‘economically fair and affordable’* (FAO, 2010).

The wide-ranging systematic review of Rao *et al.* (2013) on healthfulness of dietary patterns and their corresponding price, highlights significant differences in cost per capita for healthy versus less healthy diets. Healthy diets on average being approx. $1.5 more expensive per day, than less healthy diets. Energy-dense foods, such as fats and sugars, tend to be cheaper than more nutritious, less energy-dense foods, such as fruits and vegetables (Darmon *et al.*, 2004; Darmon and Drewnowski, 2015), and such differences in price highlight social barriers between consumers and healthy, sustainable eating choices. Such observations go back as far as the pioneering work of Sir John Boyd Orr and his work on health and nutrition during the 1930s (Pemberton *et al*., 2000).

1.4. Context for considering legumes as key components of sustainable diets

Grain legumes are often referred to as 'poor people's meat' on account of their high protein content. Compared to cereal grains (7-13%), and meat (18-25 %) grain legumes have typical protein contents between 17% and 30% (de Almeida Costa *et al.,* 2006). In addition, grain legumes are uniquely rich in dietary fibre, provide a range of essential minerals and nutrients, and have high levels of antioxidants, phenolics and low glycaemic index carbohydrates (Çakir *et al.,* 2019).

Increasing the proportion of legumes in a diet may offer a range of positive health effects from improving general gut health (Messina *et al.,* 1999; Clemente and Olias, 2017) to more specific anti-carcinogenic (Feregrino-Perez *et al.,* 2008; Caccialupi *et al.,* 2010; Lima *et al.,* 2016) and anti-diabetic properties (Venn and Mann, 2004; Mirmiran *et al.,* 2012; Ariviani *et al.,* 2018;) and a reduction in the risk of cardiovascular disease (Bazzano *et al.,* 2001; Jenkins *et al.,* 2012; Arnoldi *et al.,* 2015; Marventano *et al.,* 2017). These activities relate to the high fibre content of grain legumes, high levels of antioxidants and the presence of biopeptides, lectins, isoflavones, phytoestrogen and phenolic compounds in general (Çakir *et al.,* 2019).

Accepting these positive effects, the consumption of grain legumes in developed countries remains unfortunately low compared to recommended daily values (Micher *et al.,* 2005; Miller *et al.,* 2016; 2017). It has been calculated that for Europe and North America to adopt a healthy, environmentally sustainable diet, legume consumption would have to increase by approximately 65g per capita per day to reach the recommended value of 75g (Willets *et al.,* 2019). Underconsumption of fruits and vegetables in poorer countries is related to the cost of fresh produce (Miller *et al.,* 2016), but for developed countries the underconsumption of grain legumes may be related to the perception of legumes as poor people's meat, and also being both difficult to digest and lacking in essential amino acids (https://paleoleap.com/beans-and-legumes/).

While grain legumes have relatively low concentrations of the essential amino acids methionine, tryptophan and cysteine (De Lumen *et al.,* 1986; Iqbal *et al.,* 2006; Loehn *et al.*, 2012) it is possible to supplement these amino acids from other dietary sources. More problematic would be the presence of so-called antinutritional compounds in grain legumes such as phenolics, proteases, lectins and amylase inhibitors. These can have adverse effects on digestion, but in most cases are removed during food preparation and cooking.

As a corollary to the nutritional benefits of eating legumes, their agricultural production represents a more sustainable production of plant protein than cereals. The ability of legumes to host N_2-fixing bacteria within their root tissue can effectively reduce the need for N-fertiliser application. Legumes grown in rotation, grown within cereal crops (intercropping), or grown as green manures or within legume-enriched pastures, all have the potential to reduce greenhouse gas emissions of CO_2 and

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N_2O by virtue of a reduced requirement for N fertiliser application, increase yields and increase nitrogen-use efficiency (Jensen *et al.,* 2012; Peoples *et al.,* 2017, 2019).

In terms of soil N inputs from biological N_2 fixation, an approximate value of 9 kg N mineralized per ton of stubble may be possible for grain legume crops, with higher transfer values being recorded for forage legume systems – 15 to 20 kg N per ton of stubble (Peoples *et al.,* 2004, Peoples *et al.,* 2017). Typical rates of biological N_2 fixation for grain and forage legumes are between 100 – 200 kg shoot N ha^{-1} per year or growing season (Peoples *et al.,* 2019).

Skowrońska and Filipek (2014), in their review of LCA studies on fertiliser manufacture, provide illustrative data on the extent of GHG savings possible through reduced fertiliser production. Depending on the type of N-fertiliser, the combined GHG cost of production, packaging and delivery ranges from 1.9 to 6.3 kg CO_2e kg^{-1}. The GHG cost for P-fertiliser is considerably less, 0.6 to 1.66 kg CO_2e kg^{-1}, with manufacture of calcium carbonate for soil amendment accounting for 0.15 kg CO_2e kg^{-1} (Skowrońska and Filipek, 2014).

Using values averaged across 67 to 71 site-years of data, Peoples *et al.* (2019) report an overall reduction in N_2O emissions for legume crops compared with N fertilized crops and pastures of approximately 59%, based on average N_2O emissions of 0.47t CO_2e ha^{-1} for legume crops and 1.16 t CO_2e ha^{-1} for N-fertilized crops and pastures.

Despite considerable knowledge on the environmental benefits to legume cropping (Murphy-Bokern *et al.,* 2016; Foyer *et al.,* 2016; Peoples *et al.,* 2019), the global area of pulses grown in 2018, at 9.6 x 10^7 hectares (FAO, 2020), represents only 13% of that for cereals. Foyer *et al.* (2016) argue that globally, grain legume production lags cereals due to unstable grain legume prices, variable yields, and government price support policies for cereals.

1.5. The EAT Lancet Commission Reference Diet

This study compares the Irish Diet, as a critical example of an unhealthy diet, with a Reference Diet for healthy and sustainable eating. Comparisons are in terms of cost per capita per day, environmental impact, and in terms of dietary choice, a comparison of the cost per 100 kcals of food items in terms of increased nutritional density and decreased environmental impact.

Ireland faces a health crisis triggered by diet and lifestyle choice. Thirty seven percent of adults are overweight and 24% are obese (Flynn *et al*., 2011), this latter statistic expected to increase to 47% of Irish adults by 2030 (WHO, 2013), making Ireland set to become the most obese country in Europe. Studies show a socio-economic gap in dietary patterns among the Irish population (Friel *et al*., 2003; Kelleher *et al*., 2008; Layte *et al*., 2011), where access to affordable, nutritious food is a major challenge to low-income families.

The EAT-Lancet Commission Reference Diet has been designed to both optimise health outcomes and be able to sustainably feed a global population of 10 billion people (Willett et al., 2019). The diet consists of a high intake of fruits, vegetables, wholegrains, legumes, nuts, and unsaturated oils, while limiting the intake of red meat, added sugars, and starchy root vegetables. The diet allows for a moderate intake of poultry, fish, and dairy. The Reference Diet and proposed changes to food production systems are based on planetary boundaries set for global food production. These boundaries are specified limits on GHG emissions, nitrogen and phosphorous application, freshwater use, biodiversity loss, and land-use change associated with food production.

The diet was designed with ranges of consumption for each food type and is broad enough to accommodate most different culinary traditions around the world. If this diet was to be adopted globally, it is proposed to offer positive health outcomes with reduced incidence of the dietary non-communicable diseases, and positive environmental impacts. Along with other changes to our food production systems, this diet would allow for the adequate feeding of a world population of 10 billion people while remaining within the planetary boundaries for food production.

2. Methodology

2.2. Diet statistics

Two sources of dietary intake were used to describe the Irish Diet, general FAO food supply data in terms of total kcal capita^{-1} d^{-1} (http://www.fao.org/faostat/en/#data/FBSH), and more specific individual food consumption data, obtained from the NANS 2011 report (Flynn *et al*., 2011).

For the NANS data, representative food items were chosen to best describe the food categories listed, (Table 10, Annex 1). These representative food items were used to convert dietary intake from grams per capita intake to kcals per capita per day. For comparison with the EAT-Lancet Reference Diet, FAO food balance data for Ireland was grouped according to the Reference Diet categories as described in Williams *et al.* (2020). Prices for individual food items were calculated using online supermarket shopping resources, choosing the lowest prices available over a two-week period.

2.3. Environmental burden of food items.

Development of functional units incorporating both environmental and nutritional aspects to food pathways necessitate a review of the life cycle impacts involved. Both GWP and EP were chosen in this study, these being the most common variables published in LCA studies, and ones representing opposite extremes in scale. Protein sources chosen depended on the availability of LCA data, incorporating 53 food types for GWP (kgCO$_2$e 100kcal^{-1}, and 100g^{-1}) and 22 for EP (gPO4^{3-}e 100kcal^{-1}, and 100g^{-1}). All data was derived from journal articles and published reports. A full description of the methodology used for data collection and compilation is given in the 'TRUE Deliverable 5.1 (D29) Report on Life Cycle Assessment Methodology for Assessing the Environmental Sustainability of Legume Value Chains' (Styles *et al.,* 2018).

2.4. Nutrient Density Indices (NDIs)

The NRF Index 12:3 (based on the NRF9:3 index of Drewnowski and Fulgoni, 2008, 2009 (but with Zn, Fe and vitamin B12 added), was used to provide a measure of nutritional density per 100g of food item. Full data requirements and daily reference intakes are given in Styles *et al*. (2018), and Williams *et al*. (2020) and reproduced here in Tables 1 and 2. Nutrient and energy density per 100g raw food were obtained from the USDA (https://fdc.nal.usda.gov/), accepting that cooking and processing may alter nutrient balance. Only food items where farmgate GWP and EP data were available were chosen.

Table 1: Nutrient requirements for the Nutrient Rich Food (NRF) (12:3) nutrient density indices. RA, denotes, ‘recommended (dietary) allowance’.

	Nutrient	**Daily Reference Intake**
Macro-nutrients	Protein	50 g
	Fibre	25 g
	Essential Fatty Acids	12.4 g
Micronutrients	Vitamin A	800 RA
	Vitamin C	80 mg
	Vitamin E	12 mg
	Calcium	800 mg
	Iron	14 mg
	Magnesium	375 mg
	Potassium	2000 mg
	Vitamin B12	2.5 µg
	Zinc	10 mg
Nutrients to Limit	Added Sugar	90 g
	Saturated Fatty Acids	20 g
	Sodium	2400 g
Energy	Energy Density	2000 kcal

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Table 2: Calculation of Nutrient Rich Food (NRF) 12:3 density index.

Model	**Algorithm**	**Notes**
NRF 12:3 sub-score		
NRF 12:3$_{100g}$	$\sum_{1-12}(nutrient_i/DV_i)$	Nutrient$_i$ = nutrient per 100g DV$_i$ = daily value for the nutrient (RDV)
LIM sub-score		
LIM$_{100g}$	$\sum_{1-3}(nutrient_i/MRV_i)$	MRV$_i$ = maximum recommended value for the nutrient (grams)
NRF 12:3 complete		
NRF 12:3$_{100g}$	(NRF 12:3$_{100g}$ - LIM$_{100g}$)/ 12(energy$_{100g}$/2000)	

2.5. Environmental burden per NDI statistic

Environmental burden data per 100g weight of food item (kgCO$_2$e, gPO$_4^{3-}$e) were expressed per NDI, using the NRF12:3 per 100g values calculated above. Plotting this new attribute against the price of 100kcals of the food item in question, allows for a graphical means of illustrating the suitability of food items for inclusion in a sustainable diet. Those food items distributed within the 1st quartile range for both price and environmental burden per NDI are considered ideal.

3. Results and discussion

Fifty-three food items have been costed in this study in terms of price, GWP, EP and nutrient density, these items constituting the major food groups listed for FAO food balance estimates of national diet. This data has been used to calculate daily per capita scores for calorific intake, kgCO$_2$e and gPO$_4^{3-}$e release into the environment, and monetary cost for both the Irish and EAT-Lancet Commission diets. In addition, data from a more specific 4-day food survey of adult nutrition in Ireland (Flynn *et al*., 2011) has been costed in terms of price, and calorific intake.

As an example of assessing food items in terms of sustainability, the GWP, or EP per nutrient density attribute is presented for FAO food balance food groups, as a function of cost per 100kcals.

3.2. Comparison of food groups according to energy, nutrient density and price

Energy and nutrient density values for the 18 EAT food categories are illustrated in Figure 1, and in terms of relative cost of these attributes, Figure 2 and Table 7 (Annex 1).

3.1.1. Food groups with the highest energy densities, score the lowest for nutrition

Food groups rich in fats, ranging from peanuts (typically 44 to 56% fat) through to dairy and vegetable oils, have the highest energy density scores (>590 kcals per 100g). Sugar and sweeteners, tree nuts, soy foods and whole grains occupy the mid-range for energy density (130 – 590 kcals per 100g), with scores above the 2nd quartile. Animal products occupy the lower mid-range, with scores less than the 2nd quartile, and except for eggs, all food groups within the low energy-density range (<133 kcals per 100g), are of plant origin.

High energy densities do not coincide with high nutritional content. Using a nutrient density index, which includes a measure of twelve nutrients of benefit and three to limit (Drewnowski, 2010), then animal fats, vegetable oils and sweeteners, occupy the lowest nutritional scores (NRF<24), with poultry, fish, soy and vegetable categories scoring the highest (NRF>160). Legumes, whole grains, tree nuts, red meat and dairy occupy the mid-range (55 to 140), with legumes having nutritional density scores above the 2nd quartile.

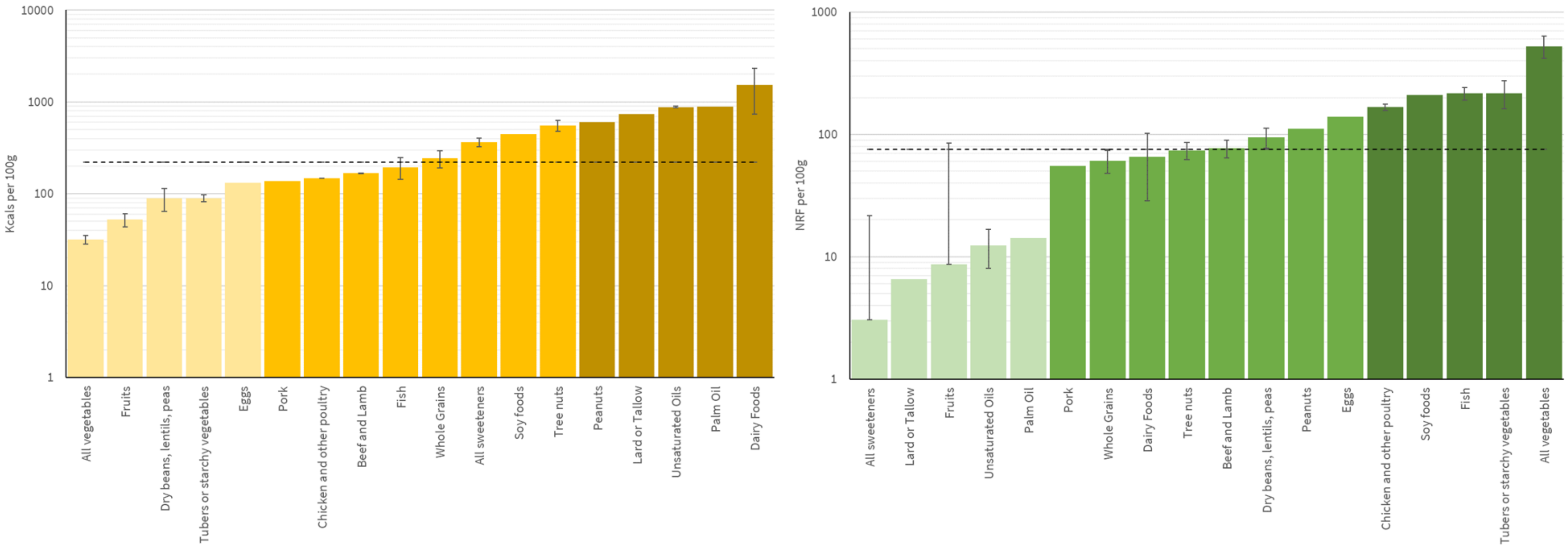

Figure 1: Energy and nutrient density content per EAT-Lancet Commission Reference Diet food categories. Each bar represents the mean of representative food items listed in Table 7. Lighter coloured bars indicate values < 1st quartile, darker coloured bars indicate values >3rd quartile, and the dotted line represents the median. Error bars where given, represent the standard error of the mean.

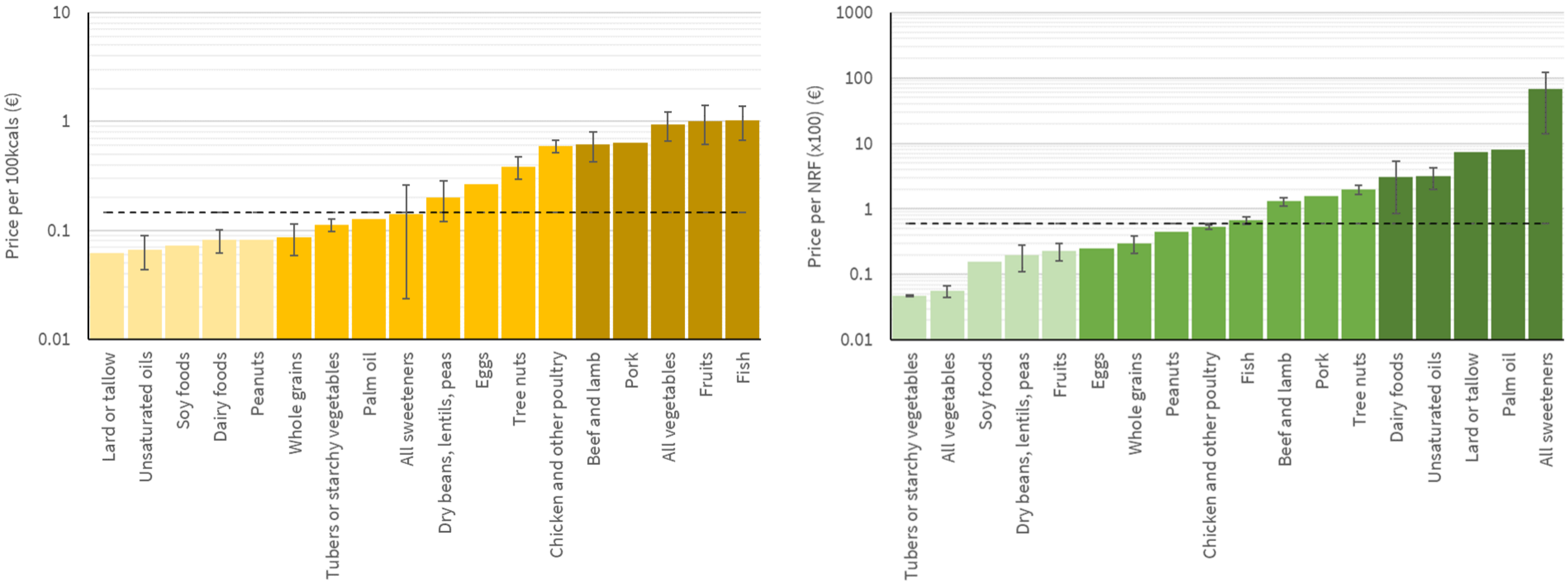

Figure 2: Price per 100 kcals, and per unit nutrient density for EAT-Lancet Commission Reference Diet food categories. Each bar represents the mean of representative food items listed in Table 7. Lighter coloured bars indicate values < 1st quartile, darker coloured bars indicate values >3rd quartile, and the dotted line represents the median. Error bars where given, represent the standard error of the mean.

3.1.2. Legumes are cheaper per unit energy or nutritional density than meat and fish

EAT-Lancet Commission Reference Diet food categories have been costed in terms of the price per 100kcals and the price per NRF unit, results of which are presented in Figure 2 and Table 7 (Annex 1). In terms of kcals, prices range from as little as 6 cents (euro) per 100kcals for animal fats to over 1 euro per 100kcals for fish, and with an overall median value of 17 cents per 100kcals (Figure 2). As expected, most food items with high energy densities (>590 kcals per 100g, Figure 1), have the lowest cost per 100kcals. However, food categories with mid-range energy densities (132 – 590 kcals per 100g), in particular, pork, beef & lamb, and fish, represent some of the highest costing foods (>60 cents per 100 kcals), with legumes priced considerably less (<26 cents per 100 kcals, and for soy and peanuts, < 9 cents per 100 kcals). Fruit and vegetables, which represent some of the lowest energy density food categories, are the most expensive, in terms of price per unit of energy.

More extreme differences appear between sources of animal and plant protein when food categories are scored in terms of price per nutrient density unit (NRF12:3). Here values have been multiplied by 100 in Figure 2, to make the data easier to interpret. In this case relative prices range from as little as 5 cents for starchy vegetables, to 67.5 euros for sweeteners. Except for tree nuts, plant protein sources occupy a price range below the median value of 60 cents, and with the exception of eggs, animal protein sources occupy a price range above 50 cents. As expected, the most nutritionally poor food categories occupy the highest price range with values greater than 3 euros.

3.3. Comparison of food groups according to environmental burden

The following section of the report covers the environmental assessment of food groups in terms of GWP (kgCO_2 e per 100g/100kcals) and EP (gPO_4^{3-} per 100g/100kcals), results of which are reproduced from the related TRUE report, The Environmental Assessment of Diets (Williams *et al*., 2020).

3.2.1. GWP for meat, dairy and fish are high compared to legumes

In addition to retail monetary costs to the consumer, environmental costs of food production may in theory be converted to financial equivalents, although in practice the cost per tonne of CO_2e varies alarmingly according to country, methodology and abatement strategies considered (Duong, 2009; Kevany and Cleary, 2018; Lanigan *et al*., 2019). Low-cost foods rich in either kcals or nutrients, may have high environmental costs in terms of emissions of greenhouse gases to the atmosphere and/or leaching of nutrients. To account for this, Deliverable 5.5 - The Environmental Assessment of Diets (Williams *et al*., 2020) of the TRUE project provided farm gate data for CO_2e emissions for over fifty different food items, incorporating 1350 separate values. This data is summarised in Figure 3 and Table 8 (Annex 1), with respect to to the EAT-Lancet Commission Reference Diet, and its 18 separate food categories.

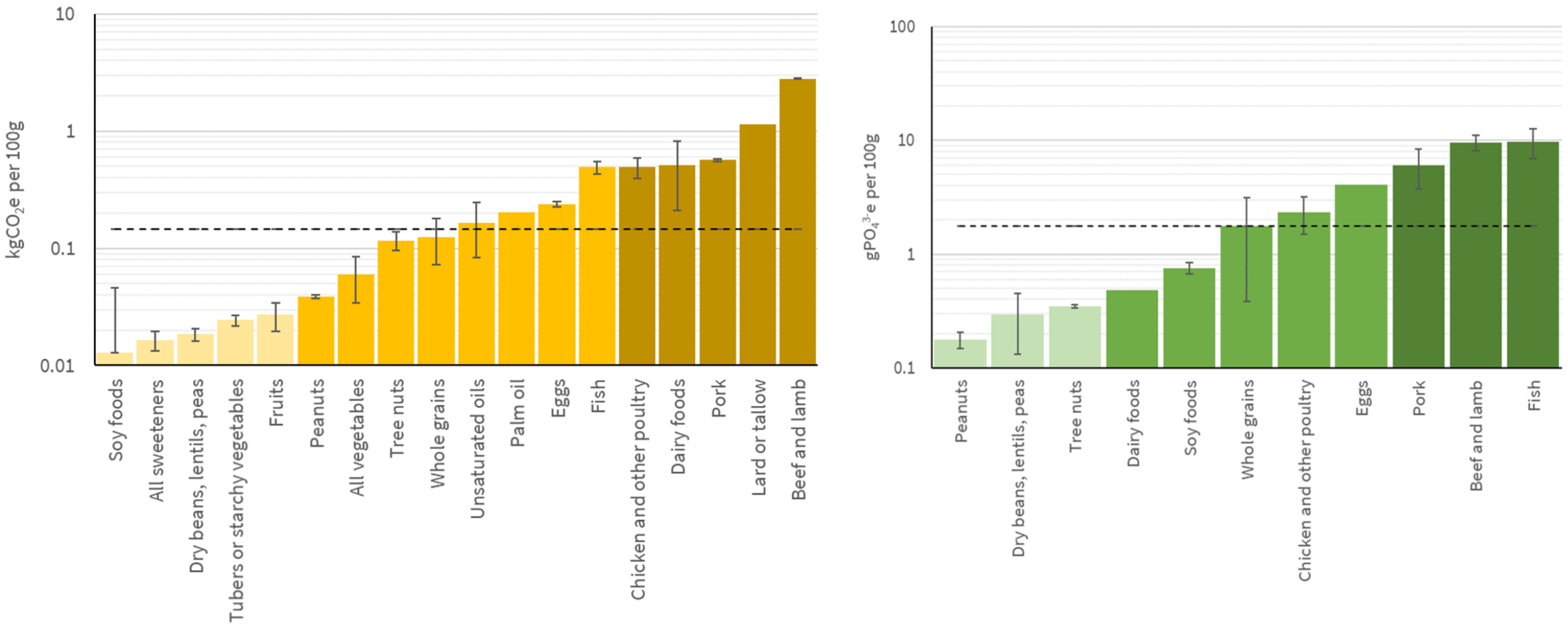

Figure 3: Farm-gate Global Warming Potential (GWP) and Eutrophication Potential (EP) values associated with the EAT-Lancet Commission Reference Diet food categories. GWP values are presented in $kgCO_2e$ per 100g, and EP values in $gPO_4^{3-}e$ per 100g. Each bar represents the mean of representative food items listed in Table 8. Lighter coloured bars indicate values < 1st quartile, darker coloured bars indicate values >3rd quartile, and the dotted line represents the median. Error bars where given, represent the standard error of the mean.

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Animal groups show the highest GWP values (>0.49 kgCO$_2$e per 100g), with legumes, starchy vegetables, fruits and sweeteners showing the lowest emissions (<0.03 kgCO$_2$e per 100g). All plant food groups had GWP values below 0.21 kgCO$_2$e per 100g and except for vegetable oils, all values for plant food groups were below the median score of 0.15 kgCO$_2$e per 100g.

High GWP emissions from animal products is to be expected, have been commented extensively in the literature, and are due primarily to methane emissions from enteric fermentation and manure management, with N_2O emissions from nitrification and denitrification related to fertiliser application (Tilman *et al*., 2011; Heller *et al*., 2013; IPCC, 2014; Poore and Nemecek, 2018). GWP emissions from the fish sector relate primarily to fuel use for net/line caught fish, and application of high N fish food in the case of farmed fish – feed accounting for up to 92% of emissions in lake, and 66% emissions in pond systems (Pelletier and Tydemars, 2010).

Unfortunately, FAO food balance statistics do not discriminate between white or brown rice, hence inclusion of white rice in the '*whole grains* category represents a bias towards high emissions. Paddy systems are associated with high emissions of methane (Thanawong *et al*., 2014), and for data used in this study, the mean GWP value for white rice is 0.37 kgCO$_2$e per 100g, as opposed to a mean of 0.076 kgCO$_2$ per 100g for the other whole grains (Table 8). Clearly, white rice is problematic if considering this food item as a staple carbohydrate in sustainable diets. However, even accepting the lower emission value for the *whole grains* category, legumes represent a better choice with regard to nutrient density and GWP overall.

3.2.2. EP scores for meat, dairy and fish are high compared to legumes

A reduced data set was available for the calculations of farmgate values for EP, representing only 22 individual food items incorporating 157 separate values (Williams *et al*., 2020). This is summarised in Figure 3 and Table 8 (Annex 1), with respect to to the EAT-Lancet Reference Diet categories.

Scoring food items in terms of eutrophication highlights a further problem with the red meat and the farmed fish sector as a source of sustainable protein, these categories producing the highest gPO$_4^{3-}$e values for the food items studied (>6 gPO$_4^{3-}$ per 100g). The high protein plant foods represented by legumes and tree nuts occupy the lowest EP range of values (<0.4 per 100g). Soy foods have an EP score less than the median value of 1.7g gPO$_4^{3-}$e, while whole grains, with the inclusion of white rice, is again biased by the unsuitability of paddy field systems for reducing eutrophication. Here, white rice accounts for 8.7 gPO$_4^{3-}$e per 100g, as opposed to a mean value for the other whole grains of 0.39 (Table 8). Excluding white rice from the calculation reduces the whole grain category to an EP value equal to that of dry beans, lentils, peas category (Figure 3).

3.2.3. Environmental, nutritional and cost attributes of food groups, favour legumes

The environmental burden per nutrient density unit as a useful attribute in LCA was first proposed by van Dooren (2016), and adapted for use with the EAT-Lancet Commission Reference Diet in the sister-report to this (Williams *et al*., 2020). Here the sustainability of food groups (FAO food balance categories) is further assessed by plotting this new attribute as a function of price per 100 kcals, similar to the work of Primavesi *et al*. (2015), but using the NRF12:3 density index to account for a wider spread of essential nutrients for each food item (Table 1). Plots of GWP per NDI, and EP per NDI are illustrated in Figures 4 and 5, with summary data given in Table 9 (Annex 1).

Essentially each graph represents a sustainability index where food items positioned below the intercept of the median values (grey solid lines), may be considered the best value food items to choose in terms of a reduced environmental burden per nutrient unit, and at the lowest cost per unit of energy. Food items positioned outside of the intercept of the 3rd quartile values (the grey dashed line) can be considered the worse value food items, while those positioned below the intercept of the 1st quartile values (dotted grey line) represent the ideal. The best, worst and ideal food items in each case are listed in Table 3.

Table 3: Best, worst and ideal food choices to increase the sustainability of diets.

GWP best	GWP worst	GWP ideal	EP best	EP ideal	EP worse
chickpea	lamb	pea	pea	pea	lamb
lentil	pork	soybean	peanut	peanut	pork
pea	salmon (farmed)		soybean	maize	salmon (farmed)
peanut	turkey		barley		
soybean			brown rice		
barley			maize		
maize			oats		
oats			milk		
onion					
potato					
sweet potato					
banana					
orange					
hazelnuts					
milk					

Food items which represent an ideal basis for sustainable, nutritional and cost-effective diets are legumes, cereals, starchy vegetables and fruit – the worst being lamb, pork and farmed salmon. For both aspects of environmental burden, GWP and EP, grain legumes are key (ideal).

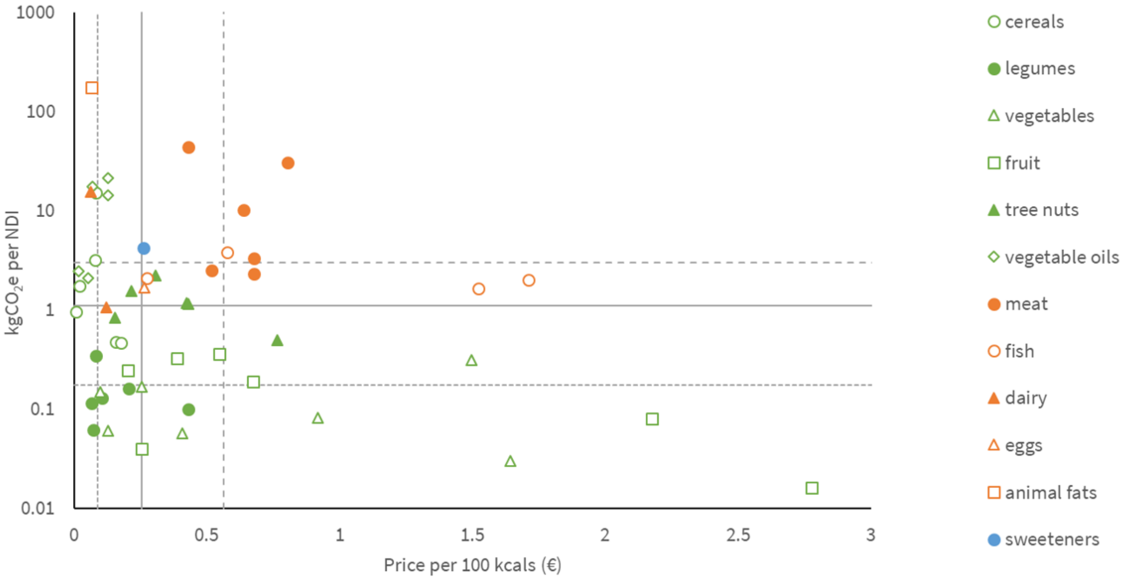

Figure 4: GWP per NDI scores for individual food items plotted against price. Grey lines indicate 1st quartile, median and 3rd quartile respectively.

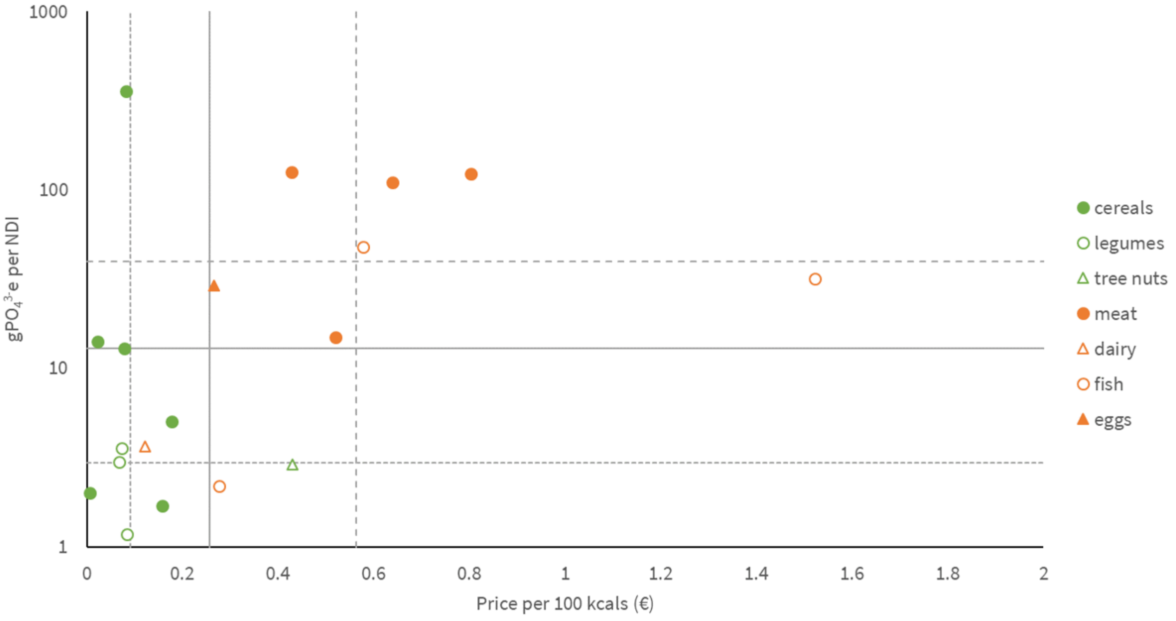

Figure 5: EP per NDI scores for individual food items, plotted against price. Grey lines indicate 1st quartile, median and 3rd quartile respectively.

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3.3 Environmental and cost assessment of the Irish Diet

Following the assessment of individual food groups in terms of environmental burden, nutritional density and cost, this last section of the report considers the Irish Diet in terms of calories consumed, environmental burden, and cost. Two sources of data have been used, FAO food balance sheets to construct a representative diet based on food availability per capita per day, and the Irish NANS study where a four-day food diary is used to construct a more detailed list of food items consumed. A full breakdown of the NANS diet is given in Table 10 (Annex 1).

3.3.1. Adoption of the EAT Reference Diet reduces costs by up to €4 per capita per day

Summary statistics from the NANS survey are given in Table 4, in terms of both the calorific intake and cost for each food group, and the percentage contribution of each food group to the total in each case. A total of 64 food items were costed using the lowest price available from on-line supermarket data (Table 10). Total calorific intake per capita per day, as given by the NANS survey (Flynn *et al.*, 2011), is 2081 kcals, which given the obesity statistics for Ireland, (WHO, 2013) would suggest an under-reporting of the food consumed. This is not surprising given the nature of the NANS study. Under reporting is less prevalent in 24-hour dietary recall surveys, than self-reporting surveys (Kye *et al.*, 2014), and major reasons influencing under-reporting include obesity (Johansson *et al.*, 2001; Johnson et al. 1998). Accepting this, the proportionality of food intake to the total calorific value is still valid.

In terms of the percentage contribution of food groups to the overall total, then the Irish Diet could be described as one rich in cereals, dairy, red meat and convenience foods (miscellaneous savoury and sweet dishes). The top 70% of the diet is made up of cereals, dairy, red meat, savoury and dessert dishes, with less than 5% of the total daily intake made up of legumes, non-starchy vegetables and fruit. Alcohol consumption represents 7% of the daily energy intake, equal to the daily energy intake from potatoes, and is over 8× the daily energy intake from legumes (Table 4). Taking into consideration the major sustainable food groups outlined in Table 3, then these constitute 47% of the daily total energy intake, dominated by inclusion of cereals and dairy (34.5% combined).

When the cost of this diet is considered in terms of euros per capita per day, the contribution of alcohol is extreme - 25% of the estimated daily cost of 5.6 euros, equal to the combined daily cost of the sustainable food items highlighted in Table 3 (24.5%), but only representing 7% of daily energy intake. Meat and savoury dishes combined, constitute approximately 30.5% of the daily cost, with sugars, sweeteners and sweet dishes constituting 10% of the total.

Considering the under-reporting of dietary intake evident, then the overall cost per 100kcals of 0.27 euros is a useful conversion factor for calculating a more realistic daily dietary cost using FAO food

balance data. This allows the comparison of the cost of the NANS diet, adjusted to FAO Irish food balance data, with the EAT-Lancet Reference Diet.

Table 5 illustrates comparative costings for the EAT reference and Irish Diets, as calculated from FAO food balance statistics, and using the lowest Irish retail prices for 53 separate food items (Table 7). Our calculations give a per capita per day cost for the EAT Reference Diet of €5.5, or 9.7% of the mean per capita disposable income for Ireland (CSO, 2020).

Hirvonen *et al*. (2020) have also costed the EAT-Lancet diet, but in global terms, and using a data set of 744 foods in 159 countries. They calculated the global median for 2011, at 2.84 US dollars per capita per day. Correcting for a differing exchange rate in 2020, this gives a value of 2.03 euros per capita per day, less than half our calculated value. Accepting that Ireland is the 8th most expensive country in Europe for food, our estimate is still high. Proportionally though, our data agree with that of Hirrvonen *et al*. (2020). The most expensive foods are fruit and vegetables, constituting 37% of the total daily cost, then legumes and nuts at 20.3%, meat, eggs and fish at 18.5%, but dairy at only 2.4%. Daily cost as a proportion of disposable income also agrees with data in Hirvonen *et al*. (2020) for higher income countries.

The Irish Diet, as calculated using FAO food balance statistics, and using the EAT-Lancet Reference Diet format, is associated with a per capita per day consumption of 3487 kcals, and a cost per day of €7.22, an increase of 30% in each case compared to the Reference Diet. Meat, fish and eggs account for approximately 39% of the assumed budget (proportional to a kcal contribution of 13.9%), fruit and vegetables 29% (proportional to a kcal contribution of 10.8%), with the next largest category being cereals at 12.8% (proportional to the highest kcal contribution of 32.7%). Legumes and tree nuts account for only approximately 2% of the total per capita per day and calorific cost. As with the NANS study, then the FAO Irish Diet can be described as one rich in cereals, dairy, red meat and sweet provisions.

A major problem in attempting to compare national diets with the EAT-Lancet diet, is that alcoholic drinks are not included, and for a country like Ireland where 25% of the cost of the daily diet is used to purchase alcohol, then daily calorific intake and cost require to be adjusted to account for this. Hence a new calorific intake for the Irish Diet illustrated in Table 5, is now not 3243, but 3487 kcals, of which approximately 244 kcals represents alcohol (7%). Also, the new daily cost is not €7.22, but €9.63 of which €2.41 represents alcohol. Using the NANS conversion factor of 100kcals = €0.27, and assuming 3487 kcals is a fairer estimate of the daily calorific value for the adult Irish Diet. Therefore, this gives a daily cost of €9.41, or 16.5% of the mean per capita disposable income (CSO, 2020a). The Household Budget Survey for Ireland gives figures for weekly food purchases of €125 per typical household for 2015-16, and €28 (22.4 %) for alcohol *and* cigarettes (CSO, 2020b).

Table 4: Proportional energy intake and cost for the Irish Diet as calculated from the NANS survey (Flynn *et al*., 2001).

	Energy intake and cost of the Irish Diet (NANS statistics 2008-2010) (per capita per day)				
NANS Food Group	**kcals**	**% contribution**	**NANS Food Group**	**€**	**% contribution**
Cereals	442.5	21.3	Alcoholic beverages	1.419	25.27
Dairy	275.0	13.2	Miscellaneous savoury	0.687	12.23
Red meat	266.3	12.8	Red meat	0.638	11.35
Miscellaneous savoury	182.3	8.8	Dairy	0.423	7.53
Miscellaneous sweet	171.6	8.2	Cereals	0.387	6.89
Starchy vegetables	147.0	7.1	White meat	0.384	6.84
Alcoholic beverages	145.2	7.0	Fish	0.374	6.67
Sugars and sweeteners	129.6	6.2	Miscellaneous sweet	0.318	5.66
White meat	103.6	5.0	Sugars and sweeteners	0.259	4.61
Fruit	56.2	2.7	Fruit	0.242	4.32
Non-alcoholic beverages	43.0	2.1	Vegetables	0.142	2.52
Fish	29.8	1.4	Starchy vegetables	0.109	1.93
Vegetables	23.2	1.1	Non-alcoholic beverages	0.105	1.87
Eggs	22.9	1.1	Nuts and seeds	0.056	0.99
Nuts and seeds	17.8	0.9	Eggs	0.056	0.99
Legumes	15.7	0.8	Legumes	0.016	0.29
Vegetable oils	9.0	0.4	Vegetable oils	0.002	0.03
TOTAL	**2080.6**	**100**	**TOTAL**	**5.615**	**100.00**

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Clearly, adoption of the EAT-Lancet diet in Ireland represents a significant saving, and equivalent to up to €3.9 per capita per day, but as illustrated in Williams *et al*. (2020), adoption of the Reference Diet may also reduce the environmental burden by 50%.

3.3.2. Adoption of the EAT Reference Diet reduces per capita GWP and EP by up to 50%

Table 6 illustrates the reductions possible in terms of diet $kgCO_2e$ and $gPO_4^{3-}e$ for an Irish adult if adopting the EAT-Lancet Reference Diet. These data have not been adjusted for alcohol consumption.

Due to lack of environmental data for alcoholic drinks in terms of per 100kcals, these data have not been adjusted for alcohol consumption. European diet data is reproduced as a comparison from Williams *et al*. (2020). In terms of GWP up to a 57% reduction is theoretically possible, and for EP, up to 48%. As discussed in section 3.2, highest GWP values are associated with meat, fish and dairy production, which including eggs, account for over 83% of the per capita per day total for the Irish Diet, and 79% for the European diet. The data set for EP is limited, not including $gPO_4^{3-}e$ values for fruit or vegetables, vegetable oils, animal fats and sweeteners. However, here meat, eggs, dairy and fish account for 76.9% of daily values, and cereals, 23%. Again, this value biased by inclusion of white rice. For European diet these values are 63.7% and 21.7% respectively. **(section 3.2)**.

Table 5: Comparison of the cost per capita per day between the Irish and EAT-Lancet Commission Reference Diets.

Food category	**EAT-Lancet Commission Reference Diet (per capita per day)**			**Irish Diet (2009-2013) (per capita per day)**		
	kcals	cost per 100kcal (€)	cost per category (€)	kcals	cost per 100kcal (€)	cost per category (€)
Whole grains	811	0.09	0.71	1062.8	0.09	0.927
Tubers or starchy vegetables	39	0.11	0.04	152.6	0.11	0.171
All vegetables	78	0.94	0.74	83.2	0.94	0.785
Fruits	126	1.00	1.26	113.2	1.00	1.135
Dairy foods	153	0.08	0.13	449.6	0.08	0.368
Beef and lamb	15	0.62	0.09	140	0.62	0.862
Pork	15	0.64	0.10	153.4	0.64	0.980
Chicken and other poultry	62	0.60	0.37	88.0	0.60	0.526
Eggs	19	0.26	0.05	34.6	0.26	0.092
Fish	40	1.02	0.41	34.8	1.02	0.355
Dry beans, lentils, peas	172	0.20	0.35	33.6	0.20	0.068
Soy foods	112	0.07	0.08	1.0	0.07	0.001
Peanuts	142	0.08	0.12	17.4	0.08	0.014
Tree nuts	149	0.38	0.57	17.6	0.38	0.067
Palm oil	60	0.13	0.08	4.4	0.13	0.006
Unsaturated oils	354	0.07	0.24	396.0	0.07	0.265
Lard or tallow	36	0.06	0.02	71.4	0.06	0.044
All sweeteners	120	0.14	0.17	389.4	0.14	0.554
TOTAL	**2503**		**5.51**	**3243**		**7.22**

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Table 6: Calorific intake, GWP and EP scores for the Irish, European and EAT-Lancet Commission Reference Diets.

Food category	**EAT Reference Diet**			**Irish Diet (2009-2013)**			**European diet (2009-2013)**		
	(per capita per day)			**(per capita per day)**			**(per capita per day)**		
	kcal	kgCO$_2$e	gPO$_4^{3-}$e	kcal	kgCO$_2$e	gPO$_4^{3-}$e	kcal	kgCO$_2$e	gPO$_4^{3-}$e
Whole grains	811	0.148	3.938	1062.8	0.179	5.160	1007.6	0.184	4.892
Tubers or starchy vegetables	39	0.012		152.6	0.048		150.6	0.048	
All vegetables	78	0.170		83.2	0.122		81.4	0.180	
Fruits	126	0.066		113.2	0.064		105	0.055	
Dairy foods	153	0.338	1.238	449.6	1.003	3.638	386.2	0.854	3.125
Beef and lamb	15	0.131	0.476	140	1.221	4.440	77.0	0.671	2.442
Pork	15	0.029	0.345	153.4	0.330	3.532	186.2	0.401	4.729
Chicken and other poultry	62	0.257	1.223	88.0	0.365	1.736	79.2	0.329	1.562
Eggs	19	0.045	0.543	34.6	0.082	0.989	49.4	0.118	1.412
Fish	40	0.153	3.405	34.8	0.129	2.962	46.6	0.178	3.966
Dry beans, lentils, peas	172	0.031	0.148	33.6	0.006	0.029	23.4	0.004	0.020
Soy foods	112	0.014	0.189	1.0	0.0001	0.002	1.2	0.0002	0.002
Peanuts	142	0.055	0.044	17.4	0.007	0.005	12.2	0.005	0.004
Tree nuts	149	0.030	0.093	17.6	0.004	0.011	24.2	0.005	0.015
Palm oil	60	0.015		4.4	0.001		30.0	0.007	
Unsaturated oils	354	0.038		396	0.052		426.0	0.045	
Lard or tallow	36	0.058		71.4	0.115		81.2	0.130	
All sweeteners	120	0.006		389.4	0.020		385.6	0.020	
TOTAL	**2503**	**1.60**	**11.64**	**3243**	**3.748**	**22.504**	**3153**	**3.234**	**22.170**

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4. Conclusions

This report is a continuation from Deliverable 5.5 - The Environmental Assessment of Diets (Williams *et al.,* 2020), and specifically addresses the question of cost per unit energy/nutrient density/environmental impact attributes as a means of assessing the sustainability of food items and dietary choice. The Irish Diet is used as an example of how reducing the intake of low sustainable foods can significantly lower per capita per day costs, increase nutritional quality and reduce the environmental burden.

4.1. Legumes are cheaper per unit energy or nutritional density than meat and fish

Fifty-three food items representative of FAO food balance data and the 18 EAT-Lancet Reference Diet food categories were assessed for cost, energy and nutrient density. High energy density does not coincide with high nutritional content. Using a nutrient density index, which includes a measure of twelve nutrients of benefit and three to limit (Drewnowski, 2010), animal fats, vegetable oils and sweeteners occupy the lowest nutritional score range (NRF< 24), with poultry, fish, soy and vegetable categories scoring the highest (NRF>160). Legumes, whole grains, tree nuts, red meat and dairy occupy the mid-range of NRF values (55 to 140), with legumes having nutritional density scores above the 2nd quartile. **(section 3.1.1)**

In terms of energy intake, prices for the 53 food items studied range from as little as 6 cents per 100kcals for animal fats to over 1 euro per 100kcals for fish. Foods with mid-range energy densities, in particular, red meat and fish, represent some of the highest costing foods (>60 cents per 100 kcals), with legumes costing considerably less (<26 cents per 100 kcals). More extreme differences appear between sources of animal and plant protein, when food categories are scored in terms of price per nutrient density unit (NRF12:3). Except for tree nuts, plant protein sources occupy a price range below the median value. **(section 3.1.2)**

4.2. Environmental, nutritional and cost attributes of food groups, favour legumes

The environmental burden per nutrient density unit as a useful attribute in LCA was first proposed by van Dooren (2016), and adapted for use with the EAT-Lancet Commission Reference Diet in the previous report to this study (Williams *et al*., 2020).

In this report both GWP per NRF unit, and EP per NRF unit are plotted against the cost per 100kcals for the 53 individual food items used in the previous analyses. Food items that occupy the area intercepted by both median lines are considered the most suitable with respect to sustainable diets, while those food items placed outside the intercept of the 3rd quartile values, are the least suitable. Ideal sustainable foods are those occupying the area intercepted by the 1st quartile values.

Food items which represent an ideal basis for sustainable, nutritional and cost-effective diets are legumes, cereals, starchy vegetables and fruit – the worst being lamb, pork and farmed salmon. **(section 3.2.3)**

4.3. The EAT-Lancet Reference Diet is associated with significant reductions in cost, calories consumed and GWP/EP

Converting the NANS dietary intake statistics of Flynn et al. (2011) to kcals and cost per day, then the Irish Diet maybe described as one rich in cereals, dairy, red meat and convenience foods (miscellaneous savoury and sweet dishes). The top 70% of the daily calorific intake is made up of cereals, dairy, red meat, savoury and dessert dishes, with less than 5% of the total daily total made up of legumes, non-starchy vegetables and fruit. Alcohol consumption represents 7% of the daily energy intake, equal to that from potatoes, and is over 8× the daily energy intake from legumes. Taking into consideration the major sustainable food groups outlined in section 4.2, then these constitute 47% of the daily total energy intake, dominated by inclusion of cereals and dairy (34.5% combined).

In terms of proportional costs, then 25% of the daily cost per capita of €5.6 is spent on alcohol, equal to the combined daily cost of the sustainable food items highlighted in section 4.2 (24.5%), but only representing 7% of daily energy intake. Meat and savoury dishes combined, constitute approximately 30.5% of the daily cost, with sugars, sweeteners and sweet dishes constituting 10% of the total.

Using FAO food balance statistics offers a similar diet profile but at a higher calorific intake and cost.

Comparing the Irish Diet with the EAT-Lancet Reference Diet highlights the considerable savings in cost possible – up to €4 euros a day dependant on which data set is used. As with data presented in Williams *et al*. (2020), then adoption of the Reference Diet would also involve reductions in diet associated emissions of CO_2e and gPO_4^{3-}e release to the environment by 57 and 48% respectively. **(section 3.3)**

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Annex 1: Summary data

Table 7: Price per 100 kcals, and per unit nutrient density for the EAT-Lancet Reference Diet categories.

EAT Food Category	**Food Item**	**price per 100kcal (€)**			**price per NRF 12:3(x100) (€)**		
		per item	per category (x̄)	se	per item	per category (x̄)	se
Soy foods	soybean	0.07	0.07		0.16	0.16	
All sweeteners	sugar	0.02			120.84		
	honey	0.26	0.14	0.12	14.18	67.51	53.33
Dry beans, lentils, peas	faba bean	0.43			0.14		
	pea	0.07			0.45		
	lentil	0.21			0.11		
	chickpea	0.11	0.20	0.08	0.08	0.20	0.09
Tubers or starchy vegetables	potato	0.10			0.05		
	sweet potato	0.13	0.11	0.01	0.05	0.05	0.002
Fruits	orange	0.26			0.03		
	mandarin	0.39			0.08		
	lemon	2.78			0.09		
	banana	0.20			0.18		
	apple	0.67			0.42		
	pineapple	2.17			0.37		
	grape	0.55	1.00	0.39	0.43	0.23	0.07
Peanuts	peanut	0.08	0.08		0.45	0.45	
All vegetables	tomato	1.50			0.06		
	onion	0.25			0.07		
	broccoli	0.92			0.04		
	cabbage	1.64			0.08		
	cauliflower	0.41	0.94	0.28	0.02	0.06	0.01
Tree nuts	walnut, shelled	0.31			3.22		
	cashew, shelled	0.22			1.37		
	pistachio, raw	0.43			2.10		
	chestnut, peeled	0.76			2.46		
	hazelnut	0.15			1.05		
	almond	0.42	0.38	0.09	1.85	2.01	0.32
Whole grains	wheat flour (unenriched)	0.02			0.28		
	brown rice	0.08			0.21		
	white rice	0.08			0.41		
	maize flour	0.01			0.03		
	oats	0.16			0.66		
	barley (hulled)	0.18	0.09	0.03	0.19	0.30	0.09
Unsaturated oils	soybean oil	0.07			5.29		
	peanut oil	0.13			4.87		
	sunflower oil	0.02			0.52		
	olive oil	0.05	0.07	0.02	1.86	3.14	1.16
Palm oil	palm oil	0.13	0.13		7.96	7.96	
Eggs	eggs	0.26	0.26		0.25	0.25	
Fish	rainbow trout	1.52			0.76		
	cod	1.71			0.59		
	mackeral	0.28			0.47		
	salmon	0.58	1.02	0.35	0.86	0.67	0.09
Chicken and other poultry	chicken	0.52			0.49		
	turkey	0.68	0.60	0.08	0.57	0.53	0.04
Dairy foods	milk	0.12			0.06		
	cheese	0.06			1.75		
	butter	0.06	0.08	0.02	7.41	3.07	2.22
Pork	pork mince	0.64	0.64		1.59	1.59	
Lard or tallow	butter equivalent	0.06	0.06		7.41	7.41	
Beef and lamb	lamb mince	0.80			1.48		
	beef mince	0.43	0.62	0.19	1.12	1.30	0.18

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Table 8: GWP (kgCO_2e) and EP (gPO_4^{3-}e) associated with the EAT-Lancet Reference Diet categories (full data in Williams *et al.*, 2020).

EAT Food Category	**Food Item**	**kgCO_2e per 100g**			**gPO_4^{3-}e per 100g**		
		per item	per category (x̄)	se	per item	per category (x̄)	se
Soy foods	soybean	0.01	0.01		0.75	0.75	
All sweeteners	sugar	0.01					
	honey	0.03	0.02	0.01			
Dry beans, lentils, peas	faba bean	0.02					
	pea	0.02			0.45		
	lentil	0.03					
	chickpea	0.02	0.02	0.00		0.45	
Tubers or starchy vegetables	potato	0.02					
	sweet potato	0.02	0.02	0.00			
Fruits	orange	0.02					
	mandarin	0.07					
	lemon	0.01					
	banana	0.02					
	apple	0.02					
	pineapple	0.02					
	grape	0.03	0.03	0.01			
Peanuts	peanut	0.04	0.04		0.18	0.18	
All vegetables	tomato	0.16					
	onion	0.02					
	broccoli	0.06					
	cabbage	0.02					
	cauliflower	0.04	0.06	0.03			
Tree nuts	walnut, shelled	0.15					
	cashew, shelled	0.14					
	pistachio, raw	0.14			0.35		
	chestnut, peeled	0.03					
	hazelnut	0.08					
	almond	0.16	0.12	0.02		0.35	
Whole grains	wheat flour (unenriched)	0.05			0.41		
	brown rice	0.18			0.73		
	white rice	0.37			8.67		
	maize flour	0.06			0.13		
	oats	0.04			0.14		
	barley (hulled)	0.05	0.13	0.05	0.53	1.77	1.38
Unsaturated oils	soybean oil	0.20					
	peanut oil	0.47					
	sunflower oil	0.08					
	olive oil	0.05	0.20	0.10			
Palm oil	palm oil	0.20	0.20				
Eggs	eggs	0.24	0.24		4.09	4.09	
Fish	rainbow trout	0.46			8.84		
	cod	0.48					
	mackeral	0.37			0.38		
	salmon	0.67	0.49	0.06	8.37	5.86	2.74
Chicken and other poultry	chicken	0.40			2.35		
	turkey	0.59	0.49	0.10		2.35	
Dairy foods	milk	0.14			0.48		
	cheese	0.89					
	butter	1.15	0.73	0.30		0.48	
Pork	pork mince	0.57	0.57		6.05	6.05	
Lard or tallow	butter equivalent	1.15	1.15				
Beef and lamb	lamb mince	2.78			11.05		
	beef mince	2.82	2.80	0.02	8.06	9.56	1.50

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Table 9: Environmental Burden per Nutrient Density Index scores associated with the EAT-Lancet Reference Diet categories.

EAT Food Category	**Food Item**	**$kgCO_2e$ per NRF(12:3) (x1000)**			**$gPO_4^{3-}e$ per NRF(12:3) (x1000)**		
		per item	per category (x̄)	se	per item	per category (x̄)	se
Soy foods	soybean	0.06	0.06		3.59	3.59	
All sweeteners	sugar						
	honey	4.22	4.22				
Dry beans, lentils, peas	faba bean	0.10			2.99		
	pea	0.12					
	lentil	0.16					
	chickpea	0.13	0.13	0.01		2.99	
Tubers or starchy vegetables	potato	0.15					
	sweet potato		0.15				
Fruits	orange	0.04					
	mandarin	0.33					
	lemon	0.02					
	banana	0.25					
	apple	0.19					
	pineapple	0.08					
	grape	0.36	0.18	0.05			
Peanuts	peanut	0.35	0.35		1.18	1.18	
All vegetables	tomato	0.31					
	onion	0.17					
	broccoli	0.08					
	cabbage	0.03					
	cauliflower	0.06	0.13	0.05			
Tree nuts	walnut, shelled	2.21					
	cashew, shelled	1.55					
	pistachio, raw	1.16			2.91		
	chestnut, peeled	0.49					
	hazelnut	0.84					
	almond	1.18	1.24	0.24		2.91	
Whole grains	wheat flour (unenriched)	1.76			14.16		
	brown rice	3.20			12.94		
	white rice	15.27			357.56		
	maize flour	0.95			1.99		
	oats	0.47			1.69		
	barley (hulled)	0.46	3.69	2.35	5.06	65.57	58.44
Unsaturated oils	soybean oil	17.58					
	peanut oil	21.47					
	sunflower oil	2.48					
	olive oil	2.08	10.90	5.04			
Palm oil	palm oil	14.37	14.37				
Eggs	eggs	1.70	1.70			0.00	
Fish	rainbow trout	1.64			31.81		
	cod	2.00					
	mackeral	2.11			2.18		
	salmon	3.81	2.39	0.49	47.96	27.32	13.40
Chicken and other poultry	chicken	2.52			14.87		
	turkey	3.35	2.94	0.42		14.87	
Dairy foods	milk	1.05			3.66		
	cheese	15.52					
	butter	176.61	64.40	56.26		3.66	
Pork	pork mince	10.29	10.29		110.10	110.10	
Lard or tallow	butter equivalent	176.61	176.61				
Beef and lamb	lamb mince	30.90			122.96		
	beef mince	44.00	37.45	6.55	125.60	124.28	1.32

Table 10: Irish Diet statistics adapted from the NANS survey (Flynn *et al.*, 2011).

NANS food group	Representative food item	kcals per day	cost per 100 kcal (€)	cost per day (€)
CEREALS				
Wholemeal brown breads and rolls	Wholemeal brown breads	90.3	0.093	0.084
White breads and rolls	White breads	95.53	0.037	0.035
Rice & pastas, flours, grains and starches	White rice	42.35	0.082	0.035
Other breakfast cereals	Porridge oats	121.44	0.152	0.185
Ready to eat breakfast cereals	Cornflakes	92.88	0.052	0.048
STARCHY VEGETABLES				
Potatoes	Potatoes	58.22	0.098	0.057
Chipped, fried & roasted potatoes	Oven-ready chips	76.97	0.056	0.043
Processed & homemade potato products	Potato waffles	11.76	0.074	0.009
VEGETABLES				
Green vegetables	Broccoli	4.42	0.918	0.041
Carrots	Carrots	4.55	0.257	0.012
Other vegetables	Onions	10.4	0.248	0.026
Salad vegetables	Lettuce	3.15	1.800	0.057
Tinned vegetables	Tinned carrots	0.69	1.009	0.007
FRUIT				
Other fruits	Apples	25.48	0.687	0.175
Bananas	Bananas	23.14	0.206	0.048
Citrus fruits	Oranges	6.58	0.234	0.015
Tinned fruits	Tinned peaches	0.96	0.475	0.005
DAIRY		0		
Whole milk	Whole milk	65.28	0.114	0.074
Low fat, skimmed and fortified milks	Low fat milk	39.06	0.174	0.068
Yoghurts	Greek yoghurt	18.91	0.230	0.043
Other milks and milk based beverages	Strawberry milk	8.908	0.462	0.041
Cheese	Cheddar cheese	56.42	0.248	0.140
Ice-cream	Vanilla ice-cream	12.42	0.116	0.014
Milk puddings	Rice pudding (tinned)	3.76	0.106	0.004
Creams	Cream	1.95	0.200	0.004
Butter (>80% fat)	Butter	21.51	0.067	0.014
Low fat spreads (<40% fat)	Low fat spreads (<40%)	11.19	0.048	0.005
Other spreading fats (40-80% fat)	Other spreading fats (40-80% fat)	35.63	0.039	0.014
RED MEAT				
Beef and veal dishes	Beef lasagne	47.26	0.360	0.170
Beef and veal	Beef mince	43.89	0.169	0.074
Lamb	Lamb mince	7.84	0.383	0.030
Lamb, pork and bacon dishes	Shepherd's pie	5.9	0.322	0.019
Meat pies and pastries	Beef pie	6.45	0.247	0.016
Burgers	Beef burger	20.88	0.431	0.090
Meat products (e.g. processed meats)	Salami	65.34	0.041	0.027
Bacon & ham	Bacon	33.6	0.313	0.105
Sausages	Pork sausages	27.5	0.191	0.053
Pork	Pork mince	7.68	0.703	0.054
WHITE MEAT		0		
Chicken, turkey and game	Chicken fillet	44.37	0.465	0.206
Poultry & game dishes	Chicken curry pie	59.25	0.300	0.178
FISH				
Fish & fish products	Cod fillet	23	1.500	0.345
Fish dishes	Fish cake	6.84	0.430	0.029
LEGUMES				
Peas, beans and lentils	Baked beans	15.66	0.105	0.016
NUTS AND SEEDS				
Nuts & seeds, herbs and spices	Cashew	17.76	0.314	0.056
EGGS				
Eggs and egg dishes	Eggs	22.88	0.243	0.056
VEGETABLE OILS		0		
Vegetable oils	Sunflower oil	9	0.018	0.002
SUGARS AND SWEETENERS				
Chocolate confectionery	Milk chocolate	53.4	0.255	0.136
Sugars, syrups, preserves & sweeteners	White sugar	38.7	0.025	0.010
Puddings & chilled desserts	Chocolate mousse	22.8	0.453	0.103
Non-chocolate confectionery	Jelly beans	14.68	0.068	0.010
MISCELLANEOUS SAVOURY				
Vegetable and pulse dishes	Tofu	23.6	0.429	0.101
Savouries (e.g. pizzas)	Margherita Pizza	83.08	0.325	0.270
Savoury snacks	Crisps (cheese and onion)	36.33	0.314	0.114
Soups, sauces and miscellaneous foods	Tomato soup	28.56	0.706	0.202

MISCELLANEOUS SWEET				
Biscuits (including crackers)	Rich tea biscuit	58.5	0.020	0.012
Cakes, pasteries and buns	Danish pastry	72.93	0.259	0.189
Other breads (e.g. scones, croissants)	Croissant	50.88	0.231	0.118
ALCOHOLIC BEVERAGES				
Alcoholic beverages	Beer (Heineken)	145.2	0.977	1.419
NON-ALCOHOLIC BEVERAGES				
Teas	Breakfast tea	4.22		
Coffees	Instant coffee	2.58		
Carbonated beverages	Cola	15.58	0.158	0.025
Diet carbonated beverages	Diet cola	0.24	3.000	0.007
Squashes, cordials and fruit juice drinks	Orange squash	5.16	0.163	0.008
Fruit juices	Orange juice	22	0.295	0.065
TOTAL		2087.398		5.615

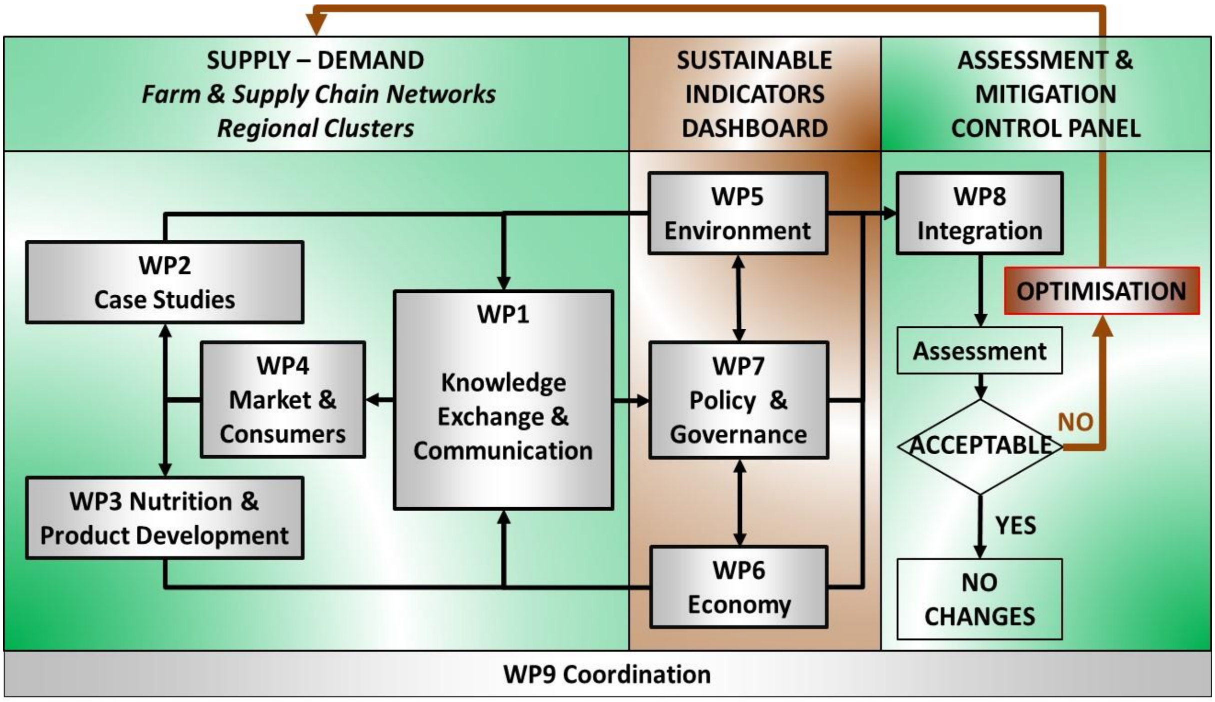
Annex 2: Background to the TRUE project

Executive Summary

TRUE's perspective is that the scientific knowledge, capacities and societal desire for legume supported systems exist, but that practical co-innovation to realise transition paths have yet to be achieved. TRUE presents 9 Work Packages (WPs), supported by an *Intercontinental Scientific Advisory Board*. Collectively, these elements present a strategic and gender-balanced work-plan through which the role of legumes in determining '*three pillars of sustainabilit*y' – '*environment*', '*economics*' and '*society*' - may be best resolved. TRUE realises a genuine multi-actor approach, the basis for which are three *Regional Clusters* managed by WP1 ('*Knowledge Exchange and Communication',* University of Hohenheim, Germany), that span the main pedo-climatic regions of Europe, designated here as *Continental*, *Mediterranean* and *Atlantic,* and facilitate the alignment of stakeholders' knowledge across a suite of 24 Case Studies. The Case Studies are managed by partners within WPs 2-4 comprising '*Case Studies*' (incorporating the project database and *Data Management Plan*), '*Nutrition and Product Development*', and '*Markets and Consumers'.* These are led by the Agricultural University of Athens (Greece), Universidade Catolica Portuguesa (Portugal) and the Institute for Food Studies & Agro-Industrial Development (Denmark), respectively. This combination of reflective dialogue (WP1), and novel legume-based approaches (WP2-4) will supplies hitherto unparalleled datasets for the '*sustainability WPs*', WPs 5-7 for '*Environment*', '*Economics*' and '*Policy and Governance'.* These are led by greenhouse gas specialists at Trinity College Dublin (Ireland; in close partnership with LCAspecialists at Bangor University, UK), Scotland's Rural College (in close partnership with University of Hohenheim), and the Environmental and Social Science Research Group (Hungary), in association with Coventry University, UK), respectively. These *Pillar WPs* use progressive statistical, mathematical and policy modelling approaches to characterise current legume supported systems and identify those management strategies which may achieve sustainable states. *A key feature* is that TRUE will identify key *Sustainable Development Indicators* (SDIs) for legume-supported systems, and thresholds (or goals) to which each SDI should aim. Data from the *foundation WPs* (1-4), to and between the *Pillar WPs* (5-7), will be resolved by WP8, '*Transition Design',* using machine-learning approaches (*e.g. Knowledge Discovery in Databases*), allied with *DEX* (*Decision Expert*) methodology to enable the mapping of existing knowledge and experiences. Co-ordination is managed by a team of highly experienced senior staff and project managers based in The Agroecology Group, a Sub-group of Ecological Sciences within The James Hutton Institute.

Work-package structure

The flow of information and knowledge in TRUE, from the definition of the 24 Case Studies (left), quantification of sustainability (centre) and synthesis and decision support (right).



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Project partners

No	Participant organisation name (and acronym)	Country	Organisation Type
1 (C*)	The James Hutton Institute (JHI)	UK	RTO
2	Coventry University (CU)	UK	University
3	Stockbridge Technology Centre (STC)	UK	SME
4	Scotland's Rural College (SRUC)	UK	HEI
5	Kenya Forestry Research Institute (KEFRI)	Kenya	RTO
6	Universidade Catolica Portuguesa (UCP)	Portugal	University
7	Universitaet Hohenheim (UHOH)	Germany	University
8	Agricultural University of Athens (AUA)	Greece	University
9	IFAU APS (IFAU)	Denmark	SME
10	Regionalna Razvojna Agencija Medimurje (REDEA)	Croatia	Development Agency
11	Bangor University (BU)	UK	University
12	Trinity College Dublin (TCD)	Ireland	University
13	Processors and Growers Research Organisation (PGRO)	UK	SME
14	Institut Jozef Stefan (JSI)	Slovenia	HEI
15	IGV Institut Fur Getreideverarbeitung Gmbh (IGV)	Germany	Commercial SME
16	ESSRG Kft (ESSRG)	Hungary	SME
17	Agri Kulti Kft (AK)	Hungary	SME
18	Alfred-Wegener-Institut (AWI)	Germany	RTO
19	Slow Food Deutschland e.V. (SF)	Germany	Social Enterprise
20	Arbikie Distilling Ltd (ADL)	UK	SME
21	Agriculture And Food Development Authority (TEAG)	Ireland	RTO
22	Sociedade Agrícola do Freixo do Meio, Lda (FDM)	Portugal	SME
23	Eurest -Sociedade Europeia De Restaurantes Lda (EUR)	Portugal	Commercial Enterprise
24	Solintagro SL (SOL)	Spain	SME
25	Public Institution Development of the Međimurje County	Croatia	Development Agency

*Coordinating institution

Objectives

Objective 1: Facilitate knowledge exchange (UHOH, WP1)

- *Develop a blueprint for co-production of knowledge*

Objective 2: Identify factors that contribute to successful transitions (AUA, WP2)

- *Relevant and meaningful Sustainable Development Indicators (SDIs)*

Objective 3: Develop novel food and non-food uses (UCP, WP3)

- *Develop appropriate food and feed products for regions/cropping systems*

Objective 4: Investigate international markets and trade (IFAU, WP4)

- *Publish guidelines of legume consumption for employment and economic growth*
- *EU infrastructure-map for processing and trading*

Objective 5: Inventory data on the environmental intensity of production (TCD, WP5)

- Life Cycle Analyses (LCA) -novel legumes rotations and diet change

Objective 6: Economic performance - different cropping systems (SRUC & UHOH, WP6)

- *Accounting yield and price risks of legume-based cropping systems*

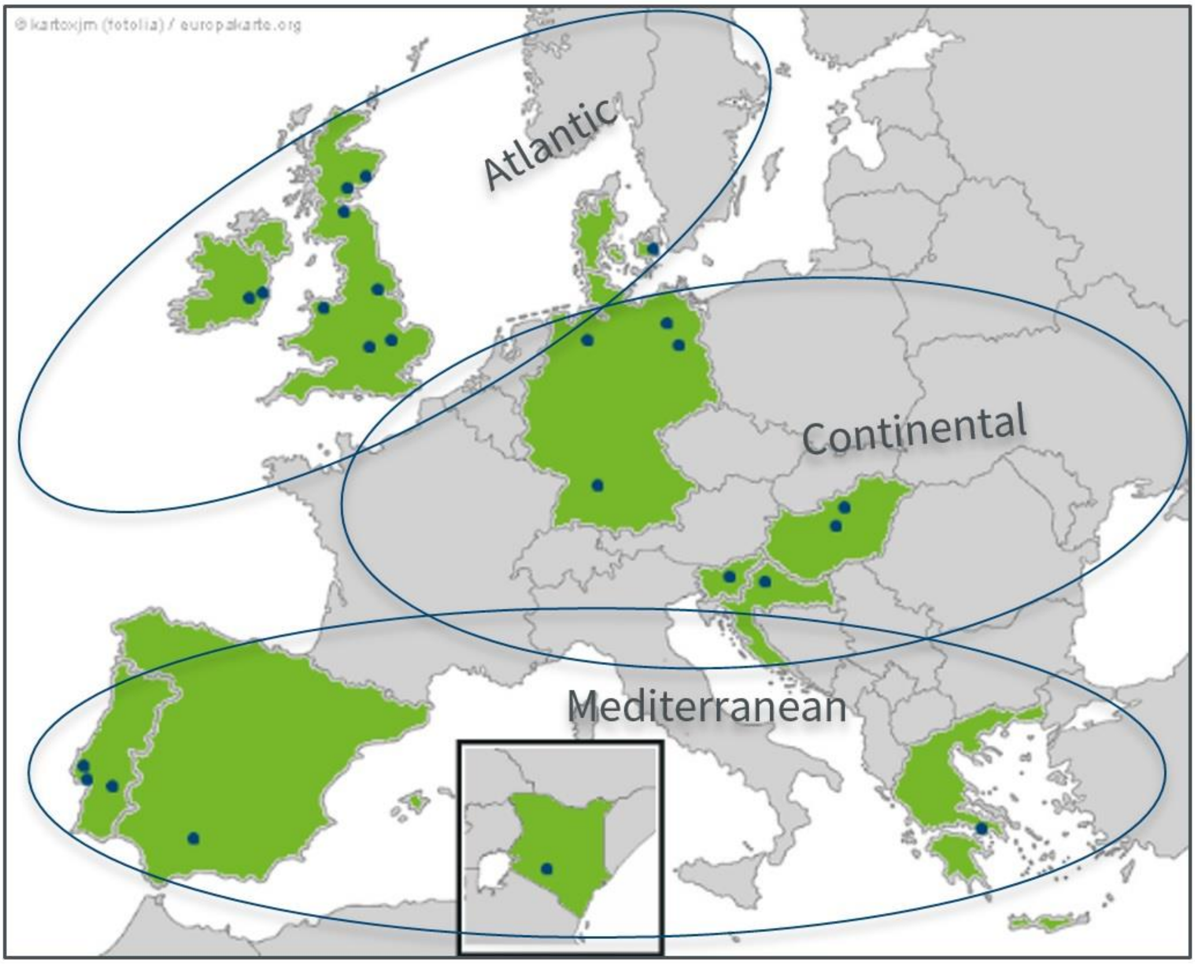
Objective 7: Enable policies, legislation and regulatory systems (ESSRG, WP7)

- *EU-policy linkages (on nutrition) to inform product development/uptake*

Objective 8: Develop decision support tools: growers to policymakers (JSI, WP8)

- *User-friendly decision support tools to harmonise sustainability pillars*

Legume Innovation Networks



Knowledge Exchange and Communication (WP1) events include three TRUE European Legume Innovation Networks (E-LINs), and these engage multi-stakeholders in a series of focused workshops. The E-LINs span three major biogeographical regions of Europe illustrated above within the ellipsoids for Continental, Mediterranean and Atlantic zones.

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