TRansition paths to sUstainable
legume-based systems in Europe

The Environmental Assessment of Diets

Work Package: 5

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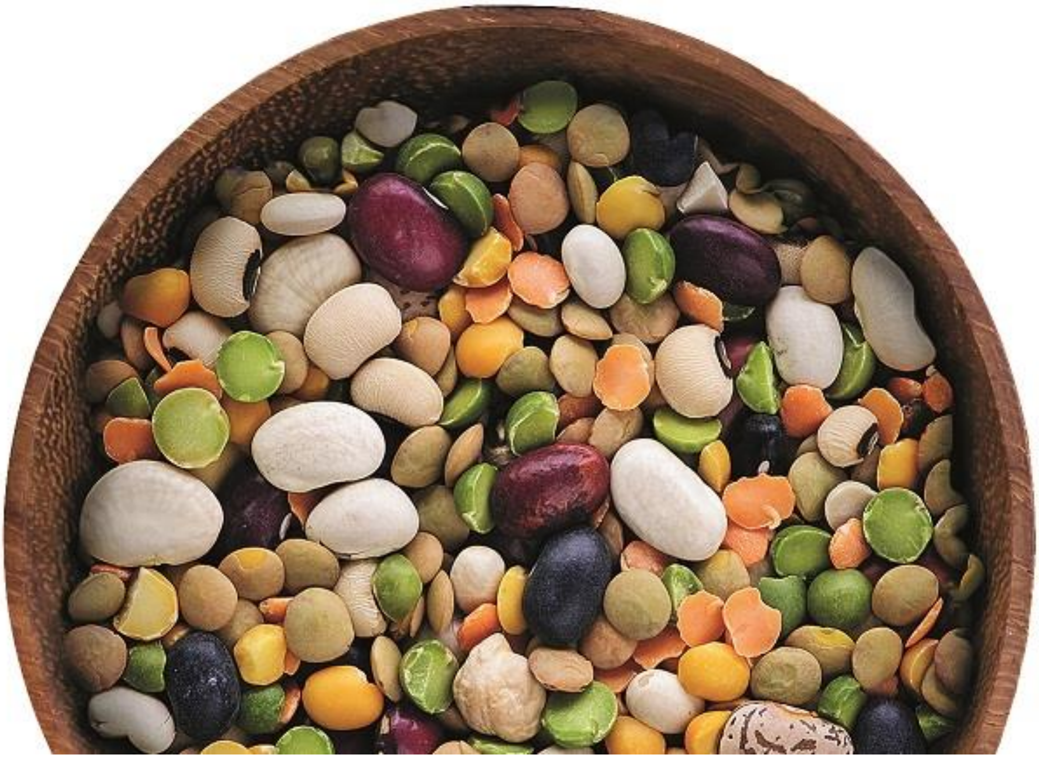

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- **Deliverable Description**

This report, ‘Environmental Assessment of Diets’, presents both an analysis of global dietary change since the 1960s as a function of income, focussing on macronutrient intake (energy, carbohydrate, protein and fat), and a more detailed environmental and nutrient density assessment of the present-day European diet. Particular emphasis is placed on the role of legumes in reducing CO_2e emissions and gPO_4^{3-} release associated with diet. The report ends with a nutritional and environmental comparison of the European diet with the recently launched EAT Lancet Commission reference diet.

- **Contributors**

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- **Key words**

- Legume; Diet; Global Warming Potential; Eutrophication Potential; Nutrient Density.

Contents

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List of Figures

List of Tables

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Executive Summary

Global diets have changed considerably since the 1960s – for a majority of countries studied, more calories are being consumed per person, and the proportion of fat and animal protein consumed has increased significantly with wealth. In contrast, the consumption of plant protein has remained static with increasing GDP. This has led to a marked decline in the healthiness of diets as personal wealth increases, as measured by the Mediterranean Diet Index. Increased cultivation and consumption of legumes can play a central role in limiting the environmental burden of diet, whilst at the same time, improving nutrition. **(section 3.1)**

Environmental assessment of food groups

Farmgate Global Warming Potential (GWP) and Eutrophication Potential (EP) data were obtained for up to 60 separate food items, incorporating up to 1364 separate values, and arranged according to the EAT Lancet Commission reference diet categories. Both in terms of per weight and per kcal units, CO_2e scores were lowest for the legume (***Soy Foods***, and ***Dried Beans, Lentils, Peas***) and ***All Sweeteners*** categories (<0.06kg CO_2e 100kcals^{-1}; <0.2 kgCO_2e 100g^{-1}) and highest for the ***Beef & Lamb***, category (>0.8kg CO_2e 100kcals^{-1}; >2 kg CO_2e 100g^{-1}). Both the ***Fish*** and ***Chicken & Other Poultry*** categories, which scored high for nutrient density, also scored high for GWP. Animal-based food items grouped almost exclusively within the very high (>0.8 kg CO_2e 100kcals^{-1}; >2 kg CO_2e 100g^{-1}), and medium to high (0.16-0.42 kg CO_2e 100kcals^{-1}; 0.24-1.5 kg CO_2e 100g^{-1}) emission ranges.

Farmgate EP data was more limited than GWP data, where only 22 food items were used in the assessment, although incorporating 157 separate values. Again, grouping food items according to the EAT reference diet categories highlights the importance of plant protein in sustainable diets. The categories ***Fish*** (dominated by the farmed fish sector), and ***Beef & Lamb*** produced the highest EP values (>3 gPO_4^{3-}e 100kcal^{-1}; >8 gPO_4^{3-}e 100g^{-1}), whilst with the exception of dairy, all low EP values (<1 gPO43- 100kcal; 100g-1) were associated with plant categories. The two legume categories ***Dried Beans, Lentils, Peas***, and ***Peanuts*** were associated with the lowest EP values (< 0.5gPO_4^{3-} 100kcal^{-1}; 100g^{-1}). **(section 3.2)**

Nutrient assessment of food groups

Individual food items were scored for nutrient density using three Nutrient Density Indices (NDIs) of differing nutrient profiles (Nutrient Density Index, NDU; Sustainable Nutrient Rich Foods, SNRF; and, Nutrient Rich Foods, NRF12:3). All three indices scored vegetables, fruit and legumes higher than red meat and dairy products. Fish and poultry scored high for two of the NDIs used.

Grouping food items according to the EAT Lancet Commission reference diet categories, highlights the importance of legumes (***Soy Foods***, ***Dried Beans, Peas & Lentils***) in providing higher nutrient densities than other major sources of protein, with the exception of the ***Chicken & Other Poultry***, and ***Fish*** categories. ***Whole Grains***, ***Beef & Lamb***, and the vegetable oil groupings ***Unsaturated Oils***, and ***Palm oil***, score the lowest of the food groups in terms of nutritional density. **(section 3.3)**

Environmental Impact per nutrient unit – a useful measure of sustainability for food production pathways

Environmental and nutritional aspects to diet assessment are inter-linked – environmental burden being associated with food production and nutrient status with suitability of the final product. Function units which incorporate environmental and nutritional aspects may play an important role in informing customers on dietary choice and the sustainability of food products. Both GWP and EP scores were expressed per NDU and the final values grouped according to the EAT reference diet categories. Here, high scores mean a high environmental burden per unit of nutrient density, and conversely, low scores indicate high sustainability of the food item in question. In the case of the GWP NDU^{-1} scores, the range of values obtained further highlight the unsuitability of red meat, farmed fish and dairy produce as sources of protein and fat in sustainable diets. ***Peanuts***, ***Dry Beans, Lentils, Peas*** and ***Soy Foods*** have the lowest values overall (0.023 $kgCO_2e\ NDU^{-1}$), whilst at the other extreme, the highest values (>0.44 $kgCO_2e\ NDU^{-1}$) were solely for red meat, animal fats, sweeteners and dairy.

This pattern is repeated for the EP NDU^{-1} scores. Again, legume categories are in the low value range (<0.21 $gPO_4^{3-}1\ NDU^{-1}$), and with the exception of the ***Whole Grains*** category, animal products are exclusively at the higher end of the spectrum (>3.87 $gPO_4^{3-}1\ NDU^{-1}$). As the major calorific component of the European diet (30.3% of total calories consumed), cereals provide both carbohydrate and protein. However, with regard to a diet high in plant products, a more sustainable mix of carbohydrate and protein intake is possible by inclusion of grain legumes. **(section 3.3)**

Calorific assessment of European diet in comparison to reference diet

The European diet scores poorly against the EAT Lancet commission reference diet. Overall, the calorific intake is 26% higher than recommended levels, with 80% of the total calorific intake associated with cereals, vegetable oils, sugar and sweeteners, meat, dairy and animal fats. Cereals make up the major component (30.3%). Legumes and nuts make up less than 2% of the daily energy intake, which is less than the daily energy obtained from alcoholic drinks. Slightly better would be the combined energy intake for vegetables and fruit, at just over 10%. In terms of reference diet categories, significant over consumption occurs for the following: ***Pork*** (+1000%), ***Beef & Lamb*** (+400%), ***Tubers or Starchy Vegetables*** (+290%), ***Sweeteners*** (+220%), ***Eggs*** (+160%), ***Dairy Foods***

(+150%) and ***Lard & Tallow*** (+126%), while significant underconsumption occurs for nuts and legumes in general: ***Tree Nuts*** (-84%), ***Dry Beans, Lentils, Peas*** (-86%), ***Peanuts*** (-91%), and ***Soy Foods*** (-99%). **(section 3.2)**

Environmental assessment of European diet in comparison to reference diet

Adoption of the EAT Lancet commission reference diet can reduce per capita diet emissions of CO_2e by 50%, and per capita diet EP scores for PO_4^{3-} leaching by a minimum of 47%, primarily by significant reductions in consumption of red meat and dairy, and with significant increases in the proportion of plant protein in the diet. In terms of the overall extra kilocalories consumed, then this accounts for both an extra 153g CO_2e and 1.55g PO_4^{3-}e per person per day.

However, in terms of individual categories ***Dairy***, ***Beef & Lamb***, and ***Pork*** categories represent over 87% of the total increase in GWP for the European diet of 1.634 kgCO_2e capita^{-1} d^{-1}, and over 78% of the total increase in EP of 10.53 gPO_4^{3-}e. **(section 3.4)**

1. Introduction

1.1. Work Package 5 (Environment) objectives

The aim of this WP is to provide a coordinated Life Cycle Assessment (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 work package will answer the following overarching questions:

- what is the environmental footprint of animal feed & food produced from legumes, considering nutrient cycling and break-crop effects in legume-rotations across major EU agro-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 as follows.

- roduce a practical report outlining the LCA methodology 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. *This Report*
- 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.

1.2. Purpose of this Report

This report provides an overview of global dietary change since the 1960s and compares the present-day European diet with the EAT Lancet Commission reference diet, aimed to provide healthy nutrition but significantly reduce the environmental footprint of food production (Willett, 2019). Using an extensive dataset of farmgate GWP and EP values from peer-reviewed literature, we present both an environmental and nutritional assessment of food items/food groups and diet, highlight the importance of plant protein in sustainable diets, and present a useful functional unit

for Life Cycle Assessment studies incorporating environmental impacts scored per nutrient density unit.

1.3. Context for the environmental and nutritional 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 C storage (Godfray *et al.,* 2010). Major challenges to the sustainability and resilience of EU food production include: (i) dependence on resource use including energy, water, fertilisers, animal feed and food; (ii) low nutrient use efficiency (NUE) & associated nutrient pollution; (iii) high levels of greenhouse gas emissions; and (iv) soil degradation (Poore and Nemececk 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 EAT-Lancet commission, for instance, urges a transformation of global food systems to focus on the production of healthy foods from sustainable systems, stating in its 2019 report, that unhealthy diets pose a greater risk to morbidity and mortality than unsafe sex, alcohol and drug abuse, and tobacco combined (Willett *et al.,* 2019). 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 had increased to over 10 million. Present day numbers are approx. 820 million, (FAO, 2018). In contrast, over 2 billion people consume unhealthy, high-calorie diets leading to an ‘epidemic’ of obesity with an extra 1 million deaths and 12 million life-years of illness each year (Burkert *et al.,* 2013), a doubling in the incidence of diabetes (WHO, 2016), and a projected increase of 90% in the occurrence of colon cancer in people aged 20-34 (Bailey *et al.,* 2015).

Evaluating the sustainability of food systems requires both a calculation of the environmental burden of a food group/product and its nutritional value, accomplished through an adjusted LCA using health-based functional units (Heller *et al.,* 2013). Studies regarding the quantitative measurement of the nutrient density of foods have seen many such indices proposed and evaluated (Guenther *et al.,* 2008; Drewnowski, 2009, 2010; Drewnowski and Fulgoni, 2008, 2009), but only recently have they been considered for use as a functional unit in LCA to link the health and environmental implications of diet and food choice (Smedman *et al.,* 2010; Arsenault *et al.,* 2012; Van Dooren *et al.,* 2016; Saarinen *et al.,* 2017).

1.4. Context for considering legumes as a key component of a sustainable diet

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 glycemic 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 approx. 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/, Leinonen *et al.,* 2019).

While grain legumes have relatively low concentrations of the essential amino acids methionine, tryptophan, lysine and cysteine (De Lumen, Becker and Reyes, 1986; Iqbal *et al.,* 2006; Loehn, Pencharz and Ball, 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 atmospheric nitrogen (N_2)-fixing bacteria within their root tissue can effectively reduce the need for N-fertilizer 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 N_2O by virtue of a reduced requirement for N fertilizer

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 (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 fertilizer manufacture, provide illustrative data on the extent of GHG savings possible through reduced fertilizer production. Depending on the type of N-fertilizer, 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-fertilizer 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 × 10^7 hectares (FAO, 2020), represents only 13% of that for cereals. Foyer *et al.,* (2016) argue that globally, grain legume production lags behind 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 report compares the environmental burden of our present European diet with that of the EAT Lancet Commission reference diet (Willett *et al.,* 2019), using a data base of farm gate Global Warming Potential and Eutrophication Potential values developed in TRUE.

The EAT-Lancet Commission reference diet has been designed to both optimize 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

2.1. Patterns in Dietary Intake

For this study food supply was used as a proxy for per capita consumption. Food supply data in terms of total kcal capita^{-1} d^{-1}, and fat and protein supply in g capita^{-1} d^{-1} was gathered from FAO food balance sheets (http://www.fao.org/faostat/en/#data/FBSH) for 84 countries listed in Table 3.1. Countries were classified into regions following the United Nations geoscheme (UNSD, 2017). FAO food balance data is provided on an annual basis, from 1961 to 2013, and listed at a country level scale for most countries in the world. More recent data is available, but uses a different methodology, so the years 1961 to 2013 were used throughout in this study.

The energy supply from protein, fats, and carbohydrates was calculated using the method applied by Gerbens-Leenes *et al.,* (2010). The fat and protein supply in g capita^{-1} d^{-1} were multiplied by their energy densities; 9 kcal g^{-1} and 4 kcal g^{-1}, respectively. The sum of these values was subtracted from the total energy supply to calculate the energy supply from carbohydrates alone.

Economic data was gathered from the World Bank:
(https://databank.worldbank.org/reports.aspx?source=2&series=NY.GDP.PCAP.KD&country)

GDP per capita in constant 2010 US dollars was used as a measure of wealth. GDP based on purchasing power parity (PPP) would be a preferable measure because it takes into account the relative costs of goods and services in a country, but this data was only available after 1990. Desiere *et al.* (2018) performed somewhat similar analysis for Sub-Saharan Africa and found that their results were similar when using either PPP or constant US dollars.

Linear regressions were carried out for the log of the macronutrient energy supplies against the log of GDP/capita. The total energy, protein, and fat supplies were divided into their plant and animal components and similar linear regressions undertaken.

MAI scores were calculated following the method of Da Silva *et al.,* (2009). Because of ambiguities in their description, our calculations may not be identical. The MAI scores represent the daily energy derived from Mediterranean foods divided by the daily energy derived from non-Mediterranean foods.

2.2. 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 global warming and eutrophication potential 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 60 food types for global warming potential (kgCO$_2$e 100kcal^{-1}, and 100g^{-1}) and 22 for eutrophication potential (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 TRUE Deliverable 5.1 (D29) - Report on Life Cycle Assessment Methodology for Assessing the Environmental Sustainability of Legume Value Chains (Styles *et al.,* 2018).

2.3. Nutrient Density Indices

The following nutrient density indices were chosen for this study: Nutrient Rich Food Index (NRF) 12:3 (based on the NRF9:3 index of Drewnowski and Fulgoni, 2008, 2009, but with Zn and vitamin B12 added), Sustainable Nutrient Rich Food Index (SNRF) of van Dooren *et al.* (2017), Nutrient Density Unit (NDU) of van Dooren, (2016). Data requirements and daily reference intakes are given in Table 2.1. 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 GWP and EP data were available, as described in section 2.2, were chosen.

The NDU is based on the nutrient content of a product per 100g, and is an additive index composed of the sum of three macronutrients (protein, essential fatty acids and dietary fibre), each divided by their dietary reference intake value (DRV) to give nutrients as a fraction of daily recommended values. Values were capped at 1 for each nutrient to prevent disproportionate weighting of a single nutrient biasing the index score.

Recommended intake values are based on the recommendations of the USDA and Department of Health and Human Services (HHS, 2015), and the Institute of Medicine DRI (IOM, 2005). The denominator in terms of the energy content as a fraction of 2000 kcal, was then multiplied by three, to average the daily values to give an energy weighted score.

$$NDU = \frac{\left(\frac{g\ Essential\ Fatty\ Acids}{12.4\ g}\right) + \left(\frac{g\ Protein}{50\ g}\right) + \left(\frac{g\ Fibre}{25\ g}\right)}{3 \times \left(\frac{kcal\ Energy}{2000\ kcal}\right)}$$

The SNRF is related to the NDU but includes negative nutrients to limit. It is designed to highlight the importance of plant protein in a sustainable diet, and so in its calculation the protein value for non-

plant-based foods, such as meat and fish, is set to zero. The nutrients to limit were divided by their Acceptable Dietary Intake (ADV) values (HHS, 2015), values being capped at 1, as for NDU. As the nutrient data obtained was for raw foods, the value for added sugar was also set to zero.

$$SNRF = \frac{\left(\frac{g\,E.F.A.}{12.4\,g} - \frac{g\,S.F.A.}{20\,g}\right) + \left(\frac{g\,Plant\,Protein}{50\,g} - \frac{g\,Na}{2.4\,g}\right) + \left(\frac{g\,Fibre}{25\,g} - \frac{g\,Added\,Sugar}{50\,g}\right)}{3 \times \left(\frac{kcal\,Energy}{2000\,kcal}\right)}$$

The NRF 12:3 index uses 12 positive nutrients to encourage, and 3 nutrients to limit (Table 1). Each nutrient was divided by its DRV/ADV, and the score calculated as the sum of nutrients to encourage, minus the sum of nutrients to limit. This was then divided by the energy density (kcals per 100g/ 2000) multiplied by 12, to average the daily values for nutrients to encourage to give an energy weighted score. The equations used in the calculation of the NRF12:3 are shown in Table 2.

Table 1: Nutrient requirements for NRF12:3, SNRF and NDU nutrient density indices.

	Nutrient	**Daily Reference Intake/Acceptable Daily Intake**	**NDU**	**SNRF**	**NRF12:3**
Macro-nutrients	Protein	50 g	√	√ (plant based)	√
	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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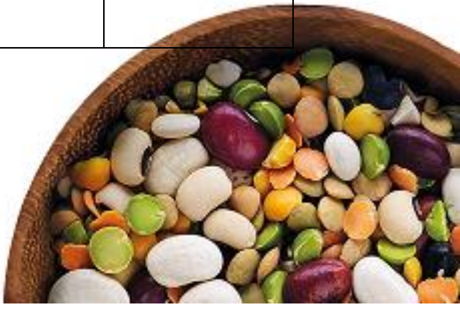

Table 2: Calculation of NRF12:3 density index

Model	**Algorithm**	**Notes**
NRF 12:3 sub-score		
NRF 12:3$_{100g}$	$\sum_{1-9}(nutrient_i/DV_i)$	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)	

The NDU was compared to the more nutrient-inclusive NRF12:3 by regression of log$_{10}$ values of all food items studied.

3. Results and Discussion

3.1. Global Patterns in Dietary Intake

Calorific intake, macronutrient intake, and animal and plant protein consumption have been calculated as a function of gross domestic product per capita for 84 countries shown in Table 3. To show trends with time, mean data from 1961- 1965, and 2009-2013 were plotted separately.

3.1.1. Calorific intake per capita increases with GDP

Figure 1 illustrates a global trend in total calorie consumption consistent for the 1960s and 2010s, where increasing GDP is translated into a higher daily calorific intake per capita for each time period. Here, although the recommended calorific intake per capita per day will vary dependent upon age, metabolism and physical activity, reasonable threshold levels are 2000 kcals a day for women and 2500 kcals a day for men. In our calculations, and consistent with the EAT-Lancet commission report, we use the 2500 kcal value. As can be seen in Figure 3.1, the proportion of countries on 1.5$ capita^{-1} day^{-1}, decreased from 18% for 1961-1965, to 6% for 2009-2013. This decrease in countries below the poverty level is reflected in an increase in calorific intake per capita. Here the proportion of countries with a mean calorific intake equal to or above the recommended threshold level has increased from 31% for 1961-1965, to 75% for 2009-2013. This increase in calorific intake though, is made up entirely of fat and protein.

3.1.2. Fat and protein intake per capita increase with GDP, but not carbohydrate intake

Figure 2 illustrates a global trend in macronutrient intake consistent for the two time periods shown – as GDP per capita increases, so does fat and protein intake, fat intake showing the highest rate of increase for both the 1961-1965, and 2009-2013 time periods. Carbohydrate intake hardly changes with GDP for both time periods. Low income countries (GDP below 1.5$ d^{-1}), derive nutritional energy mainly from carbohydrates, whereas higher income countries derive nutritional energy mainly from carbohydrates and fat. This agrees with findings of Gerbens-Leenes *et al.* (2010), although they used a far smaller data set and looked at 2001 data only. Our study also highlights an increase in protein intake with GDP.

Protein intake illustrates a trend towards over-consumption in developed countries. Recommended protein intake values per capita per day depend upon body weight, being approx. 0.8g protein per kilogram body weight (Willett *et al.,* 2019). Assuming an average body weight of 80kg, then this would give a minimum protein intake of approx. 65g per capita per day. As countries increase their GDP, then over-consumption of protein has increased. Between the years 1961-1965, only 33% of the countries in our data set had per capita protein intake values equal to, or greater than 65g per day, but between the years 2009 and 2013, this number of countries nearly doubled to 60%. This increase in protein intake though, is made up entirely of animal protein.

3.1.3. Animal protein intake increases with GDP, but not plant protein intake

Figure 3 illustrates a global trend in protein intake consistent for the two time periods shown – as GDP per capita increases, so does animal protein, plant protein intake hardly changing at all. Dietary patterns are consistent – increasing affluence increases both calorific intake, but more importantly a dietary shift with income is reflected not only in a marked increase in fat intake, but animal protein too, plant protein consumption showing a downward trend with GDP for 2009-2013.

Observations that dietary patterns change with wealth are not new. Bennett's Law is the observation that a higher portion of the energy intake of low-income people comes from cereals and starchy roots, and as incomes increase, people tend to eat more diverse diets (Bennett, 1941). How food consumption changes with income can be expressed by income elasticity, which describes the percentage change in demand for a good or service with a 1% increase in income. Products which have income elasticities less than 1 can be said to be necessities, because as income increases a lower proportion of income is spent on that product. Goods that have income elasticities greater than 1 can be said to be luxury goods, as they make up a larger proportion of expenditure as income increases. Of the macronutrients, carbohydrates had the lowest income elasticity. It was 0.034 in 1961-1965, but in 2009-13 it was very slightly negative and not statistically significant. Protein had a higher income elasticity of 0.153 in 1961-1965 and 0.136 in 2009-2013. Fats had the highest elasticity of 0.31 in 1961-1965 and 0.25 in 2009-2013.

The implications of this dietary change with GDP is that the 'healthiness' of global diets are changing too. Dietary energy supply is increasing as GDP increases, but with a shift to animal fats (data not shown) and protein. As more people adopt diets of increasingly high animal product, added fats, and added sugar content, the global health burden of overweight, obesity, and non-communicable diseases such as type-2 diabetes, cardiovascular disease, and cancers will increase.

3.1.4. Mediterranean Adequacy Index (MAI) decreases with GDP

One way to highlight the decrease in 'healthiness' of global diets is to plot the Mediterranean Adequacy Index (MAI) against GDP, this index having been developed to assess simply how close a nation's diet is to the Healthy Reference National Mediterranean diet (HRNMD), a healthful diet in which Mediterranean food patterns are inversely correlated with prevalence of risk factors to chronic disease (Da Silva *et al.,* 2009; Estruch *et al.,* 2013; Song *et al.,* 2016). In short, the MAI is the ratio of energy (kcal capita^{-1} d^{-1}) arising from Mediterranean food groups, divided by the ratio of energy (kcal capita^{-1} d^{-1}) arising from non-Mediterranean groups, eggs and dairy excluded (Da Silva *et al.,* 2009).

Figure 4 illustrates $\log_{10}$ MAI plotted against $\log_{10}$ GDP for the 84 countries, using 2009-2013 food balance data, and accepting religious and regional differences in food consumption and supply, shows a statistically significant (P<0.01), and marked decrease in the 'healthiness' of diets as income

increases. The gradient of this correlation is less than that for 1961-1965 data (-0.47 for 1961-1965, -0.35 for 2009-2013), presumably reflecting the overall increase in GDP for the majority of the 84 countries studied.

Table 3: List of countries and regions used in dietary intake analysis

Africa	**Asia**	**Europe**	**Latin America and the Caribbean**	**North America**	**Oceania**
Benin	Bangladesh	Austria	Argentina	Bermuda	Australia
Botswana	China, Hong Kong	Denmark	Bahamas	Canada	Fiji
Burkina Faso	China, mainland	Finland	Belize	USA	
Cameroon	India	France	Bolivia		
Central African Republic	Indonesia	Greece	Brazil		
Chad	Iran	Iceland	Chile		
Congo	Israel	Italy	Colombia		
Côte d'Ivoire	Japan	Netherlands	Costa Rica		
Egypt	Malaysia	Norway	Dominican Republic		
Gabon	Myanmar	Portugal	Ecuador		
Ghana	Nepal	Spain	Guatemala		
Kenya	Pakistan	Sweden	Guyana		
Lesotho	Philippines	UK	Haiti		
Madagascar	Republic of Korea		Honduras		
Malawi	Sri Lanka		Mexico		
Mauritania	Thailand		Nicaragua		
Niger	Turkey		Panama		
Nigeria			Paraguay		
Rwanda			Peru		
Senegal			Saint Vincent a. t. G.		
Sierra Leone			Suriname		
South Africa			Trinidad and Tobago		
Togo			Uruguay		
Zambia			Venezuela		
Zimbabwe					

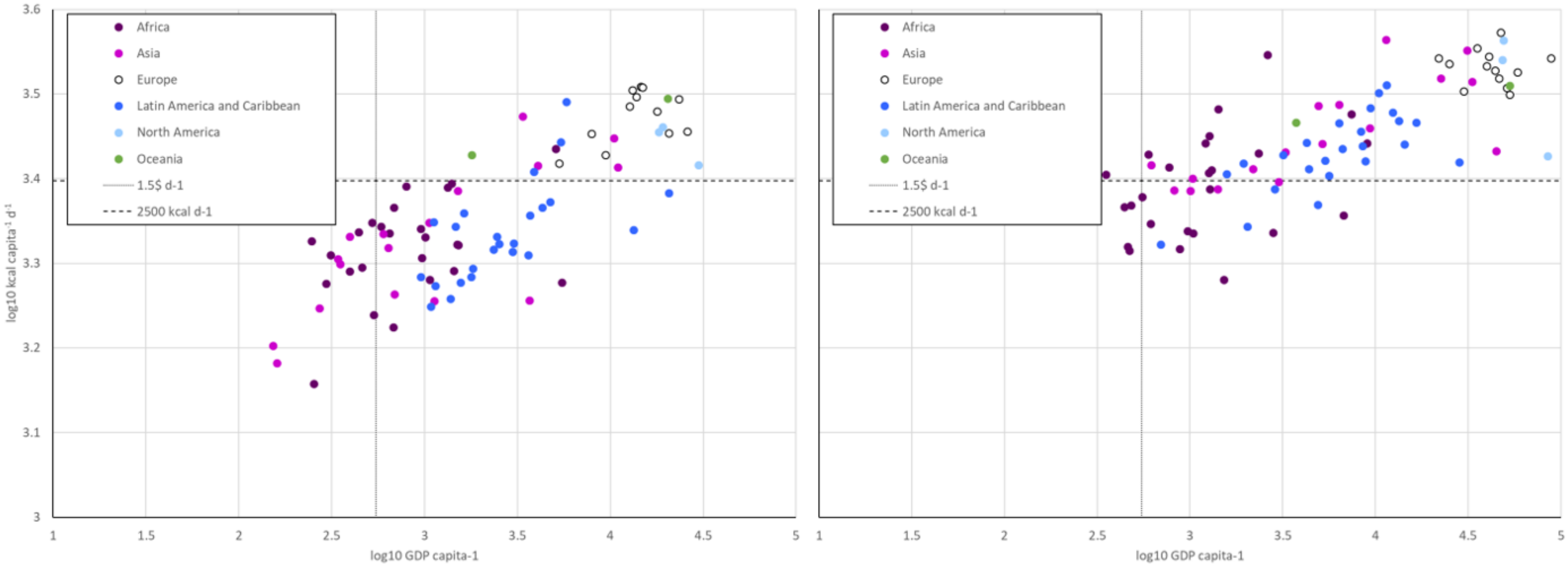

Figure 1. Calorific intake for 84 separate countries as a function of GDP. Left: 1961-1965; Right: 2009-2013.

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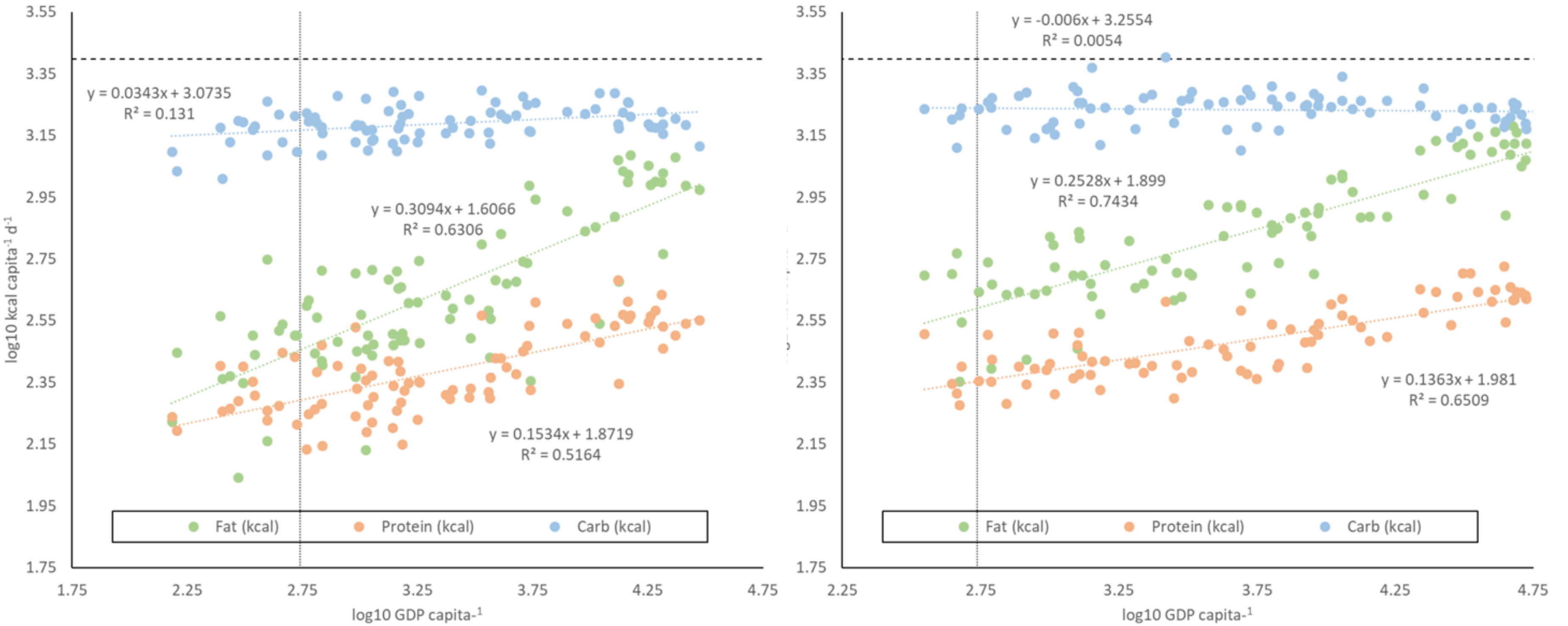

Figure 2. Macronutrient intake for 84 separate countries as a function of GDP. Left: 1961-1965; Right: 2009-20013.

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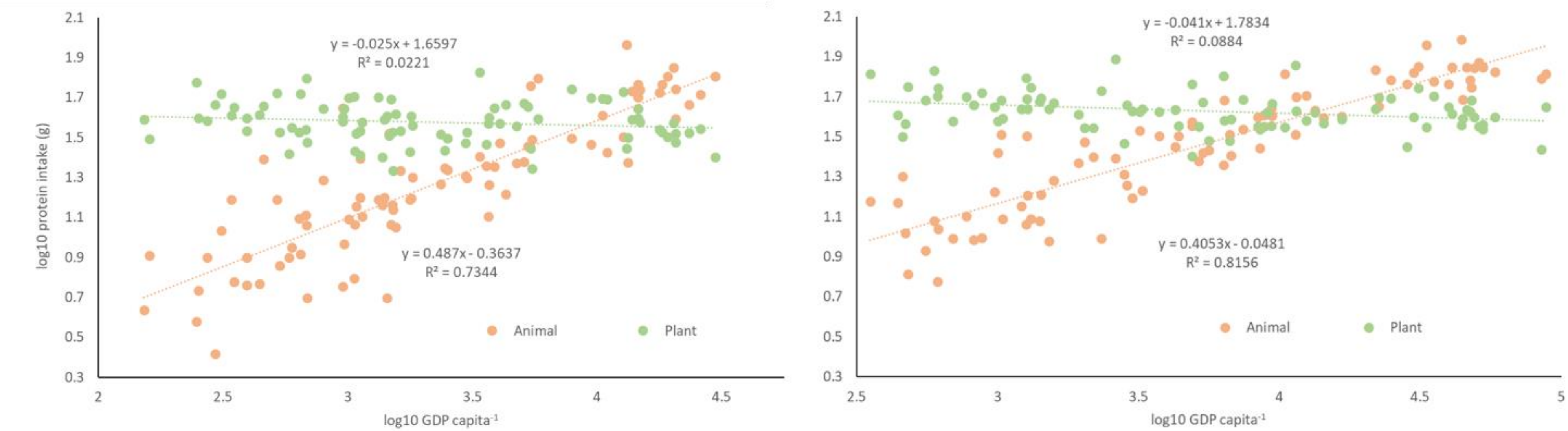

Figure 3. Protein intake for 84 separate countries as a function of GDP. Left: 1961-1965; Right: 2009-2013.

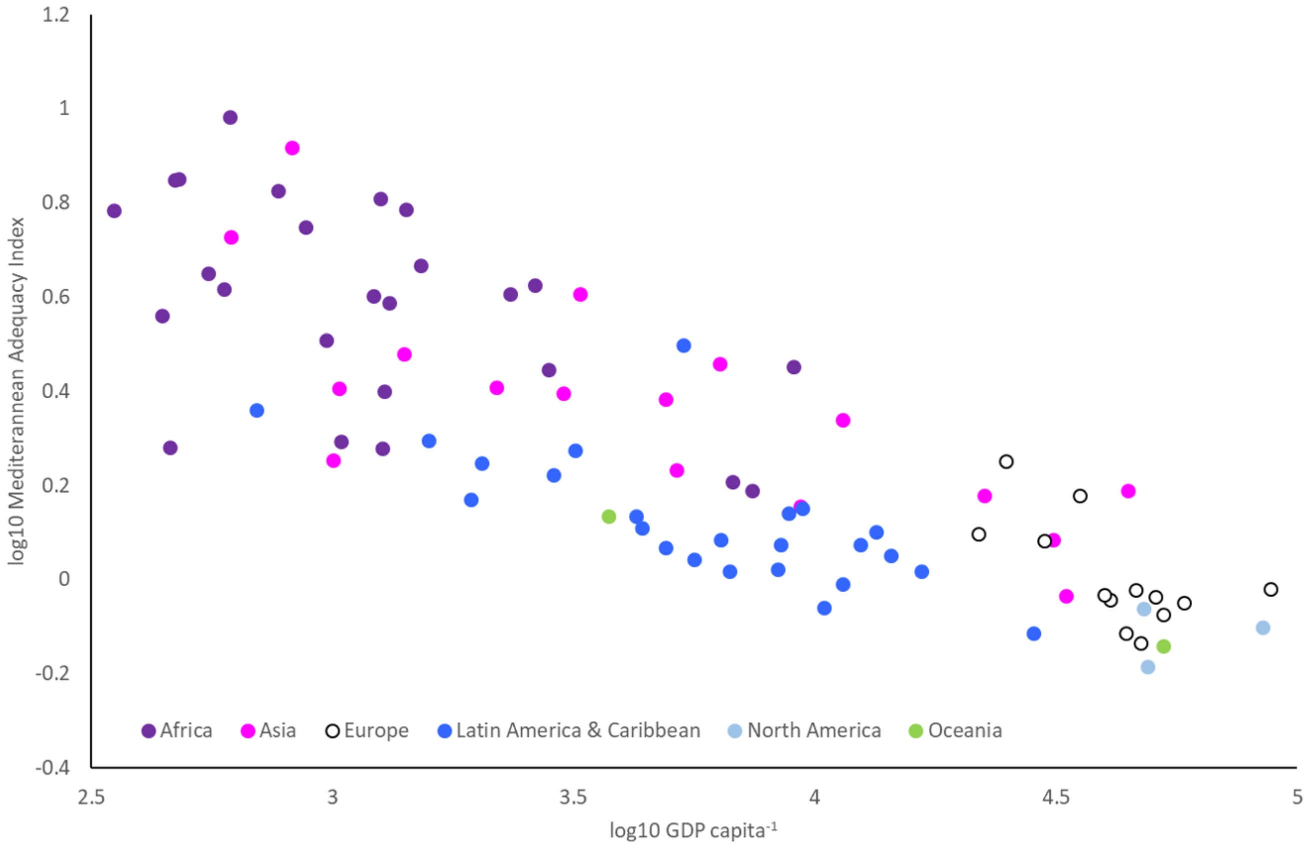

Figure 4. Mean Mediterranean Adequacy Index vs GDP for 84 countries (2009 to 2013).

3.1.5. *European Diet fails in terms of health in three major categories: total calorific intake, over-consumption of animal fats, and a marked under-consumption of grain legumes.*

The mean European diet in terms of kcals capita^{-1} d^{-1} was determined from FAO food balance data for 2009-2013 using the following FAO food groups: alcoholic drinks, cereals, dairy, eggs, fish, fish oil, fruit, meat, nuts, pulses, sugar & sweeteners, vegetables, and vegetable oils. The complete data table is illustrated in Table 4, with summary food group data arranged according to decreasing kcal intake d^{-1}, in Table 5.

Food balance data is not ideal, waste, gender or age are not accounted for, and commercial production statistics are used in the main, but while many studies have demonstrated discrepancies between food balance statistics and household survey data (Rodriguez-Artalejo *et al.,* 1996; Grünberger, 2014; Desiere *et al.,* 2018), its utility as an imperfect estimation of diet is generally accepted.

In terms of energy, the total calorific intake is high at 3153 kcal capita^{-1} d^{-1}, 80% of the total kcalorie intake is associated with cereals, vegetable oils, sugar and sweeteners, meat, dairy and animal fats, with cereals making up the major component (30.3%). Legumes and nuts make up less than 2% of the daily energy intake, which is less than the daily energy obtained from alcoholic drinks. A slightly more positive figure is the combined energy intake for vegetables and fruit, which sits at just over 10%.

Comparison with the EAT Lancet Commission reference diet, illustrates how unhealthy the mean European diet is. For this exercise, European data was divided up into a new set of food groups, concomitant with the EAT Lancet Commission study. Comparative data is illustrated in Table 6, and the differences between the two diets represented graphically in Figure 5.

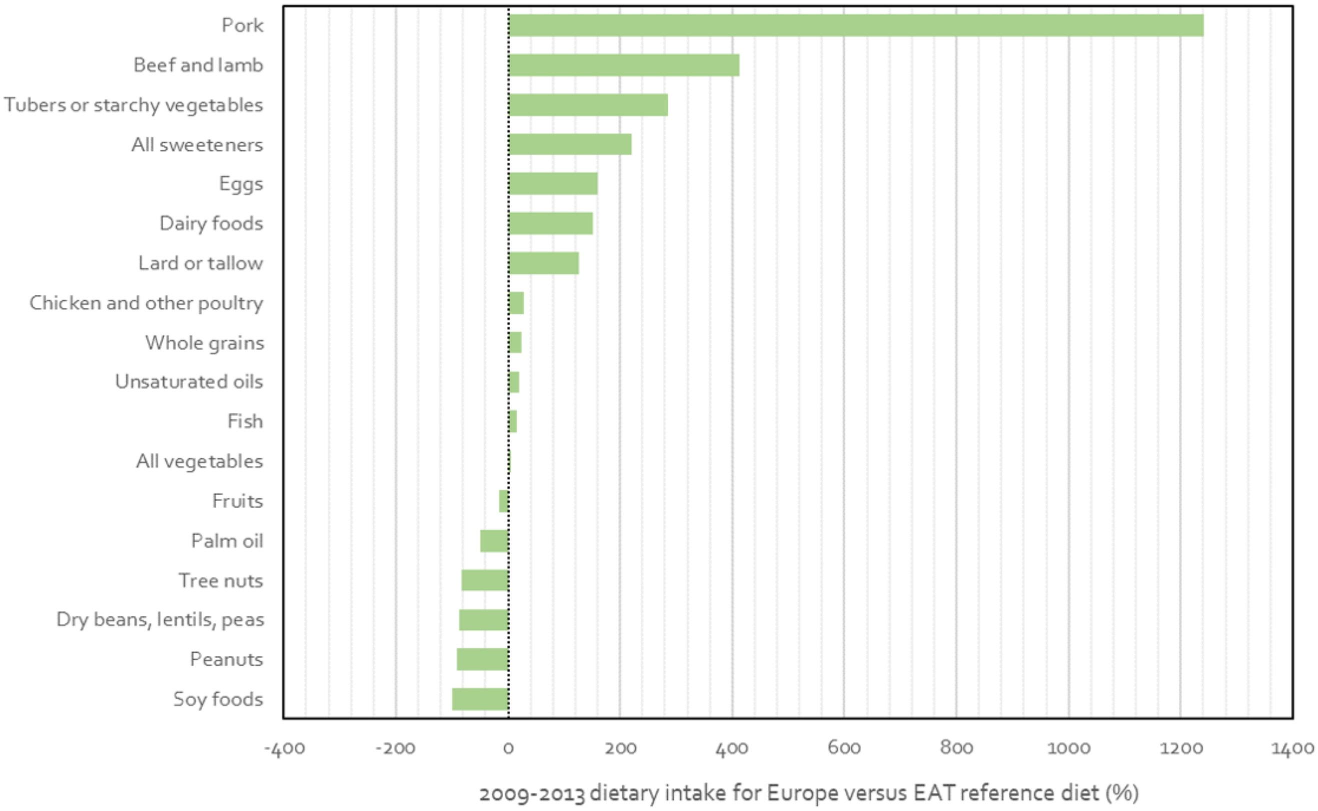

Figure 5. Comparison of mean European diet with the EAT Lancet Commission reference diet. Dotted line indicates reference diet values, European data expressed as a percentage of these.

As FAO balance sheets don't breakdown rice into white or brown rice, then the 'whole grain' food group for the European diet includes white rice. Similarly, with no breakdown listed of what offal or other meats are for FAO data, then these have been excluded, although would further increase the pork component. Important differences between the European and EAT reference diet are:

a) Too great a calorific intake at 3153 kcals capita^{-1} d^{-1}
b) Over consumption of animal fat and protein, in particular pork, beef, lamb, and dairy
c) Marked under consumption of protein crops (grain legumes).

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Table 4: European diet as determined from FAO Food Balance data for 2009-2013

Food Group	**Food Item**	**Kcals/capita/day**	
		Individual	**Total**
CEREALS	Wheat and Products	827.0	
	Rice (Milled Equivalent)	47.2	
	Barley and products	8.4	
	Maize and products	53.4	
	Rye and products	51.4	
	Oats	12.8	
	Millet and products	2.8	
	Cereals, other	4.6	1007.6
SUGAR AND SWEETENERS	Sugars and sweeteners	385.6	385.6
VEGETABLE OILS	Soybean Oil	68.2	
	Groundnut Oil	5.0	
	Sunflower Oil	162.2	
	Rape and Mustard Oil	67.4	
	Cottonseed Oil	1.0	
	Palmkernel Oil	2.4	
	Palm Oil	30.0	
	Coconut Oil	9.6	
	Sesameseed oil	1.0	
	Olive Oil	57.8	
	Maize Germ Oil	10.2	
	Oilcrops, other	11.2	426.0
MEAT	Bovine meat	64.8	
	Mutton and Goat meat	12.2	
	Pigmeat	186.2	
	Poultry Meat	79.2	
	Meat, other	7.8	
	Offal, edible	11.4	361.6
DAIRY	Milk, excluding butter	305.4	
	Cream	18.0	323.4
VEGETABLES	Potatoes and products	150.6	
	Tomatoes and products	14.4	
	Onions	11.0	
	Vegetables, other	56.0	232
ALCOHOLIC DRINK	Wine	36.2	
	Beer	90.2	
	Beverages, fermented	2.0	
	Beverages, alcoholic	45.0	173.4

ANIMAL FATS	Butter, Ghee	62.8	144.0
	Animal fats raw	81.2	
FRUIT	Oranges and mandarins	16.6	105.0
	Lemons, Limes and products	1.0	
	Grapefruit	1.0	
	Bananas	13.4	
	Plantains	0.6	
	Apples and products	21.0	
	Pineapple and products	3.0	
	Dates	1.0	
	Grapes	13.6	
	Fruits, other	33.8	
EGGS	Eggs	49.4	49.4
FISH	Freshwater fish	7.2	46.6
	Demersal Fish	16.8	
	Pelagic Fish	16.6	
	Marine Fish, other	1.0	
	Crustaceans	2.0	
	Cephalopods	2.0	
	Molluscs	1.0	
PULSES	Beans	6.0	36.8
	Peas	11.0	
	Pulses, other	6.4	
	Groundnut	12.2	
	Soyabean	1.2	
NUTS	Nuts	24.2	24.2
FISH OIL	Fish, Body Oil	1.0	1.0

Table 5: Contribution of major food groups to the mean European diet

Food Group	kcals/capita/day	% contribution
CEREALS	1007.6	30.38
VEGETABLE OILS	426.0	12.84
SUGARS AND SWEETENERS	385.6	11.63
MEAT	361.6	10.90
DAIRY	323.4	9.75
VEGETABLES	232.0	7.0
ALCOHOLIC DRINK	173.4	5.23
ANIMAL FATS	144.0	4.34
FRUIT	105.0	3.17
EGGS	49.4	1.49
FISH	46.6	1.41
PULSES	36.8	1.11
NUTS	24.2	0.73
FISH OIL	1.0	0.03
TOTAL	**3316.6**	**100.0**

Table 6: Comparison of the EAT Lancet Commission reference diet with the mean European diet calculated from FAO food balance data for 2009-2013

Food Groups	**EAT reference diet**	**European diet**
	kcals/capita/day	**kcals/capita/day**
Whole grains	811	1007.6
Tubers or starchy vegetables	39	150.6
All vegetables	78	81.4
Fruits	126	105.0
Dairy foods	153	386.2
Beef and lamb	15	77.0
Pork	15	186.2
Chicken and other poultry	62	79.2
Eggs	19	49.4
Fish	40	46.6
Dry beans, lentils, peas	172	23.4
Soy foods	112	1.2
Peanuts	142	12.2
Tree nuts	149	24.2
Palm oil	60	30.0
Unsaturated oils	354	426.0
Lard or tallow	36	81.2
All sweeteners	120	385.6
TOTAL	**2503**	**3153.0**

3.2. Environmental Assessment of European and EAT Reference diets

Having defined global patterns in dietary intake since the 1960s, and constructed a baseline European diet for comparison with the EAT Lancet Commission reference diet, the following sections of the report cover the environmental assessment of both diets in terms of global warming potential (kgCO$_2$ e per 100g/100kcals) and eutrophication potential (gPO$_4^{3-}$ per 100g/100kcals).

3.2.1. Global Warming Potentials (GWP) for animal and fish products are consistently high when compared to plant sources of protein and fat.

A comprehensive survey of peer-reviewed literature produced farm gate data for CO$_2$e emissions for 60 food types, incorporating 1364 separate values (Tables 10 and 11). Graphed data for individual food items are given in Figures 6 and 7 for GWP 100kcal^{-1} and GWP 100g^{-1}, and in Figure 8 for GWP of EAT reference diet food categories. A large variation in GWP exists between the 60 individual food items, ranging from 0.008 to 2.82 kg CO$_2$e where GWP is expressed on a per unit weight basis, and from 0.002 to 0.984 kg CO$_2$e when expressed per unit of energy (Figures 6 and 7). As this report concerns diet and dietary choice, per 100kcals is the preferred functional unit. With regard to the EAT reference diet food categories, three emission groupings are clear for the per 100kcals values (Figure 8); very high (>0.23 kgCO$_2$e), medium to high (0.02–0.23 kgCO$_2$e) and low (<0.02kg CO$_2$e 100kcals^{-1}). With the exception of the category ***Vegetables***, then the very high emissions grouping is made up exclusively of animal-based products. ***Dried Beans, Lentils, Peas***, and ***Soy Foods*** categories represent the lowest CO$_2$e emissions other than ***All Sweeteners*** (Figure 8).

Similar emission groups exist for EAT food categories when expressed on a per unit weight basis, very high (>0.49 kg CO$_2$e) medium to high (0.03-0.49 kg CO2) and low (<0.03 kg CO$_2$e), save that the ***All Vegetables*** category is now included in the medium to high emission grouping (Figure 8).

Highest CO$_2$e emissions, from the ***Beef & Lamb***, and ***Chicken & Poultry*** categories are to be expected, and have been commented extensively in the literature (Tilman *et al.,* 2011; Heller *et al.,* 2013; Poore and Nemecek, 2018). High emissions from vegetables per unit energy are a function of their low calorific content, with greenhouse tomato production having the highest emissions in the ***All Vegetables*** category (Figures 6 and 7). Grain legume production represents a consistently low CO$_2$e food production pathway (Figure 8, Peoples *et al.,* 2017). White rice would be the least sustainable of cereals with regard to GWP, the CO$_2$e emissions for both per unit energy and per unit weight basis being a factor of ten higher than the other grain crops shown (Figures 6 and 7).

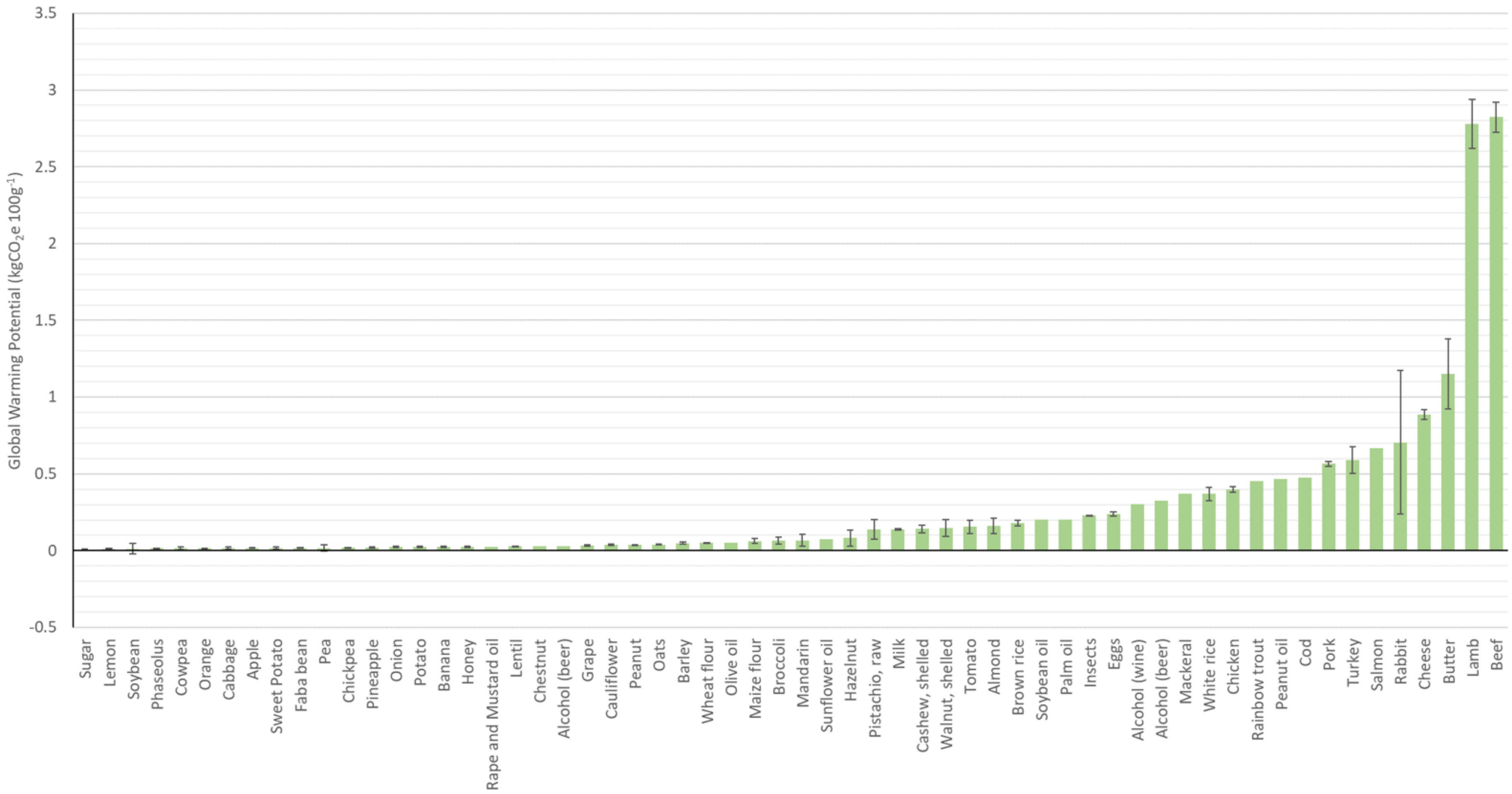

Figure 6. Farm gate Global Warming Potential values (kgCO$_2$e 100g^{-1}) for 60 individual food items. Each bar represents the mean ± standard error.

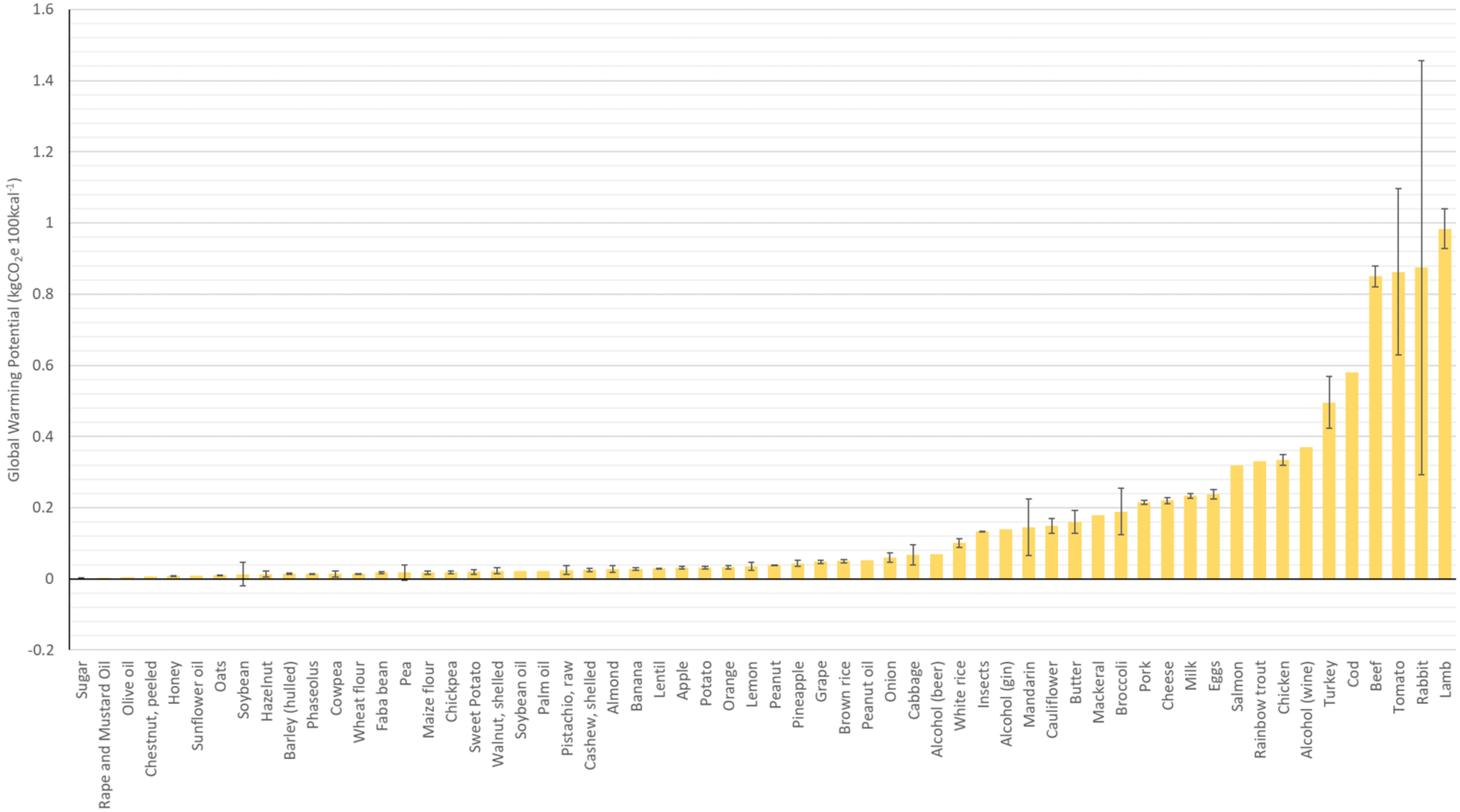

Figure 7. Farm gate Global Warming Potential values (kgCO$_2$e 100kcal^{-1}) for 60 individual food items. Each bar represents the mean ± standard error.

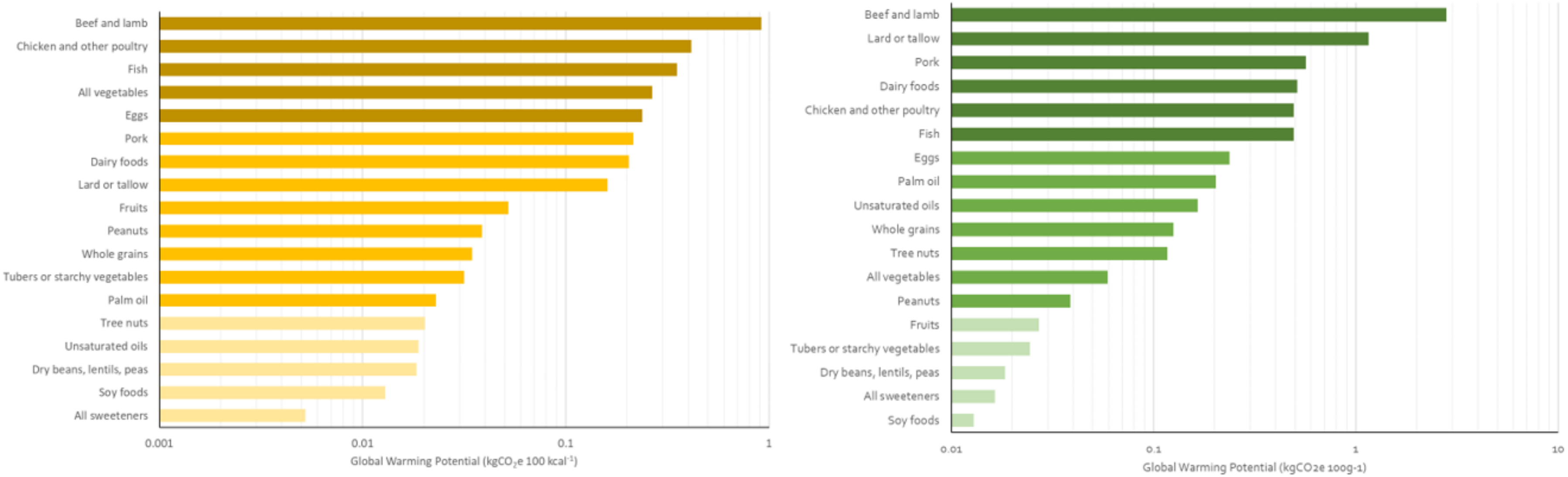

Figure 8. Farm gate Global Warming Potential values ($kgCO_2e$ $100kcal^{-1}$ and $100g^{-1}$) for EAT reference diet food categories. Dark bars indicate values >3rd quartile; light bars indicate values < 1st quartile.

3.2.2. Eutrophication Potentials (EP) for animal and fish products are consistently high when compared to plant sources of protein and fat.

As with section 3.2.1, comprehensive survey of peer-reviewed literature produced farm-gate data for PO_4^{3-}e leaching for 22 food types, incorporating 157 separate values (Table 12). Graphed data for individual food items are given in Figure 9 for EP $100kcal^{-1}$ and EP $100g^{-1}$, and in Figure 10 for EP of EAT reference diet food categories.

A large variation in EP exists ranging from 0.03 to 17.66 gPO_4^{3-}e $100kcal^{-1}$, and 0.13 to 17.13 gPO_4^{3-}e $100g^{-1}$ of food item (Figure 9). Unlike the GWP data, farmed fish production produces the highest impact, with EP values, significantly higher than beef or lamb. With the exception of white rice, all the high EP values (>2 gPO_4^{3-}e $100kcal^{-1}$ or $100g^{-1}$) were associated with animal products, whereas with the exception of mackerel and milk, all the low EP values (<2 gPO_4^{3-}e $100kcal^{-1}$ or $100g^{-1}$) were associated with plant products. Clearly, in terms of increasing the proportion of fish in a diet, farmed fish carry the highest eutrophication values, but mackerel, being net or line caught, are associated with significantly lower PO_4^{3-} equivalent values.

Grouping the food items according to EAT reference diet categories, give very high (>2.6 gPO_4^{3-}e $100kcal^{-1}$; > 5.1 gPO_4^{3-}e $100g^{-1}$), medium to high (0.13 – 2.6 gPO_4^{3-}e $100kcal^{-1}$; 0.42 – 5.1 gPO_4^{3-}e $100g^{-1}$) and low (<0.13 gPO_4^{3-}e $100kcal^{-1}$; <0.42 gPO_4^{3-}e $100g^{-1}$) EP scores (Figure 10), and further illustrate the orders of magnitude difference between ***Fish***, ***Beef & Lamb***, and the plant protein (***Dried Beans, Lentils, Peas***, and ***Peanut*** categories. Intensive production of soybean, however, with high inputs of reactive nitrogen into the soil (Jensen *et al.,* 2012; Peoples *et al.,* 2017, 2019), is also associated with medium to high EP values for the ***Soy Products*** category, albeit towards the lower value range.

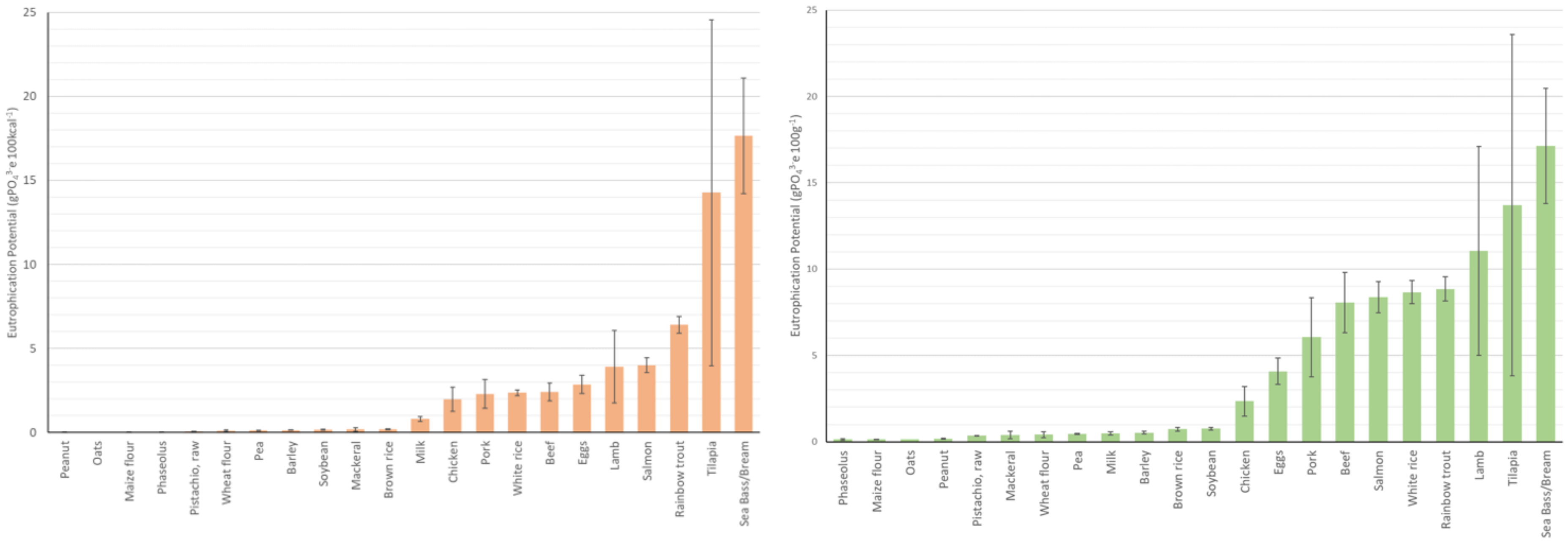

Figure 9. Farm gate Eutrophication Potential values (gPO$_4^{3-}$e 100kcal^{-1} and 100g^{-1}) for 22 individual food items. Each bar represents the mean ± standard error.

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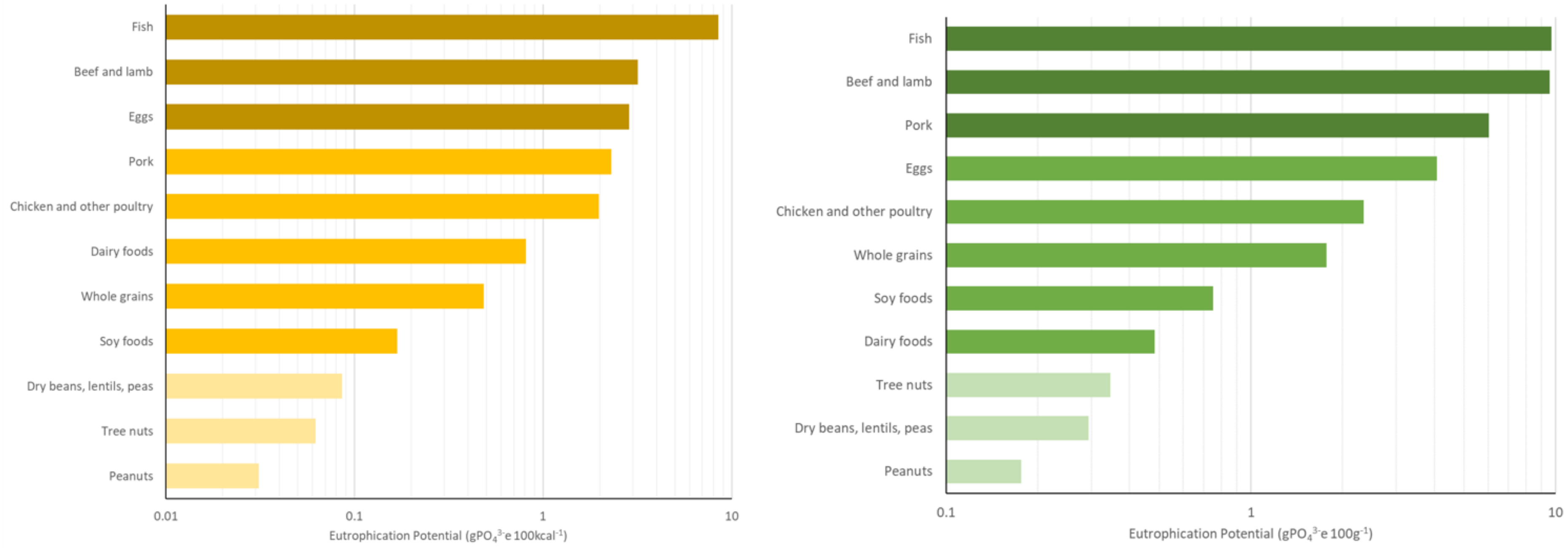

Figure 10. Farm gate Eutrophication Potential values ($gPO_4^{3-}e$ $100kcal^{-1}$ and $100g^{-1}$) for EAT reference diet food categories. Dark bars represent values >3rd quartile; light bars represent values < 1st quartile.

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3.3. Nutrient Density Indices

Nutrient Density Indices (NDI) are designed to rank foods based on their overall nutritional value and contribution to a daily diet. Foods which receive a higher index score are labelled as healthy, nutrient-dense foods, while those with a lower score indicate a lesser contribution to daily nutrition. NDIs, therefore, provide a measure of the "function" of a food, based on the assumption that the primary purpose of food is to supply nutrients (Heller *et al.,* 2013). In this study the NDU, NRF 12:3 and sNRF indices were calculated per 100g of raw food items using nutrient data obtained from the USDA database (see section 2.3). All indices were arranged according to increasing nutrient density. EAT Lancet Commission reference diet categories were used to calculate mean nutrient density indices in each case.

3.3.1. The Nutrient Density Unit achieves the best measure of nutrient status of a food item in terms of ease of calculation and data collection

Nutrient density indices for individual food items are given in Table 7 and graphed according to increasing density scores in Figures 11 to 13. Nutrient density indices for EAT reference diet food categories are illustrated in Figure 16.

Table 7: Comparison of Nutrient Density Indices for Individual Food Items

Food Group	**Food Item**	**NDU**	**NRF 12:3**	**SNRF**
CEREALS	Wheat flour (unenriched)	0.64	29.08	0.62
	Brown rice	0.67	56.25	0.62
	White rice	0.38	24.24	0.36
	Maize flour	1.08	66.15	1.02
	Oats	1.35	84.22	1.22
	Barley (hulled)	1.94	105.37	1.89
VEGETABLE OILS	Soybean oil	0.54	11.56	-0.05
	Peanut oil	0.75	21.83	0.12
	Sunflower oil	0.78	30.81	0.45
	Rape and Mustard Oil	0.75	7.94	0.32
	Palm oil	0.57	14.15	-0.19
	Olive oil	0.75	25.46	0.23
MEATS	Lamb	1.12	89.90	-0.92
	Pork	1.21	54.97	-0.70
	Chicken	2.90	157.83	0.10
	Turkey	3.13	176.11	0.27
	Beef	0.68	64.17	-1.08

	Rabbit	2.76	304.79	-0.11
DAIRY	Milk	0.90	132.32	-1.06
	Cheese	0.95	57.13	-2.04
VEGETABLES	Tomato	2.68	494.61	2.55
	Onion	1.52	142.58	1.46
	Broccoli	3.21	792.87	2.90
	Cabbage	3.39	541.72	3.14
	Cauliflower	3.26	657.63	2.75
	Potato	1.11	161.99	1.08
	Sweet Potato	1.18	273.80	1.00
ANIMAL FATS	Butter	0.24	6.52	-0.92
FRUIT	Orange	1.65	376.14	1.65
	Mandarin/Clementine	1.18	208.63	1.14
	Lemon	3.59	637.64	3.57
	Banana	0.99	100.62	0.94
	Apple	1.35	85.50	1.33
	Pineapple	0.93	269.18	0.92
	Grape	0.54	93.05	0.50
EGGS	Eggs	1.63	140.20	-0.54
FISH	Rainbow trout	2.68	278.08	0.20
	Cod	3.03	238.23	-0.10
	Mackeral	1.97	175.00	0.10
	Salmon	2.14	174.48	0.27
PULSES	Faba bean	3.07	174.02	3.04
	Pea	3.04	151.91	3.01
	Soybean	3.00	209.94	2.78
	Peanut	2.18	110.90	1.77
	Lentil	3.36	179.37	3.33
	Chickpea	2.38	142.77	2.31
	Cowpea	1.90	193.74	1.80
NUTS	Walnut, shelled	1.60	66.87	1.29
	Cashew, shelled	1.36	91.32	0.88
	Pistachio, raw	2.18	119.33	1.86
	Chestnut, peeled	0.41	60.85	0.31
	Hazelnut	1.41	98.42	1.17
	Almond	2.19	135.46	1.97

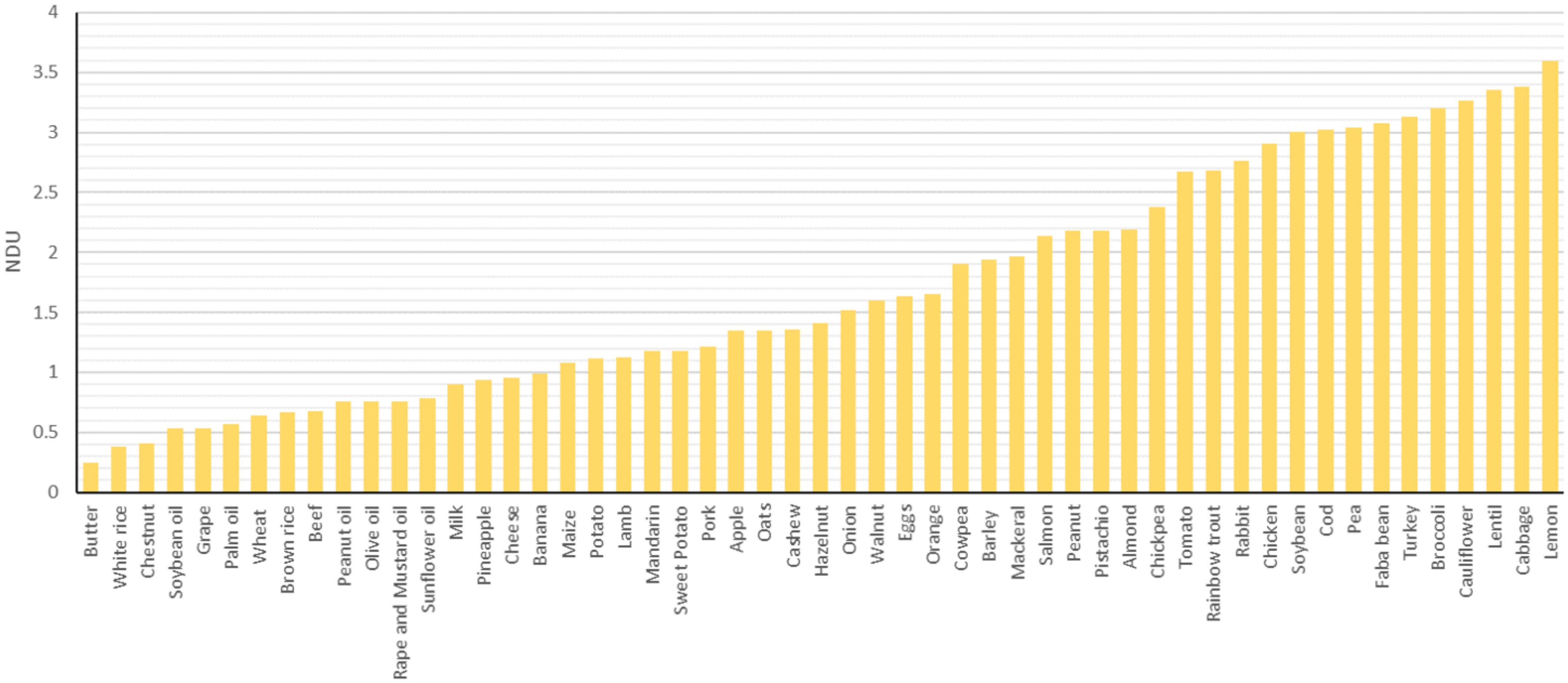

Figure 11. Nutrient Density Unit (NDU) values 100g^{-1} for food items used in this study.

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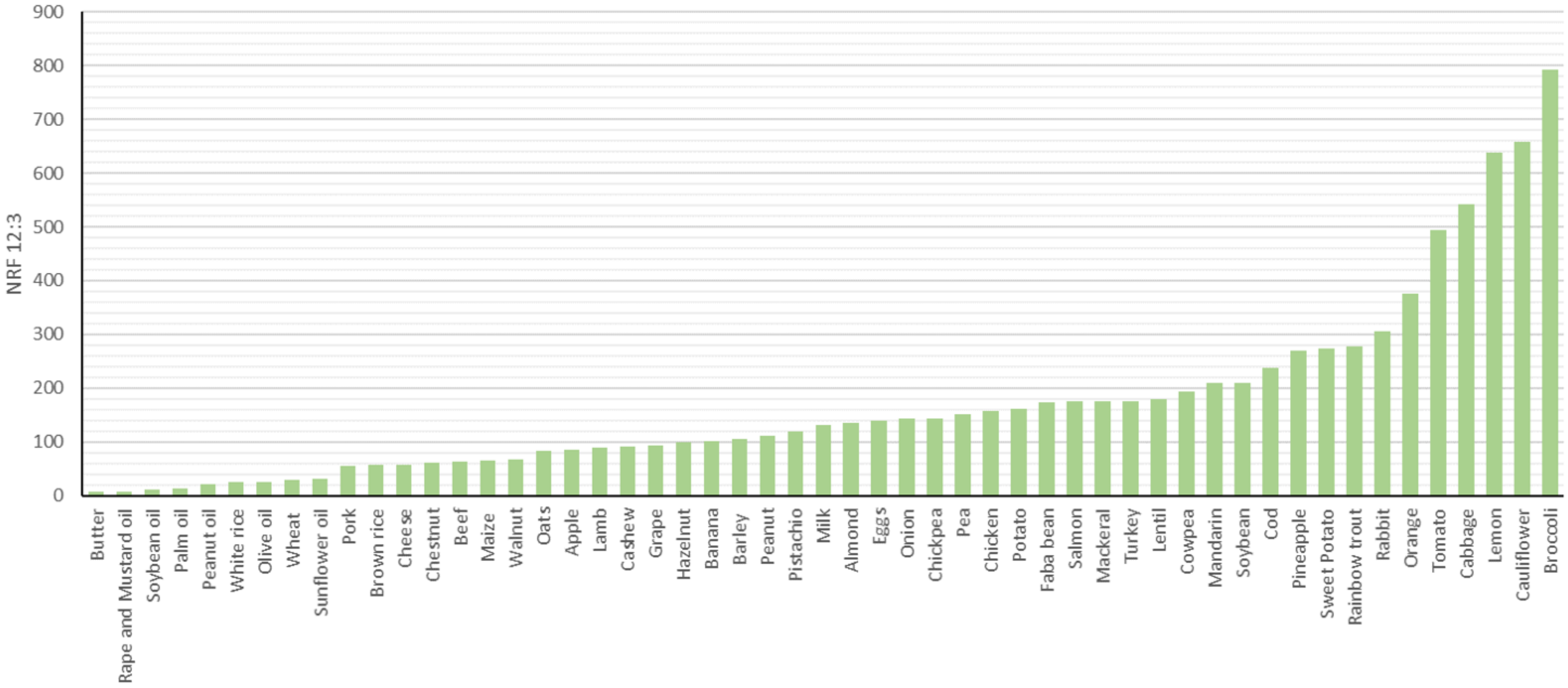

Figure 12. Nutrient Rich Food Index (NRF12:3) values 100g^{-1} for food items used in this study

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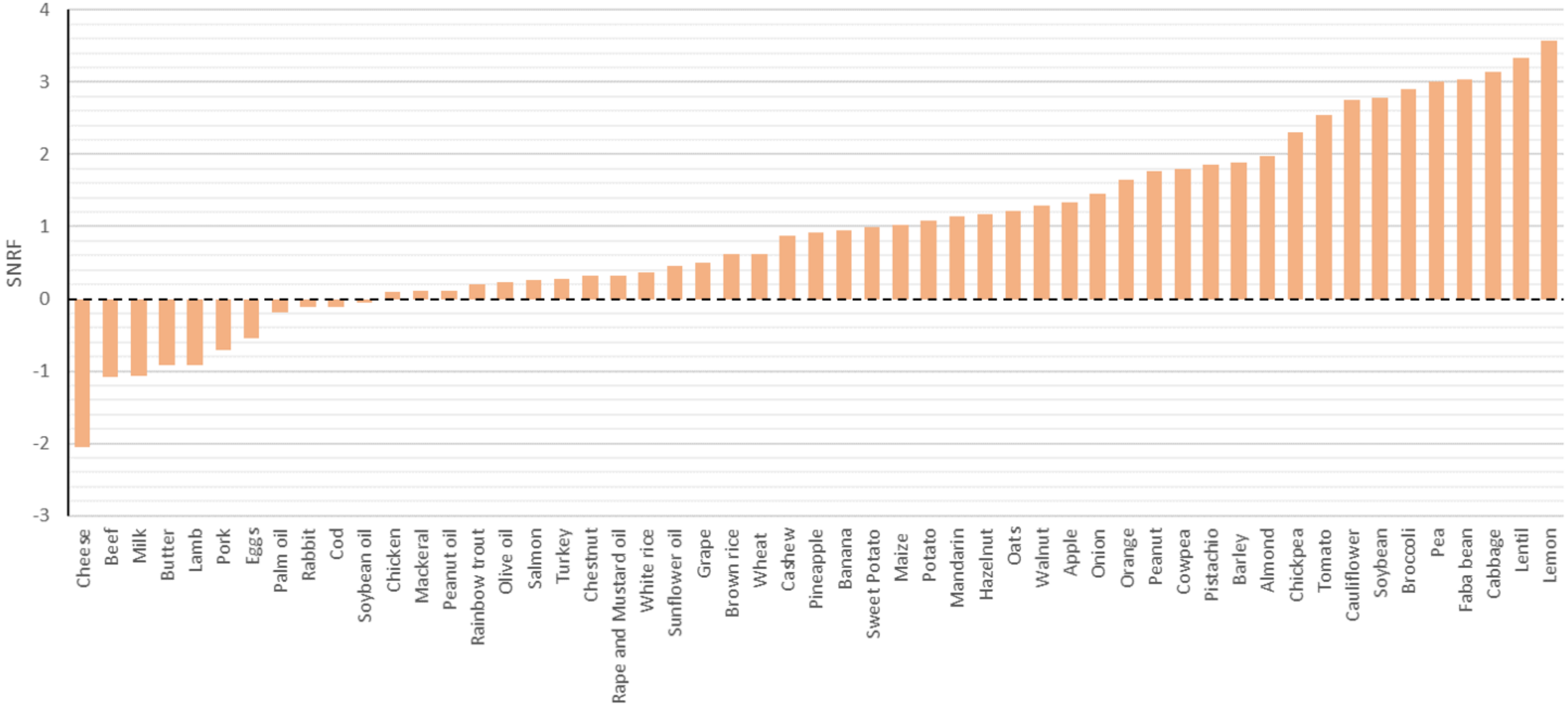

Figure 13. Sustainable Nutrient Rich Food Index (SNRF) values 100g^{-1} for food items used in this study

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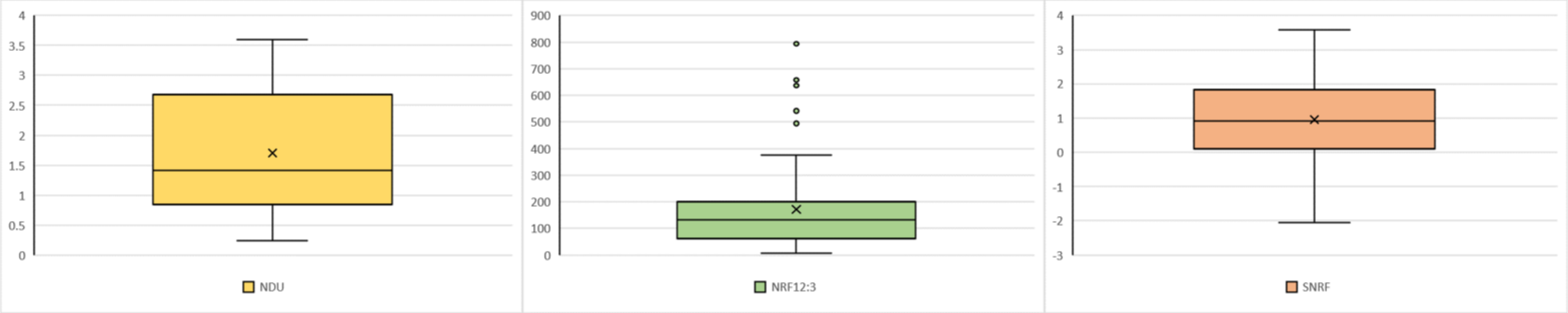

Figure 14. Box plots for NDI data

All NDIs produced a suitable spread of data for the range of food items studied, NDU values ranging from 0.24 to 3.6, NRF12:3 values from 6.5 to 792, and SNRF values from -2.0 to 3.6 (Figures 11 to 13, Table 7). Box plots for each NDI are illustrated in Figure 14. Low variance in data distribution for NDU and SNRF indices suggest these are more suitable as a functional unit for environmental burden of food production, being less susceptible to skew caused by outliers than NRF12:3. However, propensity of SNRF to produce negative values by positively weighting plant products at the outset, is problematic, making it unsuitable as a functional unit for LCA studies, and therefore this index is excluded further from our study. A high correlation coefficient for the plot of $\log_{10}$ NDU vs $\log_{10}$ NRF supports the view that simplifying calculation of nutrient density, by using the NDU index is possible, and would be encouraged (Figure 15). For instance, the Nutri-Score nutrition label, a 5-colour code labelling scheme for food products, developed by France's national public health agency in 2017, and adopted for use by France, Belgium, Germany and Spain, also uses a simplified approach to displaying nutritional density (Chantal and Hercberg, 2017; Szabo de Edelenyi *et al.,* 2019). The Nutri-score algorithm, however, awards negative points to high energy, saturated fat, sugar and sodium contents, and positive points for a high proportion of fruits, vegetables, nuts, fibres and protein in the food product. It is therefore, like the SNRF index, too subjective, and impractical for scaling, to be used as a functional unit for LCA studies.

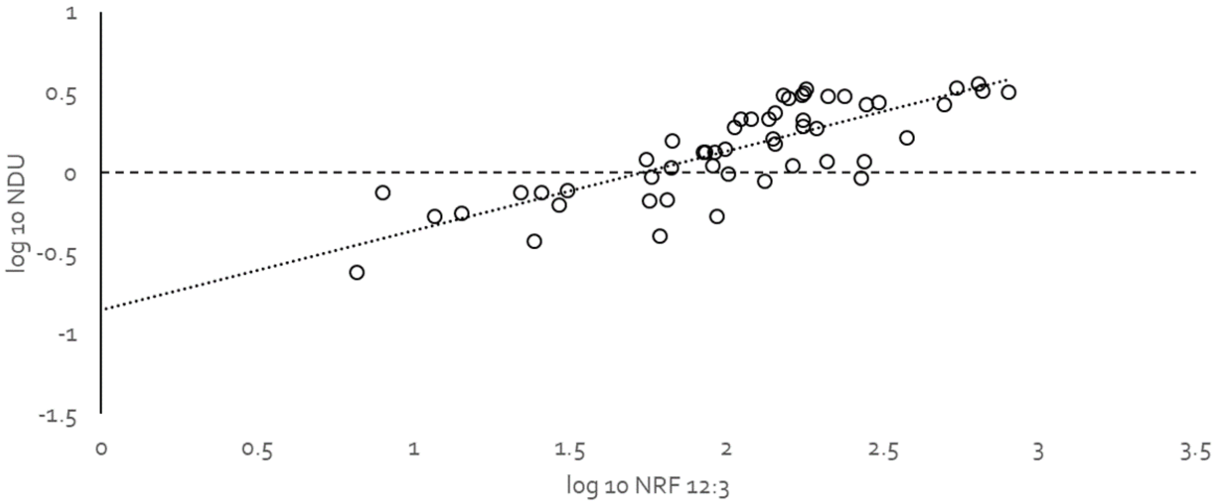

Figure 15. Plot of $\log_{10}$ NDU vs log10 NRF12:3 for individual food items covered in this study

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3.3.2. *Scoring food items and food groups according to environmental impact per nutrient unit clearly underlines the importance of grain legumes in any sustainable diet*

Arranging NDI values according to EAT reference diet categories highlights the wide variance between the nutritional status of animal and plant products (Figure 16). With the exception of the ***Chicken & Other Poultry***, and ***Fish*** categories, where NDI scores were above both the median, mean, and in the case of NDU, 3rd quartile values, ***Beef & Lamb***, and ***Pork*** categories showed nutrient density scores considerably lower than median values. ***Vegetables***, ***Soy Foods*** and ***Dry beans, Lentils & Peas*** categories showed high to mid-range nutrient density values for both indices. Grain legumes are therefore, in terms of both environmental burden (GWP and EP) and nutrient density, the best protein source to choose. To further illustrate this, a new, combined functional attribute is presented – environmental burden NDU^{-1}, where high values indicate food items having both a high GWP or EP score, coupled with a low nutrient density. Food items of a lower environmental burden NDU^{-1}, should therefore be favoured for more sustainable diets.

Environmental burden NDU^{-1} scores are illustrated in Figures 17 to 19 for both individual food items and EAT reference diet groups. Individual scores further highlight the unsuitability of red meat, farmed fish and dairy produce as a source of protein and fat in sustainable diets. Inclusion of white rice is also problematic given its low nutritional status but high environmental footprint. In terms of EAT reference diet categories, then a combination of environmental and nutritional analysis can be seen to be extremely useful in separating food groups according to sustainability. In the case of the GWP NDU^{-1} assessment, values range from low (<0.023 $kgCO_2e$ NDU^{-1}), through medium to high (0.023 – 0.44 $kgCO_2e$ NDU^{-1}), to very high (>0.44 $kgCO_2e$ NDU^{-1}) environmental burden per nutrient unit groupings. EAT reference diet categories in the low value range are exclusively plant-based, with the categories ***Peanuts***, ***Dry Beans, Lentils, Peas*** and ***Soy Foods*** having the lowest values overall, whilst at the other extreme, the highest values (>0.44) were solely red meat, animal fats, sweeteners and dairy.

This pattern is repeated for the EP NDU^{-1} scores. Here values range from low (0.21 $gPO_4^{3-}e$ NDU^{-1}), through medium to high (0.21 – 3.87 $gPO_4^{3-}e$ NDU^{-1}), to very high (>3.87 $gPO_4^{3-}e$ NDU^{-1}) environmental burden per nutrient unit groupings. Again, legume categories are in the low value range, with ***Soy Foods*** category in the lower half of the medium to high score range.

Interestingly the ***Whole Grains*** category, scored poorly in both the GWP NDU^{-1} and EP NDU^{-1} assessments, and while white rice may have biased these scores by inclusion, the use of grain legumes as a sustainable source of carbohydrate, in addition to protein, appears more beneficial than cereals on their own.

The use of nutrient density indices as functional units in environmental assessments, is now adopted by the TRUE project in their LCA analysis of novel food products.

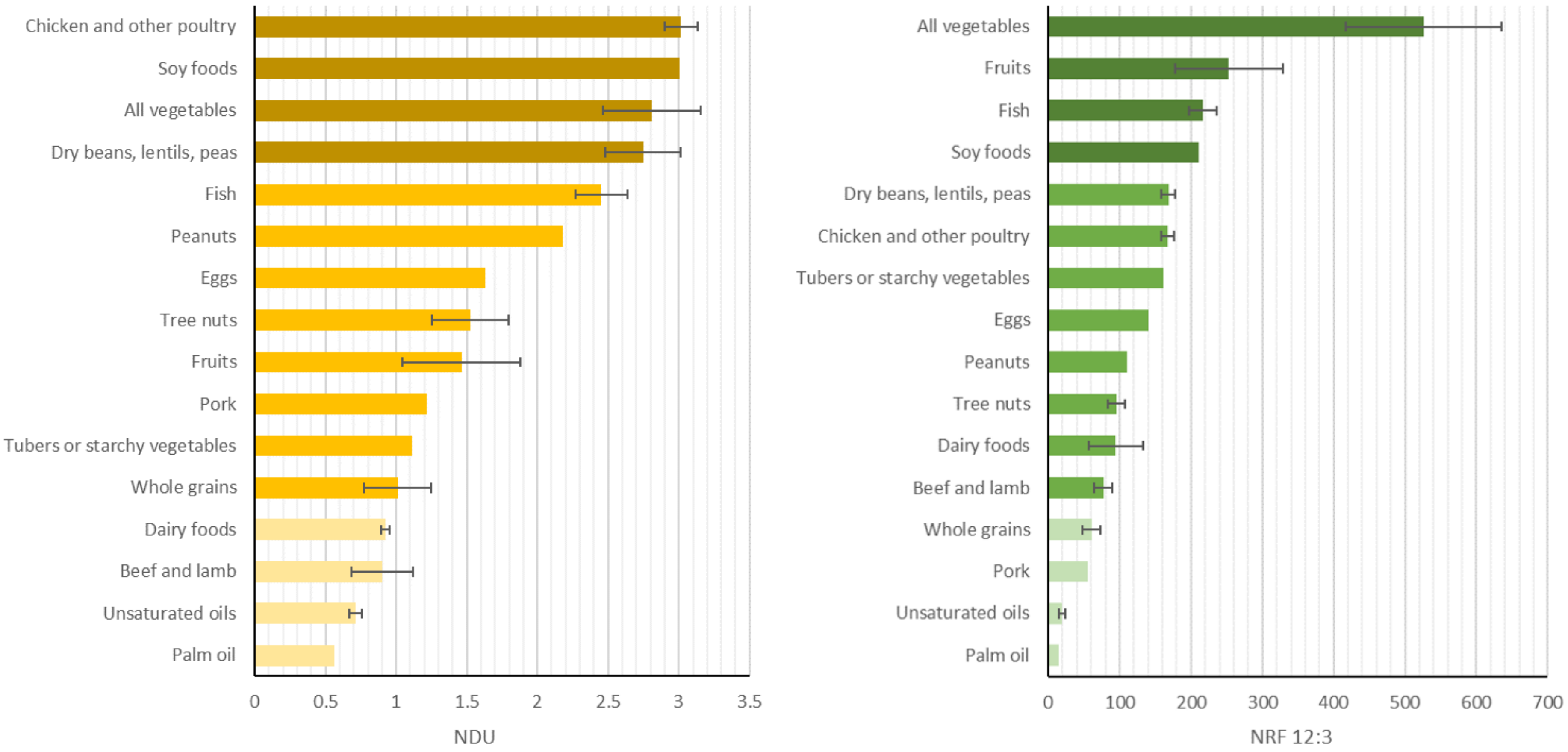

Figure 16. NDU and NRF12:3 nutrient density values per 100g for the EAT reference diet food categories. Each bar represents the mean ± standard error. Dark bars represent values > 3rd quartile; light bars represent values < 1st quartile.

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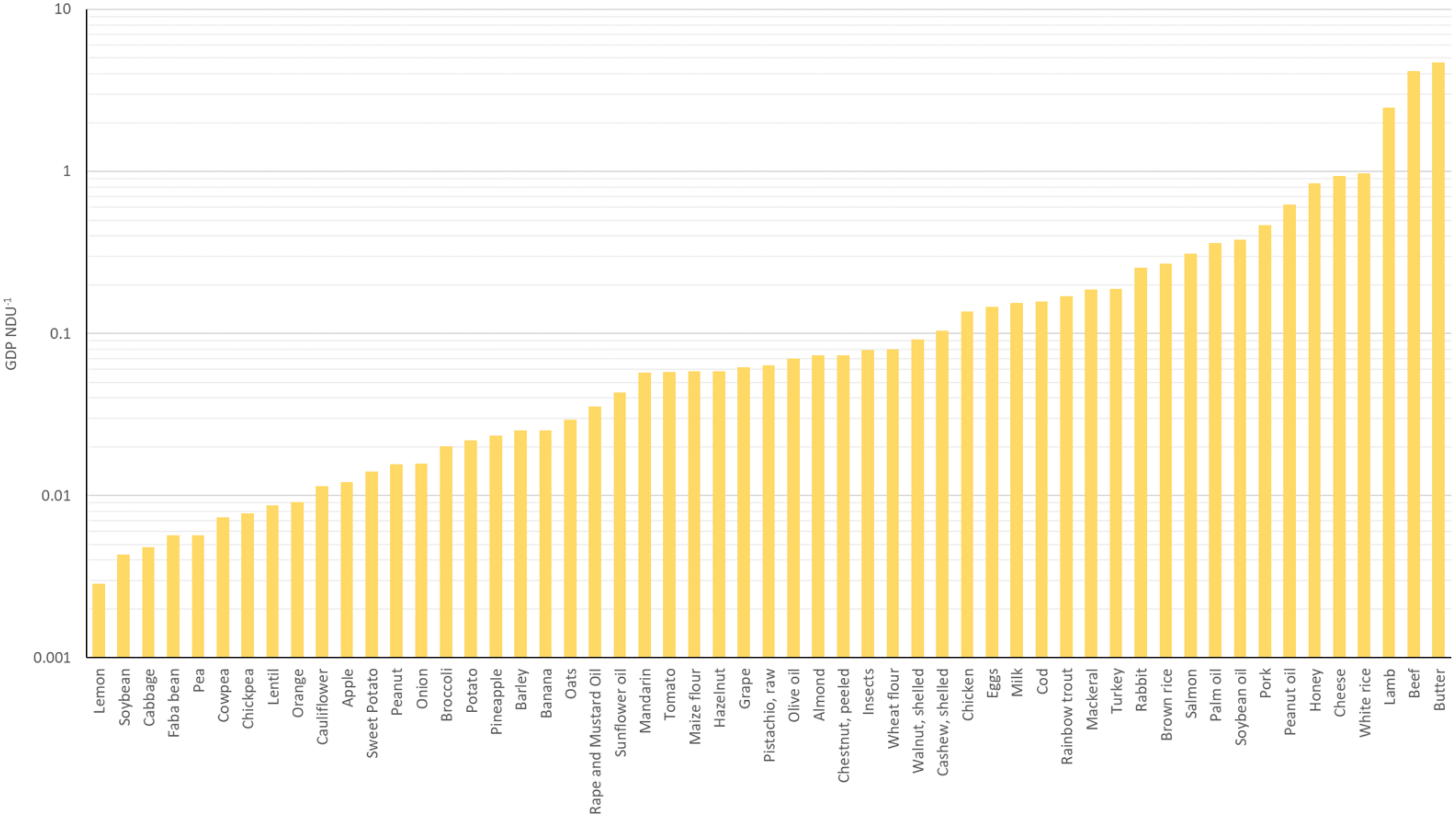

Figure 17: GWP NDU^{-1} scores for the individual food items covered in this study.

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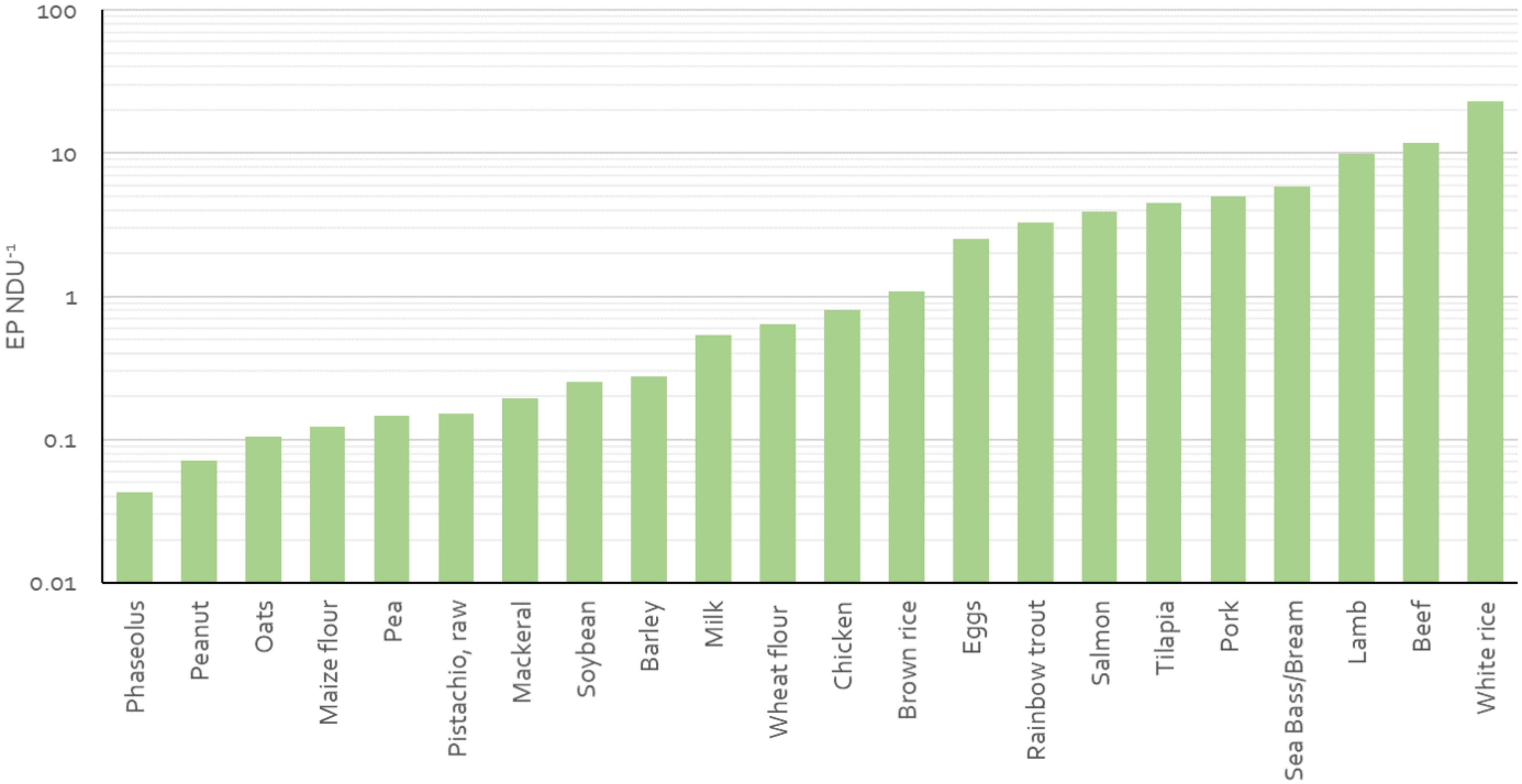

Figure 18. EP NDU^{-1} scores for the individual food items covered in this study

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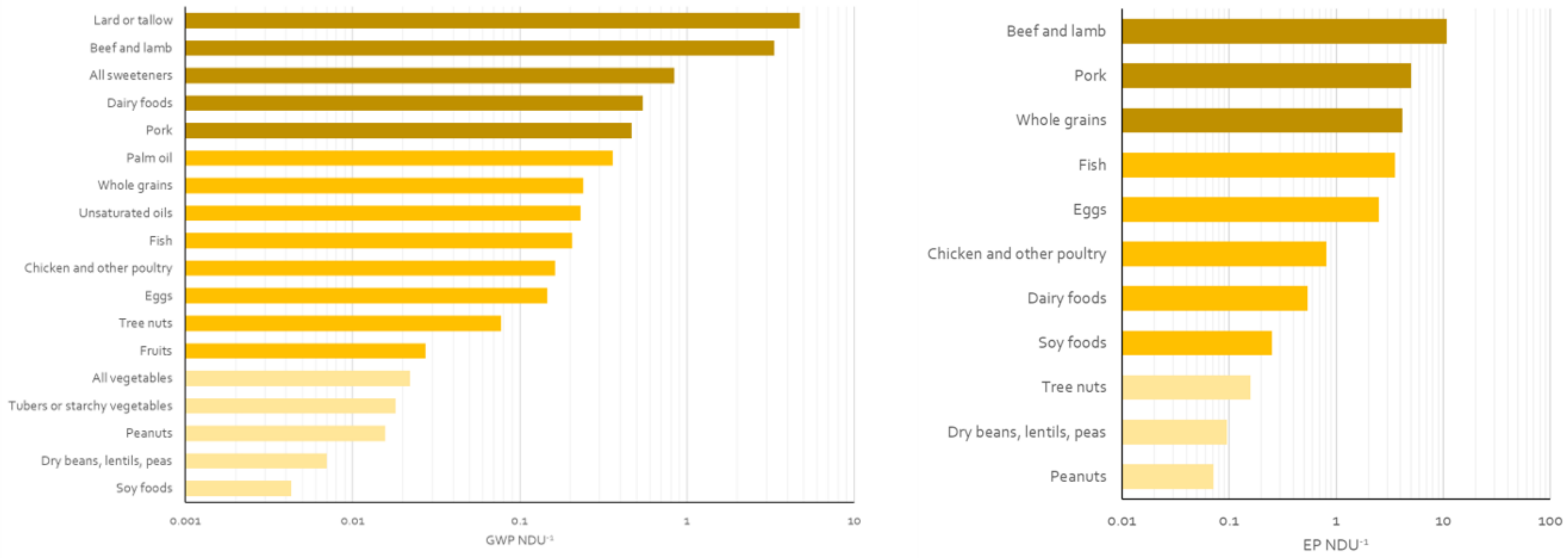

Figure 19. GWP NDU^{-1} and EP NDU^{-1} scores for EAT reference diet categories (Dark bars indicate values > 3rd quartile, light bars indicate values < 1st quartile).

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3.4. Environmental assessment of European and EAT reference diets

Calculation of environmental burden of food production, in terms of farm gate GWP and EP scores, allows a comparative environmental assessment of the European and EAT reference diets, environmental burden per 100kcals per reference food category being used in each case. This is illustrated in Table 8, using FAO food balance statistics as a framework for environmental burden calculation.

3.4.1. Adoption of the EAT reference diet can cut an individual's GWP and EP burden by almost a half.

Table 8: Comparison of nutritional and environmental aspects of the European and EAT reference diet

Food Groups	**EAT reference diet**			**European diet (2009-2013)**		
	Kcal d^{-1}	**$kgCO_2e$**	**$gPO_4^{3-}e$**	**Kcal d^{-1}**	**$kgCO_2e$**	**$gPO_4^{3-}e$**
Whole grains	811	0.148	3.938	1007.6	0.184	4.892
Tubers or starchy vegetables	39	0.012		150.6	0.048	
All vegetables	78	0.170		81.4	0.180	
Fruits	126	0.066		105	0.055	
Dairy foods	153	0.338	1.238	386.2	0.854	3.125
Beef and lamb	15	0.131	0.476	77.0	0.671	2.442
Pork	15	0.029	0.345	186.2	0.401	4.729
Chicken and other poultry	62	0.257	1.223	79.2	0.329	1.562
Eggs	19	0.045	0.543	49.4	0.118	1.412
Fish	40	0.153	3.405	46.6	0.178	3.966
Dry beans, lentils, peas	172	0.031	0.148	23.4	0.004	0.020
Soy foods	112	0.014	0.189	1.2	0.000	0.002
Peanuts	142	0.055	0.044	12.2	0.005	0.004
Tree nuts	149	0.030	0.093	24.2	0.005	0.015
Palm oil	60	0.015		30	0.007	
Unsaturated oils	354	0.038		426	0.045	
Lard or tallow	36	0.058		81.2	0.130	
All sweeteners	120	0.006		385.6	0.020	
TOTAL	**2503**	**1.60**	**11.64**	**3153.0**	**3.234**	**22.17**

In terms of GWP, the European diet correlates with far higher scores for $kgCO_2e$, in particular for the categories ***Dairy***, ***Beef & Lamb***, and ***Pork***, these three categories representing over 87% of the total increase in GWP for the European diet of 1.634 $kgCO_2e$ capita^{-1} d^{-1} (Table 8). However, the European diet also includes a higher total kcal intake overall. As such, Table 9 illustrates the GWP and EP data

for each food category, normalized to a calorific intake of 2503 kcals. The excess of 153g CO_2e per capita per day (3.234 – 3.081) is therefore associated with the extra 650 kcals consumed, and normalised emissions associated with the ***Dairy***, ***Beef & Lamb*** and ***Pork*** categories represent an increase of 0.45, 0.53 and 0.36 kgCO_2e per capita per day, respectively.

Table 9: GWP and EP values for European diet normalized to a total calorific intake of 2503 kcals

Food Groups	**EAT reference diet**			**European diet (2009-2013)**		
	Kcal d^{-1}	**kgCO$_2$e**	**gPO$_4^{3-}$e**	**Kcal d^{-1}**	**kgCO$_2$e**	**gPO$_4^{3-}$e**
Whole grains	811	0.148	3.938	800	0.146	3.884
Tubers or starchy vegetables	39	0.012		120	0.046	
All vegetables	78	0.170		65	0.177	
Fruits	126	0.066		83	0.054	
Dairy foods	153	0.338	1.238	307	0.787	2.878
Beef and lamb	15	0.131	0.476	61	0.661	2.404
Pork	15	0.029	0.345	148	0.385	4.549
Chicken and other poultry	62	0.257	1.223	63	0.323	1.537
Eggs	19	0.045	0.543	39	0.116	1.397
Fish	40	0.153	3.405	37	0.176	3.929
Dry beans, lentils, peas	172	0.031	0.148	19	0.004	0.020
Soy foods	112	0.014	0.189	1	0.0002	0.002
Peanuts	142	0.055	0.044	10	0.005	0.004
Tree nuts	149	0.030	0.093	19	0.005	0.015
Palm oil	60	0.015		24	0.007	
Unsaturated oils	354	0.038		338	0.041	
Lard or tallow	36	0.058		64	0.128	
All sweeteners	120	0.006		306	0.019	
TOTAL	**2503**	**1.60**	**11.64**	**2503**	**3.081**	**20.619**

Although data for EP are limited to only eleven of the eighteen food categories, it is possible to assess the European and EAT reference diets in terms of minimum EP scores. Again, the European diet correlates with significantly higher scores for gPO_4^{3-}e compared with the reference diet. Of the data included, the ***Pork***, ***Beef & Lamb***, and ***Dairy*** categories represent over 78% of the total increase in EP for the European diet of 10.53 gPO_4^{3-}e (Table 8), ***Pork*** representing by far the largest component (41.6%).

Following normalization of the data to 2503 kcals (Table 9), then the extra calorific intake of 650 kcals is associated with an EP score of 1.55 gPO_4^{3-}e, and PO_4^{3-}e leachate values for the ***Pork***, ***Beef & Lamb***, and ***Dairy*** categories of 4.20, 1.93 and 1.64 gPO_4^{3-}e, respectively.

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The main conclusion from the data presented in Table 8, is that Europe could theoretically reduce both per capita CO_2e emissions and $gPO_4^{3-}e$ leachate values associated with diet, by approx. 50% through adopting the EAT Lancet commission recommendations, primarily through a major reduction in the production and consumption of both animal protein and fat. Although these values are based on farmgate assessments of GWP and EP, and do not include the environmental burden associated with transport and packaging, it is assumed that environmental burden scores up to and including the farmgate stage, represent 61% of food GHG emissions, and 95% of food eutrophication (Poore and Nemecek, 2018).

4. Conclusions

Increased cultivation and consumption of legumes can play a central role in limiting the environmental burden of diet, whilst at the same time, improving nutrition.

4.1. Global Patterns in Dietary Intake

Global diets have changed considerably since the 1960s – for a majority of countries studied, more calories are being consumed per person, and the proportion of fat and animal protein consumed has increased significantly with wealth. In contrast, the consumption of plant protein has remained static with increasing GDP. This has led to a marked decline in the healthiness of diets as personal wealth increases, as measured by the Mediterranean Diet Index. **(section 3.1)**

4.2. Nutritional and Environmental Assessment of Food Groups

The nutritional status of food items can be described in terms of nutrient density indices (NDIs), where the relative nutrient content of a standard amount of food can be expressed in terms of energy provided. This same standard food amount can also be expressed in terms of Global Warming Potential (GWP) and Eutrophication Potential (EP) by use of CO_2 emission and PO_4^{3-} leachate data.

4.2.1. Nutrient assessment of food groups

Individual food items were scored for nutrient density using three NDIs of differing nutrient profiles (NDU, SNRF and NRF12:3). All three indices scored vegetables, fruit and legumes higher than red meat and dairy products. Fish and poultry scored high for two of the NDIs used.

Grouping food items according to the EAT Lancet Commission reference diet categories, highlights the importance of legumes (***Soy Foods***, ***Dried Beans, Peas & Lentils***) in providing higher nutrient densities than other major sources of protein, with the exception of the ***Chicken & Other Poultry***, and ***Fish*** categories. ***Whole Grains***, ***Beef & Lamb***, and the vegetable oil groupings ***Unsaturated Oils***, and ***Palm oil***, score the lowest of the food groups in terms of nutritional density. **(section 3.3)**

4.2.2. *Environmental assessment of food groups*

Farmgate GWP and EP data were obtained for up to 60 separate food items, incorporating up to 1364 separate values, and arranged according to the EAT Lancet Commission reference diet categories. Both in terms of per weight and per kcal units, CO_2e scores were lowest for the legume (***Soy Foods***, and ***Dried Beans, Lentils, Peas***) and ***All Sweeteners*** categories (<0.06kg CO_2e 100kcals^{-1}; <0.2 kgCO_2e 100g^{-1}) and highest for the ***Beef & Lamb***, category (>0.8kg CO_2e 100kcals^{-1}; >2 kg CO_2e 100g^{-1}). Both the ***Fish*** and ***Chicken & Other Poultry*** categories, which scored high for nutrient density, also scored high for GWP. Animal-based food items grouped almost exclusively within the very high (>0.8 kg CO_2e 100kcals^{-1}; >2 kg CO_2e 100g^{-1}), and medium to high (0.16-0.42 kg CO_2e 100kcals^{-1}; 0.24-1.5 kg CO_2e 100g^{-1}) emission ranges.

Farmgate EP data was more limited than GWP data, where only 22 food items were used in the assessment, although incorporating 157 separate values. Again, grouping food items according to the EAT reference diet categories highlights the importance of plant protein in sustainable diets. The categories ***Fish*** (dominated by the farmed fish sector), and ***Beef & Lamb*** produced the highest EP values (>3 gPO_4^{3-}e 100kcal^{-1}; >8 gPO_4^{3-}e 100g^{-1}), whilst with the exception of dairy, all low EP values (<1 gPO43- 100kcal; 100g-1) were associated with plant categories. The two legume categories ***Dried Beans, Lentils, Peas***, and ***Peanuts*** were associated with the lowest EP values (< 0.5gPO_4^{3-} 100kcal^{-1}; 100g^{-1}). **(section 3.2)**

4.2.3. *Environmental Impact per nutrient unit – a useful measure of sustainability for food production pathways*

Environmental and nutritional aspects to diet assessment are inter-linked – environmental burden being associated with food production and nutrient status with suitability of the final product. Function units which incorporate environmental and nutritional aspects may play an important role in informing customers on dietary choice and the sustainability of food products. Both GWP and EP scores calculated in section 3.2, were expressed per nutrient density unit (NDU) and the final scores grouped according to the EAT reference diet categories. Here, high scores mean a high environmental burden per unit of nutrient density, and conversely, low scores indicate high sustainability of the food item in question. This means of assessing sustainability of food groups gives a more pronounced separation of food items in terms of environmental burden per nutrient status, and the use of NDIs as functional units in Life Cycle Assessments of novel legume products has now been adopted by TRUE.

In the case of the GWP NDU^{-1} scores, the range of values obtained, further highlight the unsuitability of red meat, farmed fish and dairy produce as sources of protein and fat in sustainable diets. ***Peanuts***, ***Dry Beans, Lentils, Peas*** and ***Soy Foods*** have the lowest values overall (0.023 kgCO_2e NDU^{-1}), whilst at the other extreme, the highest values (>0.44) were solely for red meat, animal fats, sweeteners and dairy.

This pattern is repeated for the EP NDU^{-1} scores. Again, legume categories are in the low value range (<0.21 gPO_4^{3-}1 NDU^{-1}), and with the exception of the Whole Grains category, animal products are exclusively at the higher end of the spectrum (>3.87 gPO_4^{3-}1 NDU^{-1}). As the major calorific component of the European diet, (30.3% of total calories consumed), cereals provide both carbohydrate and protein. However, with regard to a diet high in plant products, a more sustainable mix of carbohydrate and protein intake is possible by inclusion of grain legumes. **(section 3.3)**

4.3. Nutritional and Environmental Assessment of Diets

Use of FAO food balance statistics, coupled with the environmental assessment described here, allows a valid comparison of the European Diet with the EAT Lancet commission reference diet.

4.3.1. Calorific assessment

The European diet scores poorly against the reference diet. Overall, the calorific intake is 26% higher than recommended levels, with 80% of the total calorific intake associated with cereals, vegetable oils, sugar and sweeteners, meat, dairy and animal fats. Cereals make up the major component (30.3%). Legumes and nuts make up less than 2% of the daily energy intake, which is less than the daily energy obtained from alcoholic drinks. Slightly better would be the combined energy intake for vegetables and fruit, at just over 10%. In terms of reference diet categories, significant over consumption occurs for the following: ***Pork*** (+1000%), ***Beef & Lamb*** (+400%), ***Tubers or Starchy Vegetables*** (+290%), ***Sweeteners*** (+220%), ***Eggs*** (+160%), ***Dairy Foods*** (+150%) and ***Lard & Tallow*** (+126%), while significant underconsumption occurs for nuts and legumes in general: ***Tree Nuts*** (-84%), ***Dry Beans, Lentils, Peas*** (-86%), ***Peanuts*** (-91%), and ***Soy Foods*** (-99%). **(section 3.2)**

4.3.2. Environmental assessment

Adoption of the EAT Lancet commission reference diet can reduce per capita diet emissions of CO_2e by 50%, and per capita diet EP scores for PO_4^{3-} leaching by a minimum of 47%, primarily by significant reductions in consumption of red meat and dairy, and with significant increases in the proportion of plant protein in the diet. In terms of the overall extra kilocalories consumed, then this accounts for both an extra 153g CO_2e and 1.55g PO_4^{3-}e per person per day for the average EU diet. However, in terms of individual categories ***Dairy***, ***Beef & Lamb***, and ***Pork*** categories represent over 87% of the total increase in GWP for the European diet of 1.634 kgCO_2e capita^{-1} d^{-1}, and over 78% of the total increase in EP of 10.53 gPO_4^{3-}e relative to the EAT Lancet reference diet **(section 3.4)**

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6. Appendix I: Summary Data

Table 10: Summary statistics for GWP 100kcal^{-1}

Food Group	Food Item	GWP Food Item (kgCO$_2$e 100kcal^{-1})					
		mean	10pctl	90pctl	median	se	n
CEREALS	Wheat flour (unenriched)	0.014	0.008	0.020	0.014	0.001	50
	Brown rice	0.050	0.039	0.066	0.045	0.005	7
	White rice	0.101	0.078	0.145	0.085	0.012	7
	Maize flour	0.018	0.012	0.029	0.013	0.004	6
	Oats	0.010	0.010	0.011	0.010	0.000	5
	Barley (hulled)	0.014	0.009	0.023	0.012	0.002	13
SUGAR & SWEETENERS	Sugar	0.002	0.001	0.004	0.001	0.001	35
	Honey	0.008	0.005	0.012	0.007	0.001	8
VEGETABLE OILS	Soybean oil	0.023					1
	Peanut oil	0.053					1
	Sunflower oil	0.009					1
	Rape and Mustard Oil	0.003					1
	Palm oil	0.023					1
	Olive oil	0.006					1
MEATS	Lamb	0.984	0.530	1.552	0.901	0.056	56
	Pork	0.215	0.140	0.304	0.212	0.006	130
	Chicken	0.334	0.200	0.521	0.295	0.016	95
	Turkey	0.496	0.290	0.682	0.591	0.072	7
	Beef	0.850	0.532	1.182	0.788	0.029	168
	Rabbit	0.875	0.211	1.710	0.447	0.582	3
	Insects (mealworm/cricket)	0.133	0.103	0.156	0.144	0.001	4
DAIRY	Milk	0.233	0.170	0.296	0.216	0.006	264
	Cheese	0.220	0.173	0.275	0.212	0.008	38
VEGETABLES	Tomato	0.863	0.035	3.878	0.222	0.233	49
	Onion	0.060	0.039	0.090	0.048	0.013	7
	Broccoli	0.189	0.098	0.352	0.119	0.066	6
	Cabbage	0.068	0.045	0.090	0.068	0.028	2
	Cauliflower	0.150	0.121	0.177	0.152	0.021	3
	Potato	0.032	0.006	0.063	0.026	0.003	42
	Sweet Potato	0.019	0.010	0.028	0.023	0.007	3
ALCOHOLIC DRINK	White wine	0.370					1
	Beer	0.070					1
	Beverages, alcoholic (gin)	0.140					1
ANIMAL FATS	Butter	0.161	0.086	0.308	0.129	0.032	8
FRUIT	Orange	0.033	0.018	0.054	0.027	0.005	13
	Mandarin/Clementine	0.144	0.016	0.302	0.062	0.080	8
	Lemon	0.035	0.019	0.051	0.046	0.012	3
	Banana	0.028	0.022	0.032	0.026	0.003	13
	Apple	0.031	0.008	0.069	0.018	0.004	62
	Pineapple	0.044	0.023	0.071	0.042	0.009	7
	Grape	0.048	0.003	0.085	0.039	0.004	114
EGGS	Eggs	0.238	0.122	0.361	0.246	0.013	40
FISH	Rainbow trout	0.330					1
	Cod	0.580					1
	Mackeral	0.180					1
	Salmon	0.320					1
PULSES	Faba bean	0.018	0.009	0.026	0.018	0.003	9
	Pea	0.018	0.005	0.032	0.011	0.022	8
	Soybean	0.013	0.009	0.018	0.011	0.033	4
	Peanut	0.039	0.008	0.090	0.013	0.001	4
	Phaseolus	0.014	0.003	0.037	0.009	0.001	22
	Lentil	0.029	0.028	0.030	0.029	0.001	2
	Chickpea	0.018	0.014	0.022	0.021	0.003	3
	Cowpea	0.014	0.010	0.017	0.014	0.009	4
NUTS	Walnut, shelled	0.023	0.007	0.039	0.021	0.009	4
	Cashew, shelled	0.026	0.018	0.034	0.023	0.005	4
	Pistachio, raw	0.025	0.016	0.034	0.025	0.012	2
	Chestnut, peeled	0.008					1
	Hazelnut	0.013	0.006	0.020	0.013	0.009	2
	Almond	0.028	0.007	0.052	0.024	0.009	6

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Table 11: Summary statistics for GWP 100g^{-1}

Food Group	Food Item	GWP Food Item (kgCO$_2$e 100g^{-1})					
		mean	10pctl	90pctl	median	se	n
CEREALS	Wheat flour (unenriched)	0.051	0.030	0.073	0.052	0.002	50
	Brown rice	0.180	0.142	0.239	0.162	0.019	7
	White rice	0.370	0.283	0.528	0.311	0.044	7
	Maize flour	0.063	0.041	0.102	0.047	0.015	6
	Oats	0.040	0.038	0.043	0.038	0.002	5
	Barley (hulled)	0.049	0.030	0.083	0.043	0.007	13
SUGAR & SWEETENERS	Sugar	0.008	0.002	0.016	0.004	0.002	35
	Honey	0.025	0.014	0.036	0.023	0.004	8
VEGETABLE OILS	Soybean oil	0.203					1
	Peanut oil	0.469					1
	Sunflower oil	0.077					1
	Rape and Mustard Oil	0.027					1
	Palm oil	0.203					1
	Olive oil	0.053					1
MEATS	Lamb	2.777	1.497	4.380	2.544	0.159	56
	Pork	0.565	0.369	0.800	0.558	0.015	130
	Chicken	0.398	0.238	0.620	0.351	0.019	95
	Turkey	0.590	0.345	0.812	0.703	0.086	7
	Beef	2.823	1.768	3.924	2.617	0.097	168
	Rabbit	0.706	0.171	1.380	0.361	0.469	3
	Insects (mealworm/cricket)	0.230	0.177	0.268	0.247	0.001	4
DAIRY	Milk	0.140	0.102	0.177	0.129	0.004	264
	Cheese	0.886	0.697	1.106	0.855	0.034	38
VEGETABLES	Tomato	0.155	0.006	0.698	0.040	0.042	49
	Onion	0.024	0.016	0.036	0.019	0.005	7
	Broccoli	0.064	0.033	0.120	0.041	0.022	6
	Cabbage	0.016	0.011	0.022	0.016	0.007	2
	Cauliflower	0.037	0.030	0.044	0.038	0.005	3
	Potato	0.024	0.005	0.048	0.020	0.003	42
	Sweet Potato	0.017	0.008	0.024	0.020	0.006	3
ALCOHOLIC DRINK	White wine	0.303					1
	Beer	0.030					1
	Beverages, alcoholic (gin)	0.323					1
ANIMAL FATS	Butter	1.152	0.615	2.208	0.925	0.229	8
FRUIT	Orange	0.015	0.008	0.025	0.012	0.002	13
	Mandarin/Clementine	0.068	0.007	0.142	0.029	0.037	8
	Lemon	0.010	0.005	0.015	0.013	0.003	3
	Banana	0.025	0.020	0.028	0.023	0.003	13
	Apple	0.016	0.004	0.036	0.009	0.002	62
	Pineapple	0.022	0.012	0.035	0.021	0.004	7
	Grape	0.033	0.002	0.059	0.027	0.003	114
EGGS	Eggs	0.238	0.122	0.361	0.246	0.013	40
FISH	Rainbow trout	0.455					1
	Cod	0.476					1
	Mackeral	0.369					1
	Salmon	0.666					1
PULSES	Faba bean	0.018	0.009	0.026	0.018	0.003	9
	Pea	0.018	0.005	0.032	0.011	0.022	8
	Soybean	0.013	0.009	0.018	0.011	0.033	4
	Peanut	0.039	0.008	0.090	0.013	0.001	4
	Phaseolus	0.014	0.003	0.037	0.009	0.001	22
	Lentil	0.029	0.028	0.030	0.029	0.001	2
	Chickpea	0.018	0.014	0.022	0.021	0.003	3
	Cowpea	0.014	0.010	0.017	0.014	0.009	4
NUTS	Walnut, shelled	0.148	0.048	0.256	0.137	0.056	4
	Cashew, shelled	0.141	0.101	0.190	0.130	0.026	4
	Pistachio, raw	0.139	0.087	0.190	0.139	0.065	2
	Chestnut, peeled	0.030					1
	Hazelnut	0.083	0.040	0.125	0.083	0.054	2
	Almond	0.160	0.042	0.299	0.140	0.051	6

Table 12: Summary statistics for EP 100kcal^{-1} and 100g^{-1}

Food Group	**Food Item**	**EP Food Item (gPO$_4^{3-}$e 100kcal^{-1})**					
		mean	10pctl	90pctl	median	se	n
CEREALS	Wheat flour (unenriched)	0.113	0.000	0.255	0.084	0.048	6
	Brown rice	0.201	0.134	0.260	0.210	0.032	5
	White rice	2.374	2.192	2.630	2.192	0.183	3
	Maize flour	0.038	0.026	0.051	0.035	0.003	13
	Oats	0.037					1
	Barley (hulled)	0.151	0.119	0.186	0.141	0.025	3
MEATS	Lamb	3.916	0.347	9.223	2.177	2.141	6
	Pork	2.303	0.342	2.629	1.931	0.868	12
	Chicken	1.972	0.491	4.523	0.765	0.714	8
	Beef	2.428	1.093	5.012	1.277	0.529	13
DAIRY	Milk	0.809	0.371	1.178	0.974	0.150	9
EGGS	Eggs	2.858	1.330	5.531	1.748	0.543	14
FISH	Rainbow trout	6.409	5.157	7.385	6.257	0.510	5
	Sea Bass/Bream	17.664	10.268	31.423	13.625	3.427	8
	Mackeral	0.186	0.045	0.341	0.152	0.108	3
	Tilapia	14.278	13.200	15.733	13.333	10.289	3
	Salmon	4.021	3.122	5.290	3.652	0.437	6
PULSES	Pea	0.133	0.108	0.147	0.131	0.011	10
	Soybean	0.169	0.122	0.228	0.148	0.019	7
	Peanut	0.031	0.018	0.038	0.037	0.005	6
	Phaseolus	0.038	0.005	0.078	0.020	0.010	13
NUTS	Pistachio, raw	0.062	0.060	0.065	0.061	0.002	3
Food Group	**Food Item**	**EP Food Item (gPO$_4^{3-}$e 100g^{-1})**					
		mean	10pctl	90pctl	median	se	n
CEREALS	Wheat flour (unenriched)	0.412	0.000	0.930	0.305	0.173	6
	Brown rice	0.728	0.486	0.940	0.760	0.114	5
	White rice	8.667	8.000	9.600	8.000	0.667	3
	Maize flour	0.132	0.092	0.178	0.124	0.012	13
	Oats	0.142					1
	Barley (hulled)	0.533	0.420	0.660	0.500	0.088	3
MEATS	Lamb	11.054	0.978	26.037	6.146	6.044	6
	Pork	6.052	0.898	6.909	5.074	2.280	12
	Chicken	2.347	0.585	5.382	0.910	0.849	8
	Beef	8.060	3.628	16.638	4.240	1.755	13
DAIRY	Milk	0.484	0.222	0.705	0.583	0.090	9
EGGS	Eggs	4.087	1.903	7.910	2.500	0.777	14
FISH	Rainbow trout	8.845	7.117	10.191	8.634	0.704	5
	Sea Bass/Bream	17.134	9.960	30.480	13.216	3.324	8
	Mackeral	0.382	0.093	0.699	0.312	0.221	3
	Tilapia	13.707	12.672	15.104	12.800	9.877	3
	Salmon	8.368	6.496	11.008	7.600	0.909	6
PULSES	Pea	0.455	0.369	0.502	0.448	0.037	10
	Soybean	0.753	0.545	1.016	0.659	0.084	7
	Peanut	0.176	0.103	0.218	0.209	0.029	6
	Phaseolus	0.131	0.016	0.268	0.070	0.036	13
NUTS	Pistachio, raw	0.347	0.332	0.364	0.342	0.012	3

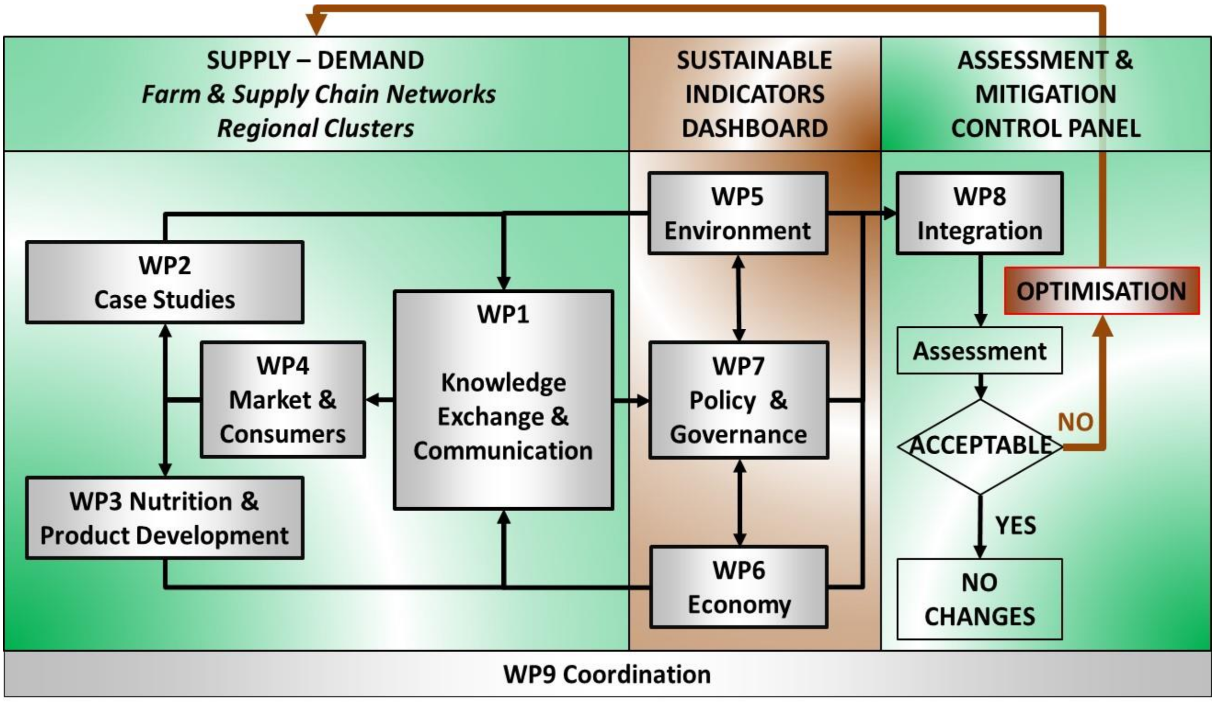
7. Appendix 2: Background to the TRUE project

7.1. 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 sustainability*' – '*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 Life Cycle Analysis specialists 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.

7.2. 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).



7.3. 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 (PIRED)	Croatia	Development Agency

[*] Coordinating institution

7.4. 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*

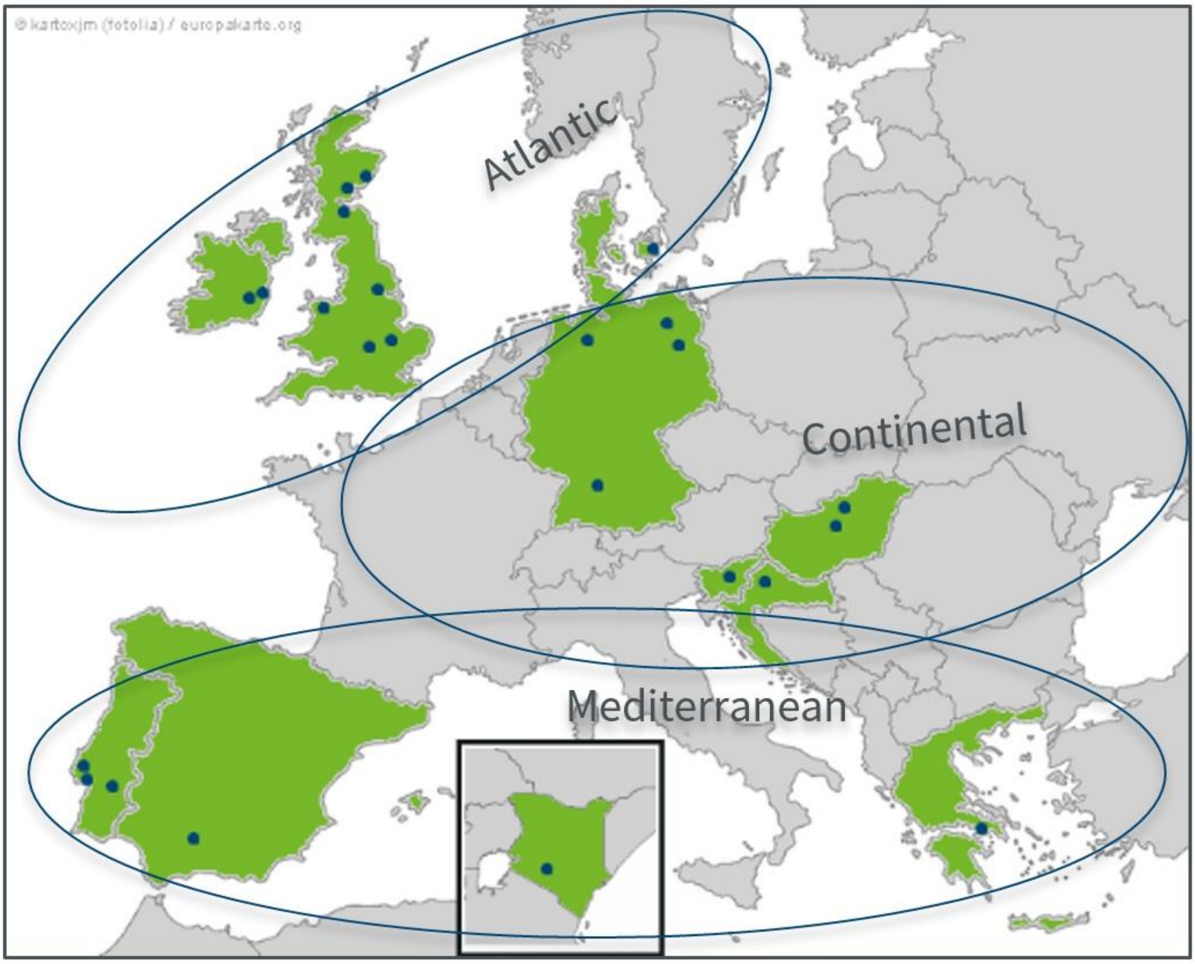
Objective 7: Enable policies, legislation and regulatory systems (ESSRG, WP7)

- *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*

7.5. 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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Disclaimer

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