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Eating your greens: a global sustainability assessment☆

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ABSTRACT

The importance of healthy diets is woven into the fabric of the Sustainable Development Goals, although there is no clear metric to define it. Employing a simulation model (MAGNET), this study examines the sustainability implications arising from the adoption of recommended daily nutrition requirements inspired by the 'Lancet' reference diet. To measure sustainability, changes in 'virtual' requirements and associated tier footprints for irrigation (blue) water, agricultural land and greenhouse gas emissions (GHG) are calculated. Assuming business-as-usual food consumption trends, between 2015 and 2050 blue water, agricultural land and emissions rise 34%, 9% and 44%, respectively, whilst corresponding increases in Sub-Saharan Africa are much higher. By 2050, the switch to the reference diet decreases agricultural land use by -8% and emissions by -9%. Global blue water and cropland requirements increase by 5%, whilst significant concomitant savings in permanent pastureland (-21%) are expected. By region, the diet switch drives rising blue water consumption in Oceania and the EU and agricultural land savings in Latin America and Oceania, accompanied by cropland increases in the EU and North Africa. The reference diet generates substantial reductions in GHG emissions, particularly in Latin America. Interestingly, Sub-Saharan Africa which abstains from the reference diet due to affordability considerations, benefits from a 'rebound' effect from falling meat and dairy prices. Finally, the diet shift could result in marginal per capita food expenditure rises arising from demand driven fish price, particularly in more vulnerable world regions. This estimate does not capture, however, second-round economic growth effects arising from increased labour productivity and reduced public health expenditures.

1. Introduction

According to Food and Agriculture Organisation (FAO) nutrition data for 2017 (FAO, 2020), average global per capita consumption is 2917 kgcalories per day (kcal/day). Putting aside the important issue of adequate food distribution, this suggests that there is more than

Abbreviations: B2015, Baseline in 2015; B2050, Baseline result in 2050; BAU, Business as usual; CGE, Computable General Equilibrium; CO2e, Carbon dioxide equivalent; EU, European Union; FAO, Food and Agriculture Organisation of the United Nations; FRD, Feasible Reference Diet; FRDRMZ, Feasible Reference Diet, Red Meat Zero; GECO, Global Energy and Climate Outlook; GHG, Greenhouse gas; GHGs, Greenhouse gases; GTAP, Global Trade Analysis Project; IMAGE, Integrated Model to Assess the Global Environment; IMPACT, International Model for Policy Analysis of Agricultural Commodities and Trade; IO, Input-Output; kcal, Kilocalories; kgCO2e, Kilogrammes of carbon dioxide equivalent; km^3, Cubic kilometres; LatinAme, Latin America; m^3, Cubic metres; mKm^2, Million square kilometres; MtCO2e, Million tonnes of carbon dioxide equivalent; MAGNET, Modular Applied GeNeral Equilibrium Tool; MidEast, Middle East; NoAfrica, North Africa; NoAmerica, North America; pc, Per capita; PE, Partial equilibrium; SDGs, Sustainable Development Goals; SSAfrica, Sub Saharan Africa; SSP2, Shared Socioeconomic Pathway Two ("Middle of the Road"); tkm^2/year, Thousand squared kilometres per year.

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sufficient food energy content world-wide to support the current population. On the other hand, even in those regions with abundant access to food, nutrient 'quality' often remains suboptimal. Indeed, Di Cesare et al. (2016) note that more people in the world are obese than undernourished. The pervasiveness of malnutrition in modern societies, in all its forms, therefore presents a heavy burden for health and social services, whilst the economic and social ramifications, owing to lower educational attainment, reduced labour productivity and persistent poverty and inequality, are far reaching.

A related issue is the pressure that unbalanced eating habits exert on our environmental planetary boundaries (Global Panel on Agriculture and Food Systems for Nutrition, 2016). With the world's population expected to reach 9,7 billion by 2050 and in the absence of any deviations in our eating patterns, FAO (2018) report that between 2012 and 2050, global agricultural output volumes, harvested (crop) areas, animal herd size and greenhouse gases (GHGs) could rise 50%, 23% (92 million hectares), 46% and 20%, respectively. With a view to promoting a more sustainably responsible food system, the Sustainable Development Goals (SDGs) (Allen et al., 2016) also draw urgent attention to the multifaceted and intertwined sustainability challenges facing human development. It is surprising, however, that a firm SDG metric for diet quality is conspicuously absent. Indeed, the paradigm of the 'wedding cake' (Folke et al., 2016) operating on the three 'layers' of economy, society and biosphere, posits that socially desirable progress toward the SDG targets is explicitly linked to healthy human diets and the transformational capacity of the food system. Similarly, the European Union's Green Deal and more specifically the 'Farm to Fork Strategy' (European Commission, 2020), also promotes a more plant-based diet aiming for a fair, healthy and environmentally-friendly food system.

Recently, Willett et al. (2020) define a universal scientifically accepted healthy 'reference' diet (dubbed the 'Lancet' diet) based on macronutrient daily intakes. This reference diet is principally based on, *"vegetables, fruits, whole grains, legumes, nuts and unsaturated oils"* (Willett et al., 2020: p.1), whilst low in meat, dairy, sugars, starchy vegetables and refined grains. Springmann et al. (2018) quantitatively assess the global sustainability implications of the reference diet employing a global agricultural simulation model (IMPACT) coupled with standard projections of population and real GDP growth to 2050 (O'Neill et al., 2014). The sustainability impacts are measured in terms of the 'virtual'[1] consumption of GHG emissions, cropland use, irrigation or 'blue' water, nitrogen and phosphorus application associated with dietary change. Comparing with the baseline, the reference diet reduces GHGs by 29%, with concomitant reductions of between 5 and 9% for the remaining indicators. In a related study, Hirvonen et al. (2020) assess the reference diet from the perspective of affordability. Employing data on food prices and household income across 159 countries, they conclude that just under a third of the daily cost would correspond to fruit and vegetables, whilst meat and dairy would account for approximately 28%. Comparing with per capita household incomes, they estimate that the diet could exceed income availability for approximately 1.58 billion people.

The primary scientific aim of this paper is to revisit the issue of healthy diets and global resource sustainability, posited in Springmann et al. (2018). Thus, in our study, a detailed baseline to 2050 captures macroeconomic, demographic, energy market and biophysical drivers. Comparing with this baseline, the key aim is to examine the proposition that *"even small increases in consumption of red meat or dairy foods would make…(remaining within a globally safe operating space)…difficult or impossible to achieve"* (pp1, Willett et al., 2020). To this end, there is a focus on meat and dairy consumption patterns consistent with the reference diet employing two alternate 30-year scenarios starting in 2020.

A key difference from the work of Springmann et al. (2018) is the choice of methodological approach. Deviating from the partial equilibrium (PE) agriculture specific sector model in Springmann et al. (2018), this paper employs the Modular Applied GeNeral Equilibrium Tool (MAGNET), a class of global economy-wide computable general equilibrium (CGE) model. Unlike the PE model representation, the CGE model fully integrates the economy-wide inter- and intra-industry intermediate input purchases within and between food and non-food production chains, as well as the competition across activities for scarce resources (e.g., land, capital). The advantage is that one can track the flows of non-tradable virtual commodities corresponding to the usage of food and non-food inputs along the food supply chain. Thus, unlike the PE model approach, the model 'internalises' the calculation of virtual consumption intensities or 'footprints' (e.g., land area per unit value of sales), thereby avoiding the need to 'borrow' estimates from other studies that employ divergent methodologies and product category definitions. In validating the veracity of our estimates, the current paper also compares with other relevant studies in the literature. A second perceived methodological advantage arising from the CGE model is that the behavioural demand systems for food are more complete since they are explicitly reconciled with non-food purchases subject to income constraints and savings rates.

As a testimony to its application, there are examples of economy-wide simulation assessments of food behaviour changes by consumers. For example, Campoy-Munoz et al. (2017), Rutten et al. (2013a) and Philippidis et al. (2019) all examine the proposition of food waste reductions across the European Union. Although they incorporate different behavioural assumptions, all three studies report EU macroeconomic costs, reductions in agricultural sector output volumes, market prices and employment.

An important advantage of MAGNET over other global CGE representations, is the availability of a specialist nutrition module (Rutten et al., 2013b) that matches calorie intake with demand for different food product categories. In this paper, this module is further modified to maintain the same total daily calorific intake in all simulation experiments, whilst in the healthy diet scenarios, the calorific share assigned to meat and dairy consumption in each of our regions is varied to be consistent with Lancet diet recommendations. Employing the equations and parameters inherent within the consumer demand system, and subject to the food behaviour changes associated with the Lancet diet recommendations, a second aim of the paper is to reassess the issue of dietary affordability examined in Hirvonen et al. (2020).

The rest of this paper is structured as follows. Section two discusses the database, the model framework, the baseline and the scenario narratives. Section three presents the results. In section four, some reflection and qualification of the results is discussed. Section five concludes.

2. Methodology

2.1. GTAP database and cge model

With a base year of 2011, this study principally employs version nine of the Global Trade Analysis Project (GTAP) database, complete with 57 tradable sectors and 140 regions (Aguiar et al., 2016). This data source contains information on intermediate input and primary factor purchases by primary-, industrial- and service activities as well as demands for finished products by private consumers, public institutions and investors. With the relevant tax and subsidy data, all demands are measured at basic-, producer- and purchaser prices. Each economy is interconnected by gross bilateral trade, tariff/subsidy and transport

[1] The amount of a resource or commodity that is embedded within the different stages of production to bring a given product 'i' to market, is referred to as the virtual commodity flow. For example, for the virtual commodity 'greenhouse gases' (GHGs) pizza, the total virtual flow within the production of a pizza accounts for the GHGs generated from the production of crop and livestock ingredients, as well as GHG emissions arising from subsequent production stages relating to the processing, packaging and transport of said pizza to the market place for final consumption.

margins data, whilst intra-regional investment and savings flows are also recorded. To ensure a closed global economic system in equilibrium, demand and supply in each commodity and factor market is assumed equal; regional income, output and expenditures in all regions are balanced, and the sum of the current and capital accounts (balance of payments) for each region nets to zero. Upon this database, is calibrated the GTAP multiregional computable general equilibrium (CGE) simulation tool (Corong et al., 2017). The MAGNET model, which is further discussed below, employs the GTAP model structure at its core.

As is typical of this class of model, GTAP combines neoclassical economic theory with mathematical functional forms to represent the behaviour of producers and consumers within the closed macroeconomic system depicted in Fig. 1. Thus, factor demands are subject to the minimisation of costs subject to constant returns to scale production technologies, whilst consumers maximise utility or welfare subject to an expenditure constraint. These behavioural equations are conditioned by the accounting conventions of the underlying database. Thus, market clearing equations for each factor and commodity 'i' ensure that demands are equal to supplies (see Fig. 1) and accounting equations enforce the conditions of zero 'economic' profits for each activity 'j' and that total macroeconomic value of output, income and expenditure are equal. A further discussion of this class of model is provided in the supplementary materials document.

2.2. MAGNET model extensions

For a rigorous impact assessment, the 'generic' GTAP model described in Section 2.1, constitutes an essential starting point. Built around the GTAP model, the MAGNET model (Woltjer and Kuiper, 2014) employs binary switches in the model code to activate a series of non-standard modelling enhancements.[2] As an improvement on the single period GTAP model treatment, the recursive dynamic treatment in MAGNET links successive discrete time periods to capture capital stock accumulation and structural economic change over medium to long term time frames. Moreover, additional model code is inserted to capture agricultural factor market rigidities (i.e., agricultural land transfer, capital and labour employment to/from agriculture); sustainable limits on available land and residue supplies and bioenergy mandates for conventional and advanced generation biofuels (Banse et al., 2011; Van Meijl et al. 2018).

As a complement to these modelling advancements, a further development on GTAP is MAGNET's in-house data splits covering bioenergy, bioindustrial and municipal waste activities, which afford the user an improved characterisation of the availability (e.g., animals, plants, organic waste, lignocellulosic biomass) and uses (e.g., food, feed, industry, energy) of biomass.[3] Thus, MAGNET provides a more elaborated definition of the resource boundaries and economic constraints within which the food system operates.

Of particular pertinence to this study is the application of the MAGNET nutrition module (Rutten et al., 2013b). Combining satellite data based on FAO nutritive factors for different food-types, the module calculates and traces annual and daily average nutrient intakes within final consumption. The current study further modifies the module to hold daily nutrient intake fixed across all scenarios to transparently model the necessary food substitution effects and the resulting sustainability and household budgetary impacts compared with the baseline. To measure the sustainability impacts arising from diet change, further model code is added to track all virtual flows matching to the total food supply chain from 'farm to fork'. The resulting virtual flow intensities are therefore akin to the calculation of tier three footprints. A detailed discussion of this extension is provided in the supplementary information document, including comparisons with other studies.

2.3. Model aggregation[4] and scenario design

To limit the computational burden of the simulations, a representative selection of regions captures both economic and geographical/cultural diversity across the world, whilst accommodating the explicit separation of significant key players. Thus, two large 'developed' country blocs (European Union (EU27),[5] North America) are joined by the rapidly growing countries of China, Brazil, Russia and India. The remaining regions are Rest of Asia, North Africa, Sub-Saharan Africa, Rest of Latin America, the Middle East, Rest of Europe and Oceania.

The emphasis on food diets necessitates a disaggregation of agri-food commodities, whilst in-house MAGNET data splits for feed and fertiliser activities allow a more flexible treatment of crop and livestock production technologies. Further non-standard activity splits in the MAGNET data explicitly represent additional sources of biomass and biobased energy and industrial applications. To incorporate the energy balance trends in Keramidas et al. (2018) (see next paragraph), fossil fuel and electricity generation technologies are also represented. Finally, a number of non biobased sectors are chosen, which either act as key 'blending' or processing activities for elaborated biobased inputs (i.e., chemicals, petroleum, food services) or group residual activities (i.e., manufacturing, services, transport) of the remaining macro economy.

Starting from a base year of 2011, the motivation and design of the business as usual (BAU) baseline borrows heavily from the European Commission's Global Energy and Climate Outlook (GECO) reference scenario (Keramidas et al., 2018; Weitzel et al., 2019).[6] Taking decade time intervals from 2010 to 2050, the GECO reference scenario enumerates emissions reductions and detailed transformations in renewable and fossil energy markets by different users, combined with economic- (e.g., real macro growth, fossil fuel prices) and population drivers. These drivers are paired with land productivity changes consistent with the 'middle of the road' shared socioeconomic pathway (O'Neill et al. 2014). To characterise gradual structural economic change and allow for rapid increases in nascent biobased technologies, the time intervals of our study are 2011–15, 2015–20, 2020–30, 2030–40 and 2040–50. Table 1 summarises the assumptions behind the main model drivers and their implementation into MAGNET.

The required change in trajectory consistent with achieving sustainable dietary change is shaped by developments in food distribution chains, globalisation,[7] education, changing social norms and even the relevant culinary preparatory skills and time. Taking the same time frame as Willett et al. (2020) and Springmann et al. (2018), it is assumed that the dietary transformations modelled here occur over a thirty year time frame to 2050. In comparison with the baseline, two alternate dietary narratives are described in Table 2 – the feasible reference diet (FRD) and the feasible reference diet with final red meat consumption at zero (FRDRMZ). The FRD is shaped by the observation that, "*Although the reference diet.....is consistent with many traditional eating patterns, for some individuals or populations this diet might seem extreme or not feasible*" (Willett et al., 2020, p454). For example, religious beliefs in the Muslim and Buddhist worlds, limit pork and red meat consumption,

[2] This paper describes the most salient features of MAGNET used for this study. The interested reader can access a full documentation of the model from https://www.magnet-model.org/.

[3] The supplementary materials document provides further detail on the additional sector splits in the MAGNET model.

[4] The supplementary material document details the exact disaggregation of sectors and regions for this study.

[5] With the imminent departure of the United Kingdom from the European Union, results are for the 27 nation bloc.

[6] Full details are available online from Keramidas et al., (2018). The supplementary information document also provides further discussion.

[7] For example, in Global Panel on Agriculture and Food Systems for Nutrition (2016), it is suggested that the spoiling of consumers for food choice has led to low-quality diet choices and obesity.

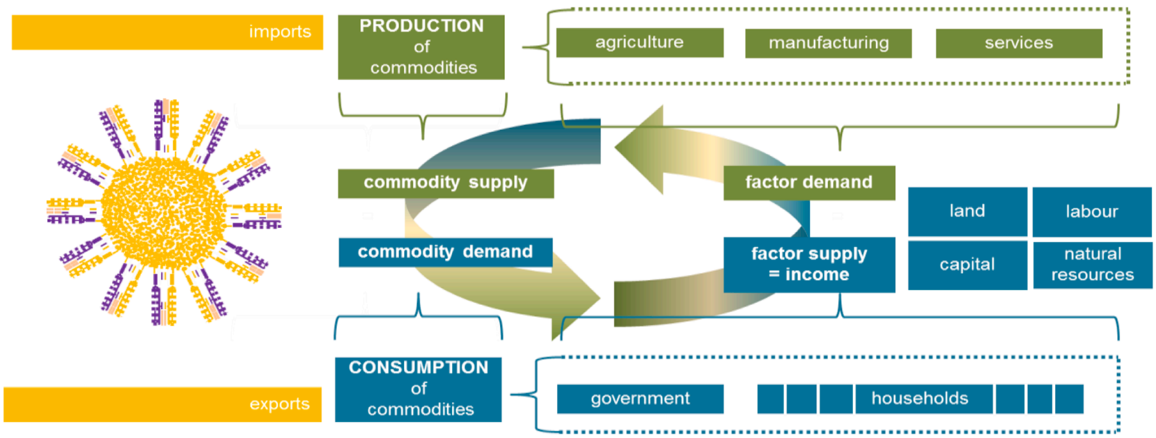

Fig. 1. A graphical representation of the CGE model framework (Philippidis et al., 2020)

Table 1
Exogenous drivers of the model baseline to 2050.

Exogenous driver	Details:
(i) Region-wide productivity	Region-wide productivity calibrated to regional real rates of GDP (Keramidas et al., 2018).
(ii) Capital stock	Changes at the same percentage rate as real GDP (fixed capital-output ratio).
(iii) Labour force	Changes at the same percentage rate as regional population (fixed long-run employment rate).
(iv) Population	Exogenous rates of population change (Keramidas et al., 2018)
(v) Carbon Tax	Global increases in the carbon tax ($/tonne) by time period on all activities (Weitzel et al., 2019).
(vi) Energy input shifters	Calibrated input-output technology shifters to mimic energy balance trends by energy type and usage (Keramidas et al., 2018).
(vii) Land productivity	Exogenous land productivity shocks from Shared Socioeconomic Pathway Two, "Middle of the Road" (SSP2).
(viii) Energy final demands	Exogenous final energy demand taste shifters to mimic pathway trends (Keramidas et al., 2018).
(ix) Global fossil fuel price	Exogenous changes in fossil fuel prices (Keramidas et al., 2018)
(x) Biofuel mandates	Exogenous mandates on first-generation and advanced-generation biofuels by region

Table 2
Summary of the scenarios.

Narrative	Acronym	Details
"Feasible Reference Diet"	**FRD**	From 2020, regions gradually adopt (linearly through time) the midpoint average daily dietary calorific shares (kcal/day) for red meat, white meat and dairy consumption as recommended by the reference diet. For some regions, commodity exceptions to the reference diet are allowed due to cultural, religious and affordability considerations. The total kcal/day in each region is assumed equal to the baseline over the thirty year period.
"Feasible Reference Diet, red meat zero	**FRDRMZ**	For red and white meat, the same average daily dietary calorific shares (kcal/day) as in the FRD. In the case of red meat, the extreme assumption of zero household consumption world-wide is applied. The total kcal/day in each region is assumed equal to the baseline over the thirty year period.

respectively, whilst cultural factors, particularly in India, China, Asia and parts of Africa, limit red meat and dairy consumption (Willett et al., 2020). Indeed, examining the estimated kcal/day food intakes from the MAGNET model,[8] red meat intake in China and India; white meat consumption in India and North Africa; and dairy consumption in China and Asia, are well below the recommended midpoints in the reference diets. These region-product combinations are therefore excluded in the FRD scenario. Moreover, for many people in the Sub-Saharan African continent, the ability to realise dietary *quality* change is infeasible, where it is estimated that up to 39% of households are food insecure, rising to 49% in lean periods (Fraval et al., 2019). Thus, in the FRD scenario, it is assumed that the Sub-Saharan African continent does not adhere to the reference diet.

3. Results

3.1. The evolution of nutrient intake to 2050

Fig. 2 shows daily per capita kilocalorie (kcal/pc/day) intake results for a selection of regions between 2015 and 2050. In generating these results, a quality control was exercised to avoid unrealistic increases arising due to projected rises in economic growth and average per capita household real incomes.[9] For example, according to the FAO (2020) food balance time series data (1961–2017), peak kcal/pc/day intakes in the EU and North America were recorded in 2017 (at 3448 kcal/pc/day) and 2005 (at 3793 kcal/pc/day), respectively. Thus, recalibrations of the income elasticities within the non-homothetic consumer demand function were implemented to remain as close as possible to these peak limits over the time horizon of the simulation. In the case of the rapidly growing middle income regions, income elasticity adjustments were also implemented to maintain the initial or pre-adjusted relativity of daily nutrient intake compared with the developed regions, whilst additional time trend quality checks for these regions examining the FAO's time series data were also applied.

[8] The following numbers correspond to 2020 MAGNET kcal/day share estimates by food type compared with the healthy reference diet 'midpoint' estimates in Willet et al. (2020). Red meat in China and India is 0,49% and 0,50%, compared with 0,60% in the reference diet. White meat in India and North Africa is 0,60% and 2,01%, compared with 3,84% in the reference diet. Dairy consumption in China and Asia is 1,79% and 3,85% compared with 6,11% in the reference diet.

[9] Even taking into account food waste rates, an initial run of the model revealed unreasonably high per capita calorie intakes in many regions.

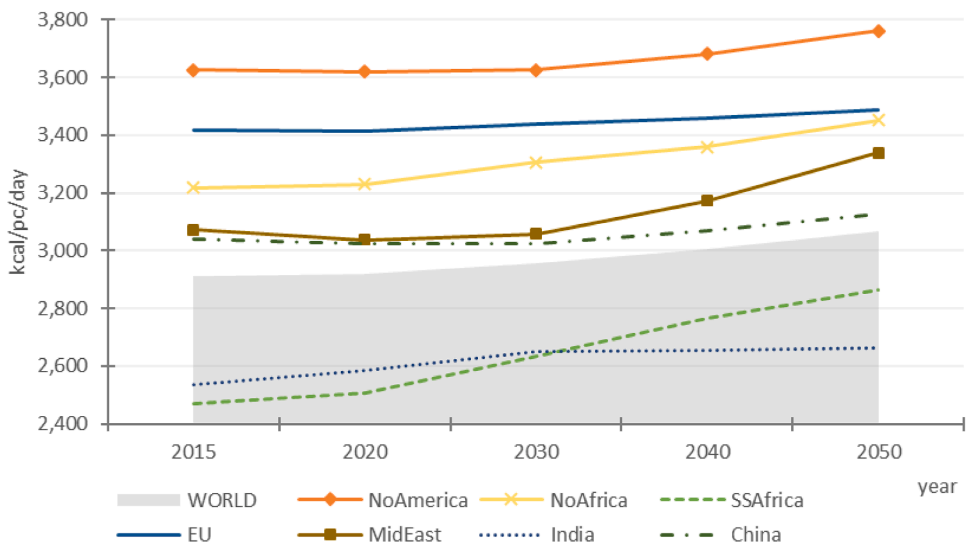

Fig. 2. Daily per capita kilocalorie trends for select regions
Notes: NoAmerica = North America; NoAfrica = North Africa; SSAfrica = Sub-Saharan Africa; EU = European Union; MidEast = Middle East.

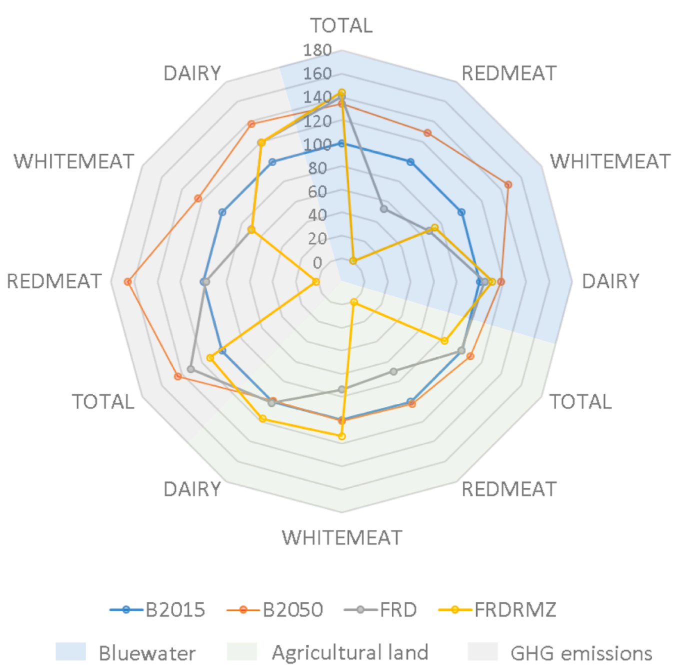

Fig. 3. Global virtual commodity consumption by scenario (2015=100)
Notes: B2015 = Baseline in 2015; B2050 = Baseline projection in 2050 (business as usual scenario); FRD = Feasible Reference Diet; FRDRMZ = Feasible Reference Diet, Red Meat Zero.

3.2. *Global virtual flows and footprints from consumer diets*

Fig. 3 presents a scaled index of consumer diet driven global virtual consumption of abstracted blue water, agricultural land and GHG emissions, respectively. Along each spine of Fig. 3 are represented the three virtual commodities corresponding to red meat, white meat and dairy consumption in the daily diet, as well as total food intake. The blue line represents the planetary boundary starting point corresponding to the year 2015 (i.e., B2015 = 100). The remaining rings correspond to the baseline by 2050 (B2050) and the two diet scenarios (FRD, FRDRMZ). Thus a move within the blue line is considered as more sustainable relative to 2015.

In the accompanying Table 3, are presented the corresponding footprints and absolute values of total virtual commodity usage. Thus, diet driven global blue water usage in 2015 is 2365 units of cubic kilometres per year (km^3/year), equivalent to a per capita footprint of 321 *m<sup>3<sup>s* per year (m^3/pc/year). Blue water commodity usage embedded in red meat, white meat and dairy consumption, estimated at 28 km^3/year, 44 km^3/year and 54 km^3/year, respectively, is entirely due to crop usage as on-farm feed inputs to live animals. Global virtual agricultural land for food in 2015 is estimated at 30 million square kilometres a year (mkm^2/year). Due to extensive livestock production systems, which often constitute the only viable activity on otherwise unusable land, the share of this total attributed to (red and white) meat and dairy products is 56%. White meat, based on intensive livestock production, records a (lower) virtual land requirement based on indirect arable land usage through feedstock inputs. The level of diet driven GHGs in 2015 is estimated at 9206 million tonnes of CO2e per year (MtCO2e/year), or an average per capita footprint in kilograms per year (kgCO2e/pc/year) of 1249 kgCO2e/pc/year.

In the BAU from 2015 to 2050, diet driven blue water, agricultural land and GHG usage rises 34%, 9% and 44%, respectively. Over the same period, the agricultural cropland area rises 19%, whilst permanent pasture increases 1%. The irrigated share of global cropland (not shown) rises slightly from 17.8% in 2015 to 20.8% by 2050. For water and GHG emissions, Table 3 shows that the 2050 footprint rises compared with 2015, whilst for agricultural land, there is a fall. Rising per capita footprints are driven by growth in per capita food demand due to rising incomes in rapidly developing economies, although the strength of accompanying population increase mitigates these effects in the case of land.

Comparing with the BAU, by 2050 the switch into plant based diets in FRD implies a further rise in global abstracted blue water to 3315 km^3/year (5%). Compensating rises in plant-based diets increase total and per capita demands for blue water on crops, despite the fact that fewer feed crops are required for livestock. By 2050, the FRD scenario encourages global agricultural land savings of 2.7 mkm2/year (8%). Indeed, agricultural land is at approximately 2015 levels. This reduction is driven by falling red meat consumption which saves 3.5 mkm^2/year of pasture land. The plant-based dietary shift simultaneously increases global cropland requirements by 0.7 mkm^2/year (5%) by 2050. As expected, the shift away from emissions intensive livestock products generates considerable global GHG reductions by 2050. Indeed, the recommended dietary change reduces emissions to 9% below 2050 levels.

The observed trends in the FRD scenario are now even stronger in the

Table 3
Summary of global virtual flows and footprints.

Annual per capita footprint					Annual virtual flow			
m^3				**Blue water**	km^3			
FRDRMZ	FRD	B2050	B2015		B2015	B2050	FRD	FRDRMZ
6.3	6.0	6.8	7.3	DAIRY	54.1	63.9	56.4	60.0
0.0	1.6	3.8	3.8	REDMEAT	28.2	36.3	14.9	0.0
3.4	3.2	6.9	6.0	WHITEMEAT	44.0	64.8	29.9	32.3
360.0	350.4	334.7	320.9	TOTAL	2,365.3	3,166.3	3,314.8	3,405.9
m^2				**Agricultural land**	mkm^2			
FRDRMZ	FRD	B2050	B2015		B2015	B2050	FRD	FRDRMZ
675.5	583.2	569.1	738.9	DAIRY	5.4	5.4	5.5	6.4
0.0	762.2	1,120.4	1,404.6	REDMEAT	10.4	10.6	7.2	0.0
89.2	57.5	79.0	100.5	WHITEMEAT	0.7	0.7	0.5	0.8
2,608.6	3,130.4	3,421.0	4,025.0	TOTAL	29.7	32.4	29.6	24.7
kgCO2e				**GHG emissions**	MtCO2e			
FRDRMZ	FRD	B2050	B2015		B2015	B2050	FRD	FRDRMZ
82.6	82.7	95.2	89.0	DAIRY	655.9	900.5	782.2	781.2
0.0	171.3	290.3	225.1	REDMEAT	1,658.8	2,746.9	1,620.2	0.0
33.2	33.3	58.7	60.8	WHITEMEAT	448.3	555.3	314.6	314.3
1,088.2	1,280.4	1,400.6	1,248.9	TOTAL	9,205.6	13,250.7	12,113.3	10,295.6

Positive trend
Negative trend

Notes: m^3 = cubic metres; m^2 = square metres; km^3 = cubic kilometres; km^2 = square kilometres; mkm^2 = million square kilometres; kgCO2e = kilogrammes of carbon dioxide equivalent; MtCO2e == Million tonnes of carbon dioxide equivalent.

FRDRMZ scenario since the fall (rise) in animal (plant-based) demands are further accentuated. Comparing with 2050 (2015), global abstracted water use rises 8% (44%), agricultural land falls 24% (17%) and GHG emissions fall 22% (rise 12%). In the latter, the GHG average footprint falls to 1088 kgCO2e/pc/year, or 13% below the corresponding 2015 figure. Although not shown, the plant-based dietary shift increases the virtual demand for cropland by 11% (1,7 mkm^2/year) compared with 2050 and 32% (4,2 mkm^2/year) compared with 2015.

3.3. *A regional impact analysis under dietary changes*

For a selection of world regions, Figs. 4, 5 and 6 show the virtual domestic absorption (right hand side scale), imports and exports (left hand side scale) for blue water, land and GHG emissions. In these figures, 'Asia' is an aggregate of China, India and the Rest of Asia region, whilst 'LatinAme' includes Brazil and the rest of Latin America. In Sections 3.3.3 and 3.3.4, unless otherwise stated, all results are discussed in comparison with the year 2050 in the baseline.

3.3.1. *B2015*

In 2015, Asia accounts for over 60% of global virtual water use and exports 88 km^3/year of water, an important proportion of which is related to rice (33 km^3/year – not shown).[10] Consequently, Asia is found to be a net blue water exporter of 42 km^3/year. Latin America, as an agricultural net exporter, also records blue water net exports of 22 km^3/year. In our calculations, the absence of irrigated water usage directly in livestock consumption, housing and cleaning explains why Oceania, as a major agricultural exporter of meat products, does not figure as a net exporter of virtual water trade. The EU, driven by (extra-EU) imports of (inter alia) fruit and vegetables, sugar, beverages and tobacco and other crops and other processed foods, is a net importer of blue water of 18 km^3/year. The Middle East and Sub-Saharan Africa are also blue water deficit regions, led by import demands for horticultural products and rice in the case of the former, and rice imports in the case of the latter.

Virtual global agricultural land use from food purchases is mainly attributed to Asia (27%), Sub-Saharan Africa (24%) and Latin America (14%). As major agricultural exporting regions, Oceania and Latin America are net exporters of land, at 513 thousand km^2/year (tkm^2/year) and 280 tkm^2/year, respectively. Significant internal absorption of resources in Asia and Sub-Saharan Africa renders both as net importers of land. The Middle East is also a large net land deficit region (276 tkm^2/year), attributed to its grains imports, whilst EU food diets generate net land leakage of 156 tkm^2/year, motivated largely by red meat and horticultural consumption.[11]

Examining global diet driven virtual GHG emissions, 37% corresponds to Asia (3438 MtCO2e/year), although due to the dietary customs, approximately only 20% of Asia's total is attributed to meat and dairy consumption. By contrast, Latin America's food demand generates 942 MtCO2e/year, of which 554 MtCO2e/year corresponds to meat and dairy. Similarly, in Sub-Saharan Africa, where livestock management practises are less developed, and despite relatively lower meat and dairy consumption in the daily diet, meat and dairy consumption emissions account for 51% of Sub-Saharan Africa's total.

3.3.2. *B2050 vs B2015*

By 2050, Sub-Saharan African blue water demand rises 102% to 217 km^3/year, driven by rapid increases in population of 980 million and per capita real incomes. With these same drivers, there is a 34% increase (from a large base) in Asian blue water demand compared with 2015. Elsewhere, Oceania records a 64% proportional increase in blue water demand (from a low base). In developed regions (North America and EU) blue water demand is below the global rate of increase, owing to moderate population increases and the plateauing of expected daily nutrient intake. Examining virtual trade flows, by 2050 the Sub-Saharan

[10] Examining the data in MAGNET, in China, India and the Rest of Asia, due to the choice of diet, the irrigated share of cropland is 43%, 36% and 33%, respectively.

[11] A side calculation reveals that if the UK had been included in the EU, the agricultural land deficit would have been 229 tkm^2/year. This is due to the UK's commonwealth trade ties with Oceania, which influences meat trade.

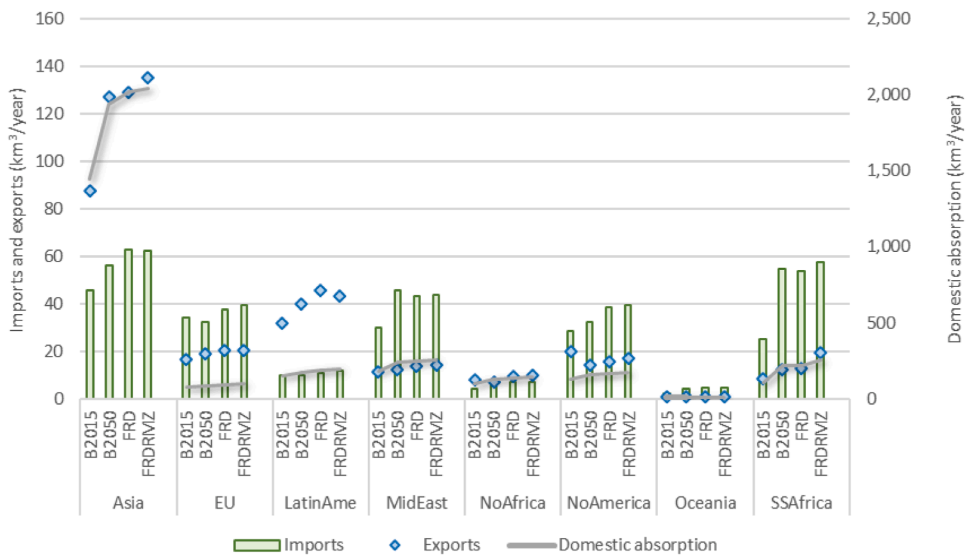

Fig. 4. Domestic absorption and trade of blue water by regions and scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

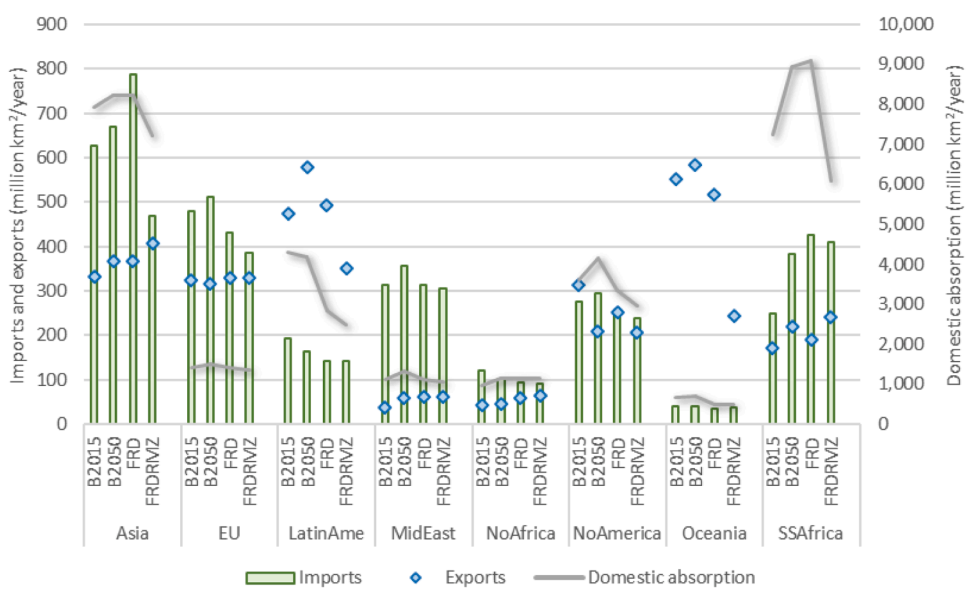

Fig. 5. Domestic absorption and trade of agricultural land by regions and scenarios.

Africa water deficit more than doubles to 42 km^3/year, whilst in the Middle East the water deficit rises to 33 km^3/year. The main net balance improvements occur in Asia (through increases in rice exports – not shown).

By 2050, global virtual land trade rises 9% (2698 tkm^2/year). Population change in Sub-Saharan Africa and the Middle East, drives agricultural land rises of 23% (1682 tkm^2/year) and 19% (216 tkm^2/year), respectively, with concomitant trade balance deteriorations. Oceania, by contrast, improves its virtual land trade surplus by 31 tkm^2/year. In the EU, the 6% increase in diet driven land consumption is met by notable rises in land imports such that EU 'land leakage' increases a further 39 tkm^2/year. Notable diet driven cropland increases of between 30 and 40% are exhibited in regions with either strong food demand (Sub Saharan Africa, North Africa, the Middle East) or significant cropland intensive exports (North America).

Compared with the global average emissions rise of 44% by 2050, food demand driven emissions rise 97% and 53% in North Africa and the Middle East respectively. In Sub-Saharan Africa, the corresponding emissions rise is 168%, such that the global share of food demand driven emissions from this continent rises from 11% in 2015, to 20% by 2050. Accompanying the rise in emissions, global virtual emissions trade rises 29% (132 MtCO2e/year) by 2050. With rising per capita incomes and population, increasing demand for meat products increases the net exports of emissions in both Latin America and Oceania by 48 MtCO2e/year and 42 MtCO2e/year, respectively.

3.3.3. FRD scenario vs B2050

Regions where the adjustment required to meet the recommended plant-based diet is more severe, lead to proportional blue water requirement rises of up to 14% in Oceania, and 10% in the EU. In this scenario, global trade of virtual water rises 18 km^3/year (7%). The net blue water trade deficit reported for the EU and North America increase by 5 km^3/year and 4 km^3/year, respectively.

For agricultural land, the largest proportional reductions are in Latin America (32% or 1322 tkm^2/year) and Oceania (31% or 216 tkm^2/year). In regions where the recommended diet is only imposed partially

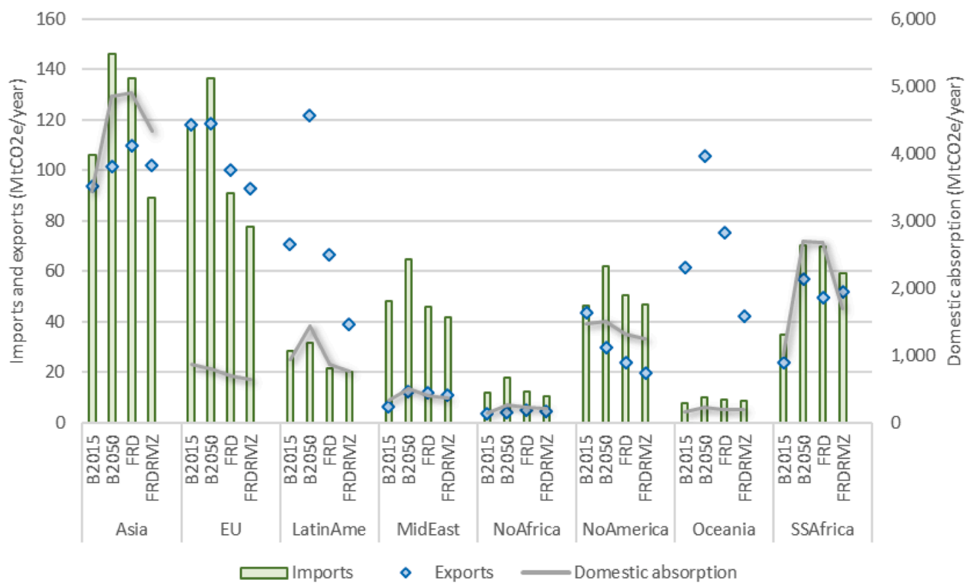

Fig. 6. Domestic absorption and trade of GHG emissions by regions and scenarios.

(Asia) or is absent (Sub-Saharan Africa), there is a 'rebound' effect arising from falling meat and dairy prices due to falling world demand for meat and feed inputs. As a result, both regions' virtual imports of agricultural land rise, whilst Sub-Saharan Africa's virtual agricultural land exports fall to cover rising internal absorption. Globally, this scenario reduces global virtual land trade by 56 tkm^2/year, whilst agricultural land leakage arising from the EU and North American food demand is greatly reduced, resulting in significant reductions in third country virtual agricultural land dependence. Proportional rises in world-wide cropland demand to maintain the dietary nutrient balance, are strongest in the EU (18%) and North Africa (12%).

A notable reduction in global virtual emissions applies in all regions except Asia (cultural exceptions to the diet) and Sub-Saharan Africa (affordability constraints on the reference diet). In Latin America, the diet switch reduces associated GHG emissions by up to 40%, whilst in the EU, North America and Latin America this scenario reverses diet driven emissions 21%, 11% and 8% respectively, below 2015 levels. Global trade in emissions falls 19%. Significant reductions in EU GHG emissions imports improves its trade balance 27 MtCO2e/year. Similarly, steep reductions in GHG emissions exports by the net meat exporting regions of Latin America and Oceania lead to GHG emissions trade balances falling by 46 MtCO2e/year and 36 MtCO2e/year, respectively.

3.3.4. FRDRMZ scenario vs 2050

The 8% global average rise in blue water requirement is accompanied by proportional rises of 18% in Sub-Saharan Africa, 14% in the EU and 12% in North America and Latin America. In absolute terms, much of the global increase is absorbed by Asia, which expands production of blue water intensive rice to meet increased crop-based demands. Across the regions, global agricultural land savings are driven by land requirement reductions in Latin America (41%) and Sub Saharan Africa (32%). As a result, agricultural land requirements in all regions, (except North Africa) are below 2015 levels. Compensatory swings toward cropland (not shown) are as high as 26% in the EU. With severe contractions in red meat demand, the virtual balance of agricultural land trade in Oceania and Latin America reduces 338 tkm^2/year and 205 tkm^2/year, respectively.

In all regions, diet driven emissions are well below 2050 levels. Indeed, in the Americas and the EU, they are also below 2015 emissions levels. In Asia, Oceania, and the Middle East, GHG emissions are 26%, 22% and 14% above 2015 levels. Significant BAU increases in GHG emissions in the African continent means that even in this scenario, Sub Saharan African and North African diet driven emissions remain 69% and 62% above 2015 levels. Global virtual emissions trade falls by 63 MtCO2e/year compared with 2015 and 195 MtCO2e/year compared with 2050. As a result, the largest GHG emissions trade balance reductions occur in Latin America and Oceania.

3.4. Food expenditures – comparing the reference diet with the baseline

Fig. 7 presents the impacts of changing diets on average per capita food expenditures in euros per year (pc/year) by 2050 compared with the baseline across a selection of regions. By 2050, it is estimated that the world-wide average expenditure on food is €1017 pc/year. At the lower end, India, Sub-Saharan Africa (SSAfrica) and China are estimated to spend €438 pc/year, €588 pc/year and €801 pc/year, respectively. The most expensive food expenditures are registered in North America (NoAmerica), Oceania and the European Union (EU) (€3193 pc/year, €2803 pc/year and €2433 pc/year, respectively).[12]

The resulting impacts on per capita food expenditure by region arising in the FRD scenario, depend upon the size of the daily kcal adjustment to plant-based diets, the associated cost of natural resource slack to accommodate changing food diets and the degree of import dependence on, and affordable access to, third country markets across different food commodities. The results show that by 2050, the switch to the reference diet moderately raises average food consumer costs world-wide to €1044 pc/year (2.6%). Decomposing by commodity, there are average global expenditures savings on meat and dairy of €88 pc/year. There are accompanying average per capita expenditure rises on the remaining part of the food basket of €115 pc/year. At the regional level, the switch to the healthy diet results in food expenditure savings in Russia, North America, the EU, China and Sub-Saharan Africa. Elsewhere, the diet switch increases food expenditures, where in India the rise in average per capita food expenditure is €176 pc/year, or 40% above the BAU 2050 level. In large part, this is motivated by the rising cost of fish due to the fact that average Indian consumption remains someway below global levels, whilst the switch to greater fish consumption is magnified by the projected 373 million rise in the Indian population.

[12] The supplementary materials document compares the MAGNET model results for food expenditures in 2015 with official secondary data.

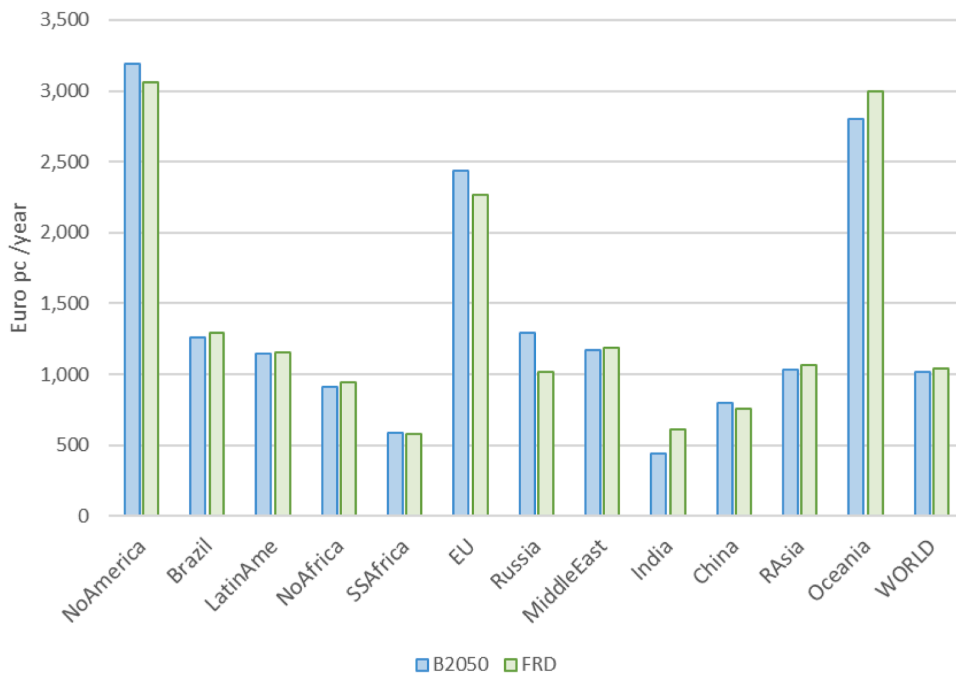

Fig. 7. Average per capita food expenditure in 2050: Baseline vs FRD scenario (euro pc/year). Notes: NoAmerica = North America; LatinAme = Latin America; NoAfrica = North Africa; SSAfrica = Sub-Saharan Africa; Rasia = Rest of Asia; B2050 = Baseline projection in 2050 (Business as Usual); FRD = Feasible Reference Diet.

4. Discussion

In the baseline period from 2015 to 2050, we report a 51% increase in agricultural production (not shown), compared with the 50% increase reported in FAO (2018) between 2012 and 2050. Our results show that this corresponds to rises of 34% in blue water, 9% in agricultural land, and a 44% increase in GHG emissions. In FAO (2018), a 20% rise in agrifood related GHGs is reported. In Springmann et al. (2018), from 2010 to 2050, they report blue water and cropland use rises of approximately 60%, whilst GHG emissions rise by as much as 90%. The reason for these differences is that our study also considers technology change and land-biased productivity improvements.[13] Indeed, the strong mitigating impact of expected technology change on resource usage is supported by Alexandratos and Bruinsma (2012), who estimate that between 2010 and 2050, 80% of future crop demand will be met by yield improvements. Notwithstanding, our baseline results still expose regional 'pressure points' for blue water (e.g., Sub-Saharan Africa, Asia) and agricultural land and GHG emissions (e.g., Sub-Saharan Africa, North Africa and Middle East).

A further point is the trade-off that emerges through the switch to plant-based diets. In the current study, by 2050, global blue water and cropland requirements rise 5%, accompanied by 9% falls in both agricultural land and GHG requirements. Springmann et al. (2018) estimate a GHG emissions fall of 29% and water and cropland savings of between 5 and 9%. Willett et al. (2020) report global GHG emissions falls of 49%, whilst cropland remains relatively static and irrigated water use rises by between 1 and 9%. The more optimistic nature of the estimates in Springmann et al. (2018) may be explained, at least partially, by their assumption of energy intake in line with recommendations on healthy body weight and physical activity, and our exclusion of Sub-Saharan Africa from adopting the healthy diet, as well as specific cultural exceptions across certain regions for red meat, white meat and dairy. Moreover, the switch to plant based diets may be more pronounced in our study due to a higher global population projection by 2050.[14] From a technical perspective, results differences between studies are also driven by different parametric assumptions in the (food) demand systems of the models.

The results also require careful interpretation. For blue water, both here and in Springmann et al. (2018), the measure is pessimistic, since meat and dairy driven virtual water demand is only embedded in animal feeds. To contextualise this observation, FAO (2019) report that the water balance of a Holstein cow is 67% drinking water, a large proportion of which is blue water. In pig rearing, FAO (2019) suggest that well over 90% of blue water usage relates to drinking, cleaning and housing. As a result, reference diet reductions in meat and dairy intake, would generate significant additional savings in blue water needs, not captured in this study.

The agricultural land saving effect from diet change is driven by reductions in permanent pasture, whilst the global cropland requirement rises 19% in the baseline, and an additional 5% by 2050, with the switch to plant-based diets. The issue of land transfer from permanent pasture to arable land is explicitly assumed to be sluggish in our model, although it remains an open question whether required cropland increases in some regions can feasibly match the dietary change. Furthermore, pasturelands constitute an important net carbon sink source and are rich in biodiversity, both of which are aided by managed animal grazing. Thus, the carbon stock in suitable pasturelands, if ploughed for cropping, would be released into the atmosphere (e.g., Vellinga et al., 2004, Willems et al., 2011), with concomitant losses in biodiversity. These land use change effects are not captured in this study.

The reference diet increases average food expenditures 2.6% worldwide. Our results show that in regions with a combined population in 2050 of 3,1 billion people (e.g., India, Middle East, North Africa and

[13] These land productivity improvements are taken from a bottom-up biophysical land use model called IMAGE (Daioglou *et al.*, 2015).

[14] The "middle of the road" population projections in Shared Socioeconomic Pathway two used by Springmann et al. (2018) projects a world population of 8.6 billion by 2050. In the GECO study used here, world population reaches 9.5 billion by 2050.

Latin America), they could face rises in the food bill, mainly due to the strong increase of fish protein in the diet. Moreover, it should be noted that the recommended diet change is not applied in Sub-Saharan Africa. The results therefore support the view in Hirvonen et al. (2020) that healthy diet change could indeed result in food expenditure exceeding available income for the most vulnerable sections of society, while improving the overall nutritional situation.

A further point of discussion surrounds the economy-wide impacts arising from this societal shift in preference pattern. Firstly, this study assumes that consumers 'choose' to adopt responsible meat and dairy consumption patterns through moral suasion (i.e., media awareness campaigns regarding animal welfare and environment, lifestyle changes to flexitarian/vegetarian/vegan diet). On the other hand, the price and fiscal implications from more direct market interventions to change consumption patterns akin to 'sugar' or 'fat' taxes, are not considered. Moreover, the endogenous beneficial causal linkage between improved nutritive quality, increased cognitive capacity and labour productivity improvements is not modelled here. Nor is there any consideration of the expected health expenditure savings to the taxpayer. Indeed, Global Panel on Agriculture and Food Systems for Nutrition (2016) suggest that undernutrition could be costing the Asian and African economies up to 11% in GDP per year. If improved diets had even a partial impact, and if managed properly through redistributive fiscal policies, the virtuous circle of economic growth, prosperity improvements and greater food purchasing power compounded over time, could be considerable.

From a methodological perspective, the virtual flow and footprint estimates reported here contain a degree of uncertainty. As noted above, the data supporting some model calculations is partial (i.e. blue water relating to crop use only, land use change effects and carbon sinks ignored within the carbon cycle). Furthermore, the underlying GTAP database relies on input-output (IO) data contributions from network members with varying reference years. Thus, for some countries, the structure of the IO relationships may be outdated. Moreover, on receipt of said data submissions, the GTAP centre also implements manipulations to the IO data to meet macroeconomic, trade, protection and energy data targets to accommodate the accounting balance requirements of CGE modelling. As a result, some further perturbations in the resulting data structures from the original source IO data, may occur. Notwithstanding, whilst alternate data sources such as EXIOBASE[15] and WIOD[16] are available, it is difficult to judge and compare the degree of accuracy of one data source over another. At the current time, all are anchored to a similarly recent benchmark year, whilst in terms of commodity and regional coverage, each dataset offers its own merits. As a final point, by lacking a stochastic behavioural element, 'deterministic' simulation modelling approaches are less adept at capturing issues relating to uncertainty and market risk, whilst they should not be considered as forecasting models since monetary and fiscal policy drivers are held constant over the time frame of the experiment.

Despite these methodological caveats, an advantage of this work is that virtual commodity intensities by region are internalised within the model solution. Thus, a fruitful avenue of further research, subject to the availability of additional comprehensive and consistent global datasets, would be to extend this approach to consider additional virtual flow indicators (e.g., fertiliser application, biomass content, employment).

5. Conclusions

The issue of diet quality is not explicitly quantified within the Sustainable Development Goals, although Willett et al. (2020) provide a quantifiable definition of a healthy reference diet. This study employs a global computable general equilibrium (CGE) simulation model to assess the sustainability impacts from a switch to healthy diets in terms of the embedded virtual demand for irrigation (blue) water, agricultural land and greenhouse gases (GHGs) emissions. An underlying conclusion is that even a switch toward a plant based diet assuming unchanged average per capita calorie intake, can have important impacts on our planetary boundaries. In global terms, the diet switch strongly contributes to the reduction of GHG emissions from the food system, but also invokes resource trade-offs. More specifically, by 2050, increasing blue water and cropland requirements are accompanied by savings in permanent pasture and (in particular) GHG emissions, whilst average per capita annual food expenditure is expected to rise slightly.

For the regions, compared with 2050, plant-based healthy diets drive percentage increases in blue water requirements in Oceania and the EU, met partly by rising blue water exports from Asia. Important agricultural land savings in Latin America and Oceania from falling demand for meat and dairy, are accompanied by proportional cropland increases in the EU and North Africa. For reducing GHG emissions, the healthy diet is found to have substantial mitigating benefits, particularly in Latin America. Interestingly, with diet switching behaviour in other regions, Sub-Saharan Africa benefits from a 'rebound' effect as meat and dairy affordability is increased. Under the extreme assumption of eliminating red meat from the household diet, the above reported virtual resource trends are accentuated. In particular, global diet driven emissions fall back to 12% above 2015 levels.

The affordability considerations regarding healthy diets are highlighted, mainly due to the higher price of fish protein. Nevertheless, public policy steered initiatives to enhance economic performance through improved diets represent important investments in human capital leading to virtuous circles of growth, incomes and prosperity for human development. To kick-start this process, concerted action and leadership by higher-income countries is essential. This could take the form of knowledge sharing and investments in improved food logistics, educational programs to encourage responsible eating patterns from a young age, including waste avoidance, and in the shorter term, direct government intervention to grant improved and more affordable access to food.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105460.

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