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Quantifying synergies and trade-offs in the global water-land-food-climate nexus using a multi-model scenario approach

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Abstract

The human-earth system is confronted with the challenge of providing a range of resources for a growing and more prosperous world population while simultaneously reducing environmental degradation. The sustainable development goals and the planetary boundaries define targets to manage this challenge. Many of these are linked to the land system, such as biodiversity, water, food, nutrients and climate, and are strongly interconnected. A key question is how measures can be designed in the context of multi-dimensional sustainability targets to exploit synergies. To address this, a nexus approach is adopted that acknowledges the interconnectedness between the important sub-systems water, land, food, and climate. This study quantifies synergies and trade-offs from ambitious interventions in different components of this water-land-fod-climate nexus at the global scale. For this purpose, a set of six harmonized scenarios is simulated with the model of agricultural production and its impact on the environment and Integrated model to assess the global environment models. The multi-model approach improves robustness of the results while shedding light on variations coming from different modelling approaches. Our results show that measures in the food component towards healthy diets with low meat consumption have synergies with all other nexus dimensions: Increased natural land improving terrestrial biodiversity (+4% to +8%), lower greenhouse gas emissions from land (−45% to −58%), reduced irrigation water withdrawals to protect or restore hydrological environmental flows (−3% to −24%), and reductions in nitrogen surpluses (−23% to −35%). Climate mitigation measures in line with the Paris Agreement have trade-offs with the water and food components of the nexus, as they adversely affect irrigation water withdrawals (+5% to +30% in 2050 compared to reference scenario) and food prices (+1% to +20%). The analysis of a scenario combining all measures reveals how certain measures are in conflict while others reinforce each other. This study provides an example of a nexus approach to scenario analysis providing input to the next generation of pathways aiming to achieve multiple dimensions of sustainable development.

1. Introduction

The human population is expected to grow to around 9.4–10.1 billion people in 2050 and to become wealthier (Dellink *et al* 2017, UN 2019). These developments lead to continued increases in the use of key natural resources such as land, water, and energy, thereby further aggravating environmental degradation throughout the world (UNCCD 2017, FAO 2018). A crucial question is how the provision of natural resources to sustain societies can be reconciled with maintaining a sustainable state of the environment and how this can be achieved. Climate change impacts further exacerbate these challenges (IPCC 2019).

The ambition to achieve sustainable resource use and protect the environment along multiple dimensions is manifested in the sustainable development goals (SDGs) (UN 2015) and the planetary boundaries (PBs) (Rockström *et al* 2009, Steffen *et al* 2015). The SDGs and PBs cover a wide range of topics including socio-economic targets on energy and food security as well as environmental ambitions on excessive nutrient use and climate change. Implementing policies to achieve certain goals without considering interactions might negatively impact other goals. For example, climate change mitigation could involve large-scale bioenergy deployment which might negatively affect food security and terrestrial biodiversity (Hasegawa *et al* 2015, Smith *et al* 2016). On the other hand, policies might also synergistically benefit other targets, for example achieving universal electricity access in Sub-Saharan Africa could greatly reduce respiratory diseases as well as deforestation (Dagnachew *et al* 2018). Understanding these interlinkages and accounting for potential synergies and trade-offs is crucial to design effective policies and to achieve policy coherence (Nilsson *et al* 2016, UN Environment 2019).

To take many relevant relationships into account, a nexus approach is useful. It recognizes that components of a system are inherently interconnected and must be investigated and managed in an integrated, holistic manner (Hoff 2011). A meta-study investigating the literature on the water-energy-food nexus found that only 30% of nexus studies applied quantitative methods (Albrecht *et al* 2018). The majority of these studies focus on the local or regional scale (Karlberg *et al* 2015, Yang *et al* 2016). Nexus studies with a global perspective have been relatively few, although the number is increasing (Obersteiner *et al* 2016, OECD 2017, Humpenöder *et al* 2018, Van Vuuren *et al* 2019). To our knowledge this is the first multi-model study on the global nexus. While modelling at the global scale inherently involves simplifications and high uncertainty, the global scale of the challenges concerned makes it important to also assess them on the global level in addition to local and regional studies. Global-level modelling studies make it possible to define overall targets, to guide policy ambitions and to pinpoint risks for policy coherence. Integrated assessment models, originally designed to study the interactions between the energy, land, and climate systems, are developing their representation of multiple sustainable development dimensions and the nexus (van Soest *et al* 2019). As they already represent numerous human-environment interactions and possible policy interventions, they are well-suited for global quantitative nexus assessments (Johnson *et al* 2019).

The goal of this study is to quantify synergies and trade-offs in the water-land-food-climate (WLFC) nexus based on a multi-model scenario analysis at the global scale while also accounting for local relationships. The analysis uses a set of scenarios with harmonized assumptions and input that focus on aspects broadly related to the land system such as biodiversity, water, food, nutrients and climate. The four components of the WLFC nexus are selected as developments in each of these components affects and is affected by the other components. Furthermore, they are at the core of the PB concept (Rockström *et al* 2009, Steffen *et al* 2015) and central to the SDGs (UN 2015). Six scenarios are simulated: one business-as-usual scenario, four scenarios focusing on measures in individual nexus components, and one scenario combining measures in all nexus components. The scenario focusing on water addresses excessive water use and negative implications for aquatic biodiversity (Vörösmarty *et al* 2010), which corresponds to the PBs on freshwater use and the nitrogen cycle as well as to SDG6 on Clean Water. The scenario focusing on land represents an ambitious conservation scheme that protects half of the earth to support terrestrial biodiversity (Wilson 2016), which responds to the PBs on biodiversity loss, the nitrogen cycle and land-use change and to SDG15 on Life on Land. The scenario focusing on food addresses the importance of healthy diets and their impact on the environment (Stehfest *et al* 2009, Springmann *et al* 2018), in line with the EAT-Lancet report proposing healthy diets from sustainable food systems (Willett *et al* 2019) and SDG2 on Zero Hunger. The scenario focusing on climate aims to limit climate change to reduce its risks and impacts in line with the Paris Agreement (UNFCCC 2015) as well as the PB on climate change and SDG13 on Climate Action. In all the scenarios, climate change impacts and adaptation are taken into account. The scenarios are analysed using the following set of indicators: Irrigation water withdrawal, natural land, food prices, land-based greenhouse gas (GHG) emissions and nitrogen surpluses in agriculture.

The scenarios are implemented in two models: The land-systems modelling framework model of agricultural production and its impact on the environment (MAgPIE) 4.3 (Dietrich *et al* 2019) and the integrated assessment model integrated model to assess the global environment (IMAGE) 3.2 (Stehfest *et al* 2014, Van Vuuren *et al* 2021). Both models cover the WLFC nexus in high detail and are extensively applied to study these topics (Humpenöder *et al* 2018, Van Vuuren *et al* 2019). While the representation of biophysical components (crop yields, water and carbon) is similar in both models, the solution concepts and methods differ. MAgPIE is a partial equilibrium model of the agricultural sector, which is solved recursive dynamically with the objective function of cost minimization (optimization model). IMAGE combines a global general equilibrium approach with a grid-based analysis and high biophysical detail. By implementing these scenarios in two models the variation in results dependent on modelling approaches is highlighted: this provides additional insights and improves the robustness of the results.

2. Methods

In this study, we implement a set of six scenarios with harmonized assumptions covering different components of the nexus in the MAgPIE and IMAGE models. The models are described in section 2.1 and in further detail in SI sections 1.2 and 1.3 (available online at stacks.iop.org/ERL/17/045004/mmedia). Detailed descriptions of the scenarios, assumptions and input data are provided in sections 2.2 and SI section 1.5. The results are analysed and compared across models, scenarios and at the global and regional level using a set of five indicators as described in section 2.3. Additional detail on the modelling procedures and key differences and similarities in IMAGE and MAgPIE is provided in SI section 1.4.

2.1. Model descriptions

2.1.1. MAgPIE

The MAgPIE 4.3 modular open-source land-systems modelling framework[7] (Dietrich *et al* 2019) simulates possible future land-use patterns and crop production using a recursive dynamic partial equilibrium approach (Lotze-Campen *et al* 2008) (for detailed model description see SI section 1.2). Based on biogeophysical inputs at 30 arc-minute spatial resolution from the global dynamic vegetation, crop and hydrology model LPJmL (Bondeau *et al* 2007, Müller and Robertson 2014), country-level socio-economic data and policy scenarios, it derives optimal land use patterns and future land-use changes. The objective is to meet global food (Bodirsky *et al* 2020), feed (Weindl *et al* 2017a, 2017b), material and bioenergy demand (Popp *et al* 2011) while taking international trade (Schmitz *et al* 2012), resource constraints (land, water, and nutrient availability), biophysical conditions (spatially explicit crop and pasture yields, carbon densities) and possible future socio-economic scenarios into account.

To determine the optimal amount, type, and location of agricultural production, MAgPIE's constrained optimization follows a global production cost minimization approach (Popp *et al* 2011). Future food demand is estimated based on food intake, dietary composition, and food waste. Food intake is projected based on population size, per capita income, sex and age structure, and the population's physical activity level, while dietary composition and food waste ratio depend in the model solely on per-capita income (Bodirsky *et al* 2020). Feed demand depends on regional livestock production and regionally-dynamic feed efficiencies and dynamic feed basket composition (Weindl *et al* 2017a, 2017b). Bioenergy demand is set exogenously (Popp *et al* 2011, Klein *et al* 2014, Kriegler *et al* 2017), but MAgPIE endogenously determines the optimal location of the three biomass types (bioenergy grasses, bioenergy trees, and residues). Climate change affects production via its impacts on available water and attainable yields that are provided by LPJmL leading to adaptation in the food system such as changes in crop type, spatial relocation within a region, international trade, irrigation, or management intensification. GHG emissions arise from the transformation of natural land into cropland or pastureland as well as from livestock and cropland production. N_2O emissions are accounted for in the Nitrogen (N) flow module (Bodirsky *et al* 2012, 2014) that transforms all biomass flows into N flows.

2.1.2. IMAGE

IMAGE 3.2 is an integrated assessment modelling framework[8] that simulates the interactions between human activities and the environment (Stehfest *et al* 2014) to explore long-term global environmental change and policy options in the areas of climate, land, and sustainable development (for detailed model description see SI section 1.3). IMAGE consists of various sub-models describing land use, agricultural economy, the energy system, natural vegetation, hydrology, and the climate system. Socioeconomic processes are modelled at the level of 26 regions. Most environmental processes are modelled on the grid-level at 30 or 5 arc-minutes resolution.

Agriculture, forestry, and land-use dynamics are modelled on the IMAGE-LandManagement model's grid-level (Doelman *et al* 2018). Demand for crop and livestock products, trends in agricultural intensification, and trade dynamics are provided by the economic general equilibrium model MAGNET (Woltjer *et al* 2014). Gridded land-use dynamics are implemented in the dynamic global vegetation

[7] The MAgPIE modular framework code is open-source and can be found on GitHub: https://github.com/magpiemodel/magpie. The code is comprehensively documented under https://rse.pik-potsdam.de/doc/magpie/4.3/ and a model description is available in the model description article published in Geosci. Model Dev. (https://gmd.copernicus.org/articles/12/1299/2019/).

[8] For more information on the IMAGE model visit the online documentation: http://models.pbl.nl/image.

model LPJmL to model effects on the carbon and hydrological cycle (Müller *et al* 2016, Schaphoff *et al* 2018) and to the global nutrient model to model the nitrogen and phosphorus cycles (Beusen *et al* 2015). LPJmL provides data on potential crop and grass yields, land-use change emissions, and irrigation water use while considering the impact of climate change. Adaptation to climate change in the food system is included by informing MAGNET about the regional impact of climate change leading to changes in agricultural production and trade flows. The simulation model TIMER represents the energy system with high technological detail for 12 primary energy carriers, including bioenergy. Land use for the production of bioenergy as determined by TIMER is implemented on the grid-level in IMAGE-LandManagement. GHG emissions from energy, industry, and land use are inputs to the simple climate model MAGICC, which emulates complex climate models to calculate global mean temperature change (Meinshausen *et al* 2011). The climate policy model FAIR-SimCAP uses marginal abatement cost curves (MACC) to determine cost-optimal emission pathways to achieve specific climate targets (den Elzen *et al* 2008).

2.2. Scenario description

In this study, six scenarios are analysed over the period from 2015 to 2050 to shed light on nexus synergies and trade-offs. The reference (REF) scenario is the baseline for all scenarios. The WATER, LAND, FOOD and CLIMATE scenarios focus on improvements in one component of the WLFC nexus each. The TOTAL scenario aims for improvements in all nexus components. Climate impacts and adaptation effects are considered an integral aspect of each nexus component and are accounted for in all scenarios. Specifically, impacts on crop yields, water use and availability, and natural vegetation growth are included, which are key impacts in the WLFC nexus (for more detail see section 2.1 and SI sections 1.2 and 1.3). In the REF, WATER, LAND and FOOD scenarios the RCP 6.0 is used representing impacts under a likely climate change pathway without widespread implementation of climate change mitigation measures (Hausfather and Peters 2020). In the CLIMATE and TOTAL scenarios RCP 2.6 is used representing impacts with climate change mitigation measures in line with a 2 °C target (van Vuuren *et al* 2011). Climate data in line with these RCPs are adopted from the Inter-Sectoral Impact Model Intercomparison Project, specifically using results from the IPSL-CM5a-LR model (Frieler *et al* 2017). The scenarios are described in more detail in the following sections and table 1.

2.2.1. Reference scenario

The REF scenario represents a *business-as-usual* future where trends do not shift markedly from historical patterns. The main drivers follow updated SSP2 scenario trends (O'Neill *et al* 2017, Popp *et al* 2017): This includes continued uneven economic growth with some countries experiencing substantial growth while in other countries growth remains below global average. Population growth levels off slowly as no additional efforts are implemented to speed up the demographic transition. Pressure on the natural system increases from growing demand for food and other biomass uses and climate change.

2.2.2. Water scenario

In the WATER scenario, the focus is on preventing excessive water use and adverse impacts on aquatic ecosystems, in line with the PBs on freshwater use and the nitrogen cycle and SDG6. To achieve this, the quantity of water withdrawals is limited to ensure sufficient water flows in the hydrological system and fertilizer use efficiency is increased to improve water quality. In IMAGE, environmental flow requirements are implemented following the variable monthly flow method developed by Pastor *et al* (2014) where 60%, 45% and 30% of the mean monthly natural flow is reserved for ecosystems in low, intermediate and high flow periods, respectively. MAgPIE follows the method outlined in Smakthin *et al* (2004) that derives the baseflow (low flow requirements) based on the 90th percentile of monthly discharge and high flow requirements based on mean annual runoff depending on the variability of the river flows (Bonsch *et al* 2015). In both models, environmental flow protection measures imply that water withdrawals for irrigation and other uses cannot exceed a prescribed quantity as this would reduce water levels below the respectively prescribed minimum flow requirement. To reduce the impact of excessive nitrogen runoff in the environment on aquatic biodiversity (Howarth *et al* 2011), fertilizer use efficiency is assumed to improve to 70% in MAgPIE. In IMAGE, 70% convergence to a maximum achievable nutrient use efficiency (NUE) based on Zhang *et al* (2015) is assumed (SI section 1.5.4).

2.2.3. Land scenario

In the LAND scenario, the aim is to stop the conversion of natural ecosystems and terrestrial biodiversity loss by an ambitious area-based conservation effort preserving half of the Earth's land to protect nature as proposed in the literature (Wilson 2016, Pimm *et al* 2018). For this purpose, a map of protected areas developed by Kok *et al* (2020) is implemented. This map protects—where possible—50% of the terrestrial area in each ecoregion (Dinerstein *et al* 2017) (SI figure 8; SI section 1.5.3). Expansion of agriculture in these locations is not allowed. To reduce the impact of nitrogen deposition on terrestrial biodiversity (Bobbink *et al* 2010), fertilizer use efficiency is assumed to improve to 70% in MAgPIE. In IMAGE

Table 1. Overview of scenario-specific assumptions and settings.

	SCENARIO					
Measures	REF	WATER	LAND	FOOD	CLIMATE	TOTAL
Environmental flow requirements		Limit water extraction, ensuring sufficient water to ensure a fair condition of aquatic ecosystems				Limit water extraction, ensuring sufficient water to ensure a fair condition of aquatic ecosystems
Biodiversity protection			Biodiversity protection extended to 50% of all terrestrial ecoregions by 2050			Biodiversity protection extended to 50% of all terrestrial ecoregions by 2050
Fertilizer efficiency		Large improvement in fertilizer efficiency	Large improvement in fertilizer efficiency		Moderate improvement in fertilizer efficiency	Very large improvement in fertilizer efficiency
Diet change				Diet change towards healthy diets by 2050 as proposed by Willett *et al* (2019)		Diet change towards healthy diets by 2050 as proposed by Willett *et al* (2019)
Food waste				50% reduction in food waste		50% reduction in food waste
GHG price					GHG price for 2 °C climate mitigation 2030: 55 US\$/tCO_2 2050: 87 US\$/tCO_2	GHG price for 2 °C climate mitigation 2030: 55 US\$/tCO_2 2050: 87 US\$/tCO_2
Bioenergy production					Bioenergy for 2 °C climate mitigation 2030: 61 Ej yr^{-1} 2050: 96 Ej yr^{-1}	Bioenergy for 2 °C climate mitigation 2030: 61 Ej yr^{-1} 2050: 96 Ej yr^{-1}
Climate impacts	RCP 6.0	RCP 6.0	RCP 6.0	RCP 6.0	RCP 2.6	RCP 2.6

70% convergence to a maximum NUE is assumed (SI 1.5.4).

2.2.4. Food scenario

Dietary change towards healthy daily caloric intake, lower meat consumption and increased vegetable and pulses consumption can have considerable health benefits (Willett *et al* 2019) and environmental co-benefits reducing GHG emissions and limiting pressure on the land system (Stehfest *et al* 2009, Springmann *et al* 2018). Also, there is very large potential to reduce waste in the food system, which could further lower agricultural production required to feed the global population (Gustavsson *et al* 2011). In the FOOD scenario, ambitious changes in the food system are assumed towards the year 2050 by implementing a transition towards healthy diets proposed by Willett *et al* (2019), which includes a strong reduction in meat consumption in regions that currently have intake above healthy levels (SI section 1.5.2). Additionally, a reduction in food waste is assumed in line with SDG target 12.3 which aims to halve per capita global food waste and losses at consumer level and along the production and supply chains (UN 2015). In IMAGE this is implemented as a 50% reduction in food waste in all regions. In MAgPIE food waste is reduced to a maximum of 20% of food intake, which is in line with the IMAGE assumption as this amounts to 50% reduction of current food waste ratios in high-income countries.

2.2.5. Climate scenario

In the CLIMATE scenario, global warming is limited to 2 °C above preindustrial temperatures by 2100 to reduce the risks and impacts of climate change (IPCC 2014). Climate mitigation measures are implemented in both models based on a GHG price as calculated by FAIR-SimCAP (climate policy module of IMAGE) in line with a 2.6 W m^{-2} radiative forcing target (SI table 1): The global GHG price increases up to 55 US\$/tCO_2 in 2030 and 87 US\$/tCO_2 in 2050, which is substantially higher than the average European emission trading scheme price in 2010–2020 of about 12 US\$/tCO_2 (Sandbag 2021) and in line with 2 °C scenarios in the literature (Rogelj *et al* 2018). The GHG price steers technical mitigation in non-CO_2 GHG emissions based on MACC (Harmsen *et al* 2019) and protection of all forests and other carbon-rich land cover types (Overmars *et al* 2014, Popp *et al* 2014). The same bioenergy demand from mitigation measures in the energy system is implemented in both IMAGE and MAgPIE, as derived from the energy module of IMAGE (SI table 1) (Daioglou *et al* 2019). This increases up to 96 Ej yr^{-1} in 2050, a strong increase compared to the 4.65 Ej yr^{-1} used in 2015 (IEA 2017), which is required to achieve the ambitious 2 °C mitigation goal. In line with reduced N_2O emissions from fertilizer based on the MACC information fertilizer efficiency is assumed to increase moderately, with 65% in MAgPIE and by 50% in IMAGE relative to the maximum NUE (SI section 1.5.4). For IMAGE, climate mitigation measures are implemented in MAGNET through reductions in land supply due to forest protection, which affects the food system and therefore also food prices. Bioenergy expansion is assumed not to affect food prices based on a food-first approach (Daioglou *et al* 2019). In MAgPIE, mitigation measures affect the food system because of land demand for forest protection, bioenergy use and afforestation (for more detail see SI section 1.5.1).

2.2.6. Total scenario

In the TOTAL scenario, all measures are combined to investigate how they might reinforce or counteract one another (table 1). This includes among others protection of forests and carbon-rich natural land for climate mitigation as well as protection for terrestrial biodiversity purposes, the introduction of healthy diets and reduced food waste, and limitations on water extraction. As improvements in fertilizer use efficiency are implemented in the CLIMATE, LAND, and WATER scenarios, we assume that the measures partially add up implying a very large improvement in fertilizer efficiency in the TOTAL scenario: We assume a 75% increase in MAgPIE and an 80% increase in IMAGE relative to the maximum NUE (SI section 1.5.4).

2.3. Indicator description

A set of indicators as described in the following sections is used to analyse and compare outcomes under different scenarios. All indicators are endogenous results from the models and underlying model dynamics are described in detail in section 2.1 and SI sections 1.2 and 1.3. All indicators are presented and described at the global and the regional level. The regional results are presented at the level of ten world regions (SI figure 1): North America (NAM), Central and South America (CSA), Middle East, and Northern Africa (MEN), Sub-Saharan Africa (SSA), Western and Central Europe (EUR), Russia and Central Asia (RCA), South Asia (SAS), China region (CHN), Southeast Asia (SEA), and Japan, Korea and Oceania (JKO). Additionally, these regions are categorized into different income classes, i.e. high (NAM, EUR, JKO), middle (CSA, MEN, RCA, CHN), and low (SSA, SAS, SEA). Finally, in section 3.6 we analyse synergies and trade-offs by comparing the percentage change in each indicator in each scenario compared to the REF scenario in 2050.

2.3.1. Irrigation water withdrawal

Excessive freshwater use has major impacts on aquatic biodiversity as well as on the availability of water for human use (Vörösmarty *et al* 2010). Water use for irrigation in agriculture is responsible for about 70% of freshwater use globally and therefore of crucial importance. Here we present irrigation water withdrawal, which is an endogenous output of both IMAGE and MAgPIE, defined as the total amount of water in km^3 yr^{-1} extracted for irrigation of crops.

2.3.2. Natural land share

The loss of natural ecosystems due to the expansion of human land use has been the dominant reason for terrestrial biodiversity loss historically (IPBES 2019). Projected development in the share of natural land is therefore a relevant indicator for the impact of human land use on terrestrial biodiversity. To understand the underlying dynamics of these changes, in the results section we present the developments in seven major land use classes in terms of land-use change from 2015 to 2050 in million hectares (Mha): rainfed and irrigated cropland, grazing land, bioenergy, built-up area, forest and other natural land. The simplified indicator share of natural land as presented in the synergies and trade-off analysis includes the two land use classes forest and other natural land and is calculated as the sum of these two classes divided by total terrestrial land area. We do not account for changes in managed forest.

2.3.3. Food price index

Changes in the price of primary agricultural products are presented as a simple indicator of food security (van Meijl *et al* 2020). Both IMAGE and MAgPIE include food prices for a large range of commodities: In the result section we discuss aggregated prices for crop, livestock and total agricultural products to provide additional insight in underlying dynamics. The indicator shows the impact of different nexus measures on the affordability of food and pressure in the food system. It should however be cautioned that final food prices are considerably higher than agricultural commodity prices due to processing and marketing, and that any price variation also gets diluted by the value-added in up-stream supply chains that we do not simulate here. For IMAGE and MAgPIE, the development of average primary agricultural products prices is represented by the Laspeyres index based on a constant food basket in the year 2015. For MAgPIE, the food price index is corrected for the GHG emissions tax revenue to exclude the effect that GHG taxes are passed through to consumers (SI section 1.5.1). The indicator is an index of aggregated changes in food prices from 2015 to 2050.

2.3.4. Agriculture, forestry, and land use (AFOLU) GHG emissions

Total changes in GHG emissions from the AFOLU sectors are assessed as these are indicative of the role of the WLFC nexus on climate change (IPCC 2019). GHG emissions from the AFOLU sector result from numerous activities: Carbon dioxide (CO_2) emissions are predominantly caused by land-use change like the conversion of natural land to agricultural land. Methane (CH_4) and nitrous oxide (N_2O) emissions are mainly caused by agricultural activities such as organic and inorganic fertilizer application, manure management, enteric fermentation from ruminants, and rice production. The indicator used in this study comprises total AFOLU GHG emissions from all aforementioned sectors in terms of CO_2-equivalents.

2.3.5. Nitrogen surplus in agriculture

Excessive nitrogen input into the environment has detrimental effects on terrestrial and aquatic biodiversity (Bobbink *et al* 2010, Howarth *et al* 2011), human health, and the suitability of surface water for human use (van Vliet *et al* 2021). As human impacts on the nitrogen cycle are dominated by agriculture (Liu *et al* 2010), the surplus of nitrogen in the agricultural system (including crop and livestock production) is a good indicator of improving or worsening developments. It describes the difference between the total inputs (sum of nitrogen in manure, fertilizer, deposition and fixation) and output (nitrogen removed by crop and grass harvest and grazing), which can enter the environment in different forms of nitrogen. The indicator represents total surplus of nitrogen in agriculture in million tons of nitrogen per year (Mt N yr^{-1}).

3. Results

3.1. Irrigation water withdrawal

Total global irrigation water withdrawals in the historical period (2015) differ slightly between MAgPIE and IMAGE with 1850 and 2020 km^3 yr^{-1}, respectively (figure 1). Regional discrepancies are larger, with relatively more withdrawals in MAgPIE in low-income regions and more withdrawals in IMAGE in middle-income regions, which is a consequence of differences in irrigation efficiency assumptions, spatial distribution of crop types and cropping intensity of irrigated areas between the models. As estimates for contemporary irrigation water withdrawal show variations up to 30% (Wisser *et al* 2008) the estimates in IMAGE and MAgPIE are fairly well aligned. For the future, MAgPIE shows a substantial increase in water withdrawals in the REF scenario (+240 km^3 yr^{-1} in 2015–2050) resulting from the expansion irrigated areas (figure 2), while withdrawals in IMAGE are nearly constant due to small irrigated area increases and higher water use efficiency.

The measures in the different scenarios mainly affect irrigation water withdrawals in MAgPIE that includes endogenous investments into irrigation infrastructure and therefore is flexible to expand irrigated areas, while irrigated area development in IMAGE is set exogenously and does not change between the scenarios (section 3.2). MAgPIE projects increases in water withdrawals in the LAND and CLIMATE scenarios (+450 and +780 km^3 yr^{-1} in 2050, resp.), mainly in low-income regions and in the case of the CLIMATE scenario for North America. These additional irrigated agricultural areas are due to the pressure on the agricultural system resulting from land protection in both scenarios and additional demand for crop production for bioenergy in the CLIMATE scenario. This leads to higher food prices, making it more worthwhile to invest in irrigation to increase crop production (section 3.3 for further details). In IMAGE, where irrigated areas are set exogenously, only the CLIMATE scenario shows slightly higher withdrawals (+70 km^3 yr^{-1} compared to REF in 2050) as lower levels of CO_2 fertilization reduce irrigation efficiency due to higher transpiration levels. The restriction of irrigation water availability that allows fulfilling environmental flow requirements has a large impact on irrigation water withdrawals in both MAgPIE and IMAGE, resulting in a reduction of −550 and −570 km^3 yr^{-1} respectively in WATER compared to REF in 2050. In the FOOD scenario lower meat consumption and food waste reduce irrigation water withdrawals with a similar order of magnitude in MAgPIE (−510 km3 yr^{-1} compared to REF in 2050) and even lead to lower water withdrawals than in 2015 (−260 km3 yr^{-1} compared to 2015).

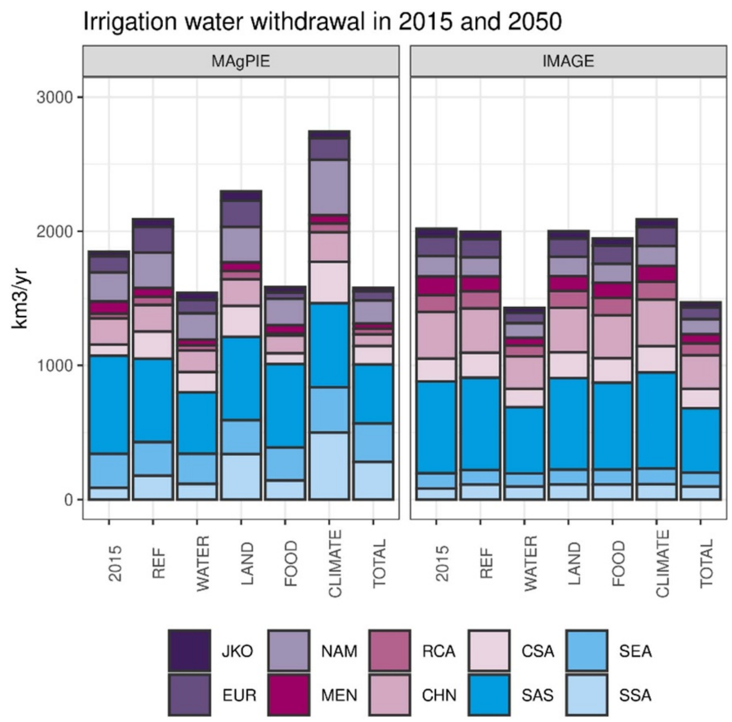

Figure 1. Irrigation water withdrawal in IMAGE and MAgPIE for all regions in 2015 and for all scenarios in 2050 for different regions (high-income: Japan, Korea and Oceania (JKO), North America (NAM), Western and Central Europe (EUR); middle-income: Middle East, and Northern Africa (MEN), Russia and Central Asia (RCA), China region (CHN) Central and South America (CSA); low-income: Sub-Saharan Africa (SSA), South Asia (SAS), Southeast Asia (SEA).

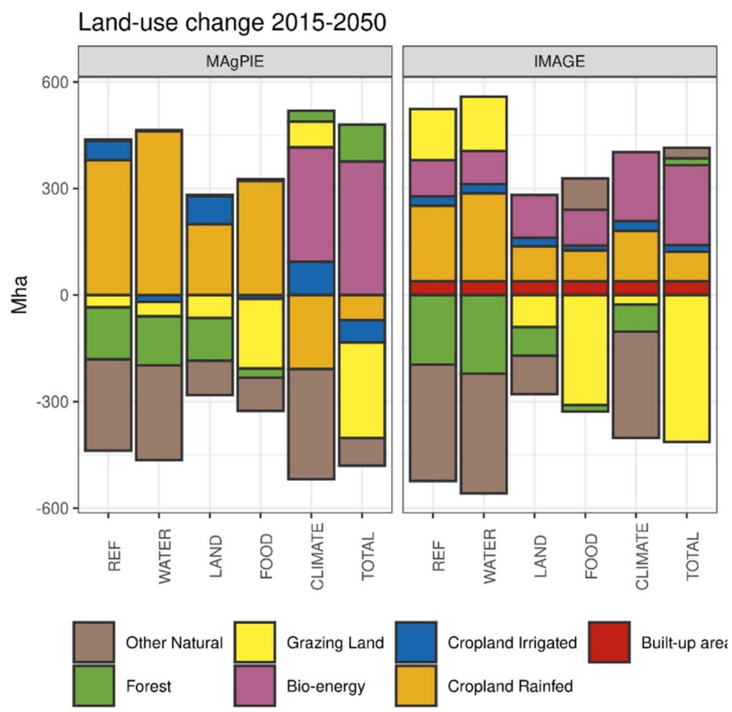

Figure 2. Global land-use change in IMAGE and MAgPIE in the 2015–2050 period for all scenarios for 7 land-use categories. Negative values indicate area reduction in a land use category, positive values indicate expansion of a land use category.

3.2. Natural land share

Changes in natural land (forest and other natural land) (figure 6) are a result of developments in land use by humans, predominantly for agriculture. Both MAgPIE and IMAGE show a substantial increase in agricultural land in the REF scenario in the 2015–2050 period (figure 2). In MAgPIE, this results from expansion in cropland (+440 Mha) while grazing land is slightly reduced (−30 Mha). In IMAGE, both cropland and grazing land expand

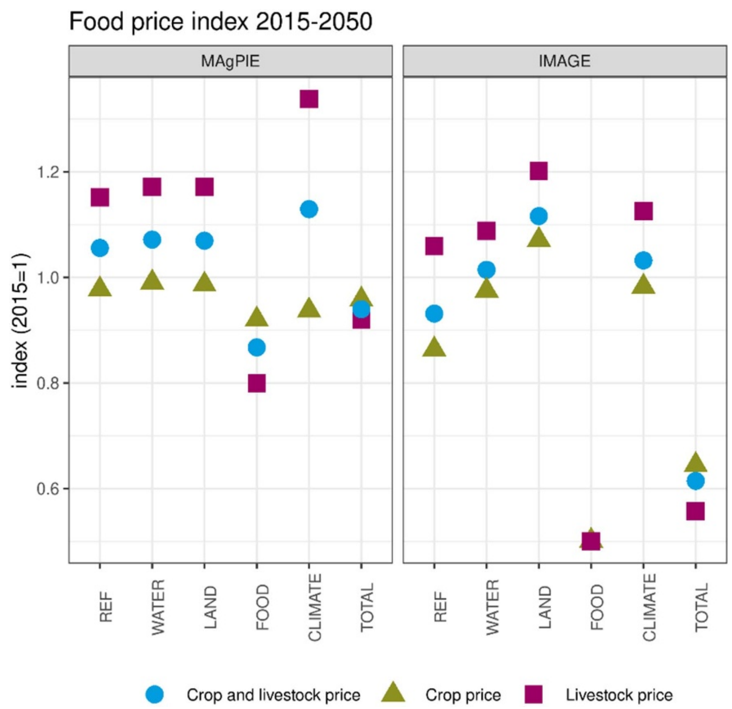

Figure 3. The globally averaged food price index in IMAGE and MAgPIE for crops, livestock, and crops and livestock combined for the 2015–2050 period.

(+340 and +140 Mha, resp.). A substantial share of IMAGE cropland expansion results from increased demand for bioenergy (100 Mha), projected also under business-as-usual conditions while it remains very low up to 2050 in MAgPIE. IMAGE also includes the expansion of built-up area (40 Mha), although this is assumed not to change between the scenarios. Because of these land-use dynamics, natural land decreases substantially in REF in MAgPIE (−400 Mha) as well as IMAGE (−520 Mha), with the largest losses occurring in Sub-Saharan Africa in both models (SI figures 2–4).

Natural land is reduced slightly more in WATER than in REF in both MAgPIE and IMAGE, as yield reductions on irrigated cropland due to irrigation restrictions lead to higher agricultural land requirements to fulfil crop demand. In the LAND scenario, a substantial expansion of protected areas leads to a significant reduction in agricultural land expansion, resulting in lower natural land losses than REF and WATER. In the FOOD scenario, dietary change with lower demand for livestock products drives reductions in grazing land and cropland. IMAGE shows a stronger reduction than MAgPIE as in MAgPIE extensification of grazing land (i.e. reducing animals per hectare) is allowed, while in IMAGE this is assumed not to take place. Consequently, MAgPIE still shows a slight reduction in natural land while IMAGE shows a small increase. The abandonment of grazing land in IMAGE typically occurs on lands with relatively low productivity that often coincide with other natural lands, leading to a small increase in this land use category in the FOOD scenario. The strongest abandonment takes place in IMAGE in Central and South America where livestock production systems typically use a lot of land per animal, resulting in a strong increase in natural land share SI figure 4. In the CLIMATE scenario, protection of forests and other carbon-rich natural lands leads to reduced deforestation, preventing forest loss in both models. In MAgPIE a small increase in forest area is observed as afforestation in line with current national climate policies is included. Simultaneously, a substantial increase in bioenergy production occurs. In the TOTAL scenario the combination of dietary change with pressure on land from protection for biodiversity and forest for climate mitigation leads to substantial reductions in grazing land in both models and reductions in cropland in MAgPIE. Bioenergy increases and counteracts the positive impact on natural land in both models, resulting in eventually only slight increases in natural land.

3.3. Food price index

In the business-as-usual REF scenario, livestock prices increase both in MAgPIE and IMAGE (+15% and +6%, resp.) (figure 3). This is due to strong increases in demand for ruminant meat and dairy products in developing regions such as Sub-Saharan Africa and South Asia (SI figure 5), which causes a relative scarcity of grazing land in these regions leading to higher prices. Crop prices are almost stable in MAgPIE (−2%) while they show a moderate decrease in IMAGE (−14%). In IMAGE, the WATER scenario

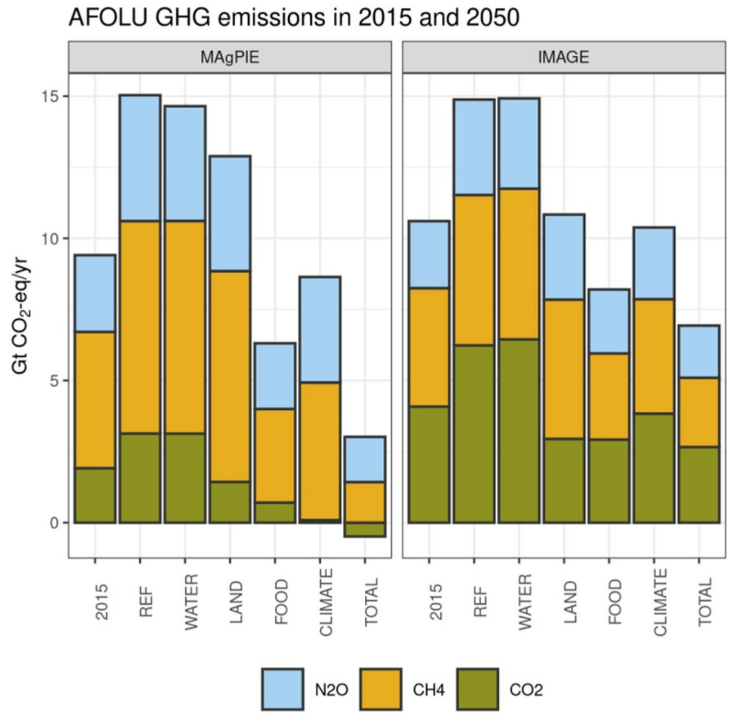

Figure 4. Global CO_2, CH_4, and N_2O emissions in IMAGE and MAgPIE in 2015 and in 2050 for all scenarios for the AFOLU sector.

shows less of a decrease in crop prices compared to the REF scenario due to reduced crop productivity from the reduced application of irrigation in line with environmental flow restrictions (−2% compared to −14%). The same process occurs in MAgPIE, but the assumption on improved fertilizer efficiency outbalances its effects, resulting in negligible change compared to REF. The LAND and CLIMATE scenarios result in increases in food prices due to land protection and increased demand for bioenergy increasing the pressure on the agro-economic system. In FOOD, the opposite effect occurs as diet change leads to reduced demand which lowers the pressure on the agro-economic system leading to strong decreases in both models, most notably in IMAGE. In TOTAL, the latter effect dominates, leading to the second-lowest prices of all scenarios, although the opposite effects of natural land protection, lower irrigated yields and demand for bioenergy somewhat reduce the price decreases. Climate change also impacts agricultural prices with increases in tropical regions due to negative climate change impacts on crop yields. In boreal regions, prices decrease due to positive climate change impacts on crop yields. However, the effect is still quite moderate by the year 2050 and on the global level these counteracting effects level out. Therefore, in our results the impacts of the nexus measures on agriculture prices dominate.

3.4. AFOLU GHG emissions

Both MAgPIE and IMAGE project an increase of GHG emissions from 2015 to 2050 in the REF scenario due to continued expansion of agricultural land and higher agricultural production (figure 4) (5.6 and 4.3 $GtCO_2$-eq., resp.). The LAND scenario, on the other hand, shows substantial reductions in CO_2 emissions as agricultural land expansion is restricted, leading to less conversion of natural land. The same is the case for the FOOD scenario, where also non-CO_2 GHG emissions from agriculture are much lower due to reduced food and feed production. In the CLIMATE scenario, emissions are also substantially reduced due to protection of forests and other carbon-rich natural lands and mitigation measures in agriculture leading to lower emissions from land-use change and reduced non-CO_2 GHG emissions. Emission reductions vary widely between regions, with the largest reductions in land-use change CO_2 emissions in SSA and CSA and major reductions in agricultural non-CO_2 emissions in SAS and CHN (SI figure 6). In the TOTAL scenario, the strongest emission reduction of all scenarios is achieved due to the combination of all measures: In 2050, emissions are reduced by 12.5 and 7.9 $GtCO_2$-eq compared to REF in MAgPIE and IMAGE, respectively.

3.5. Nitrogen surplus in agriculture

For the historical period (i.e. 2015), MAgPIE and IMAGE find surpluses of 146 and 132 Mt N yr^{-1}, respectively (figure 5). Both models show a strong increase of this surplus in REF up to 2050 (+79 and +47 Mt N yr^{-1} compared to 2015, resp.). In MAgPIE the increases predominantly take place in high and low income regions while in IMAGE

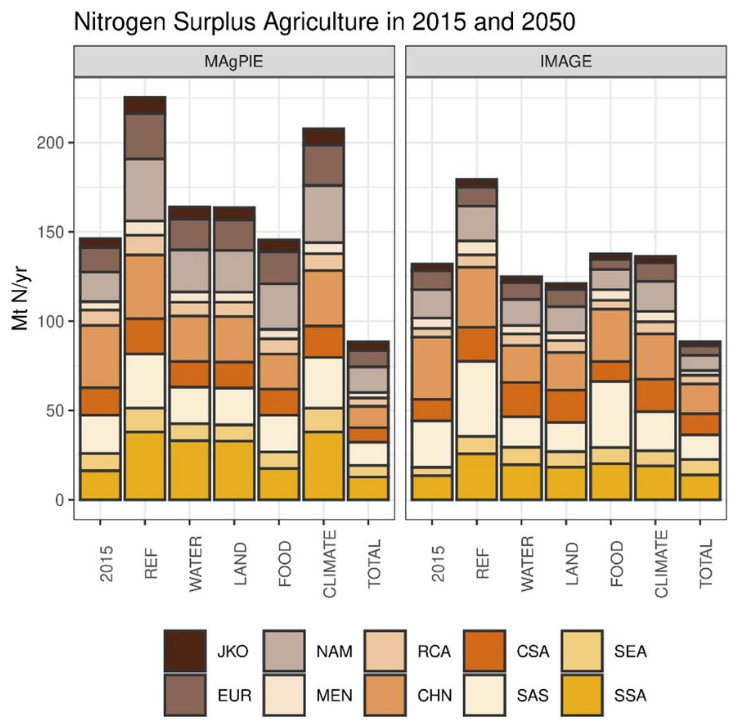

Figure 5. Regional nitrogen surplus in IMAGE and MAgPIE in 2015 and for all scenarios in 2050 for different regions (high-income: Japan, Korea and Oceania (JKO), North America (NAM), Western and Central Europe (EUR); middle-income: Middle East, and Northern Africa (MEN), Russia and Central Asia (RCA), China region (CHN) Central and South America (CSA); low-income: Sub-Saharan Africa (SSA), South Asia (SAS), Southeast Asia (SEA).

Table 2. Global percentage difference of scenario indicators in IMAGE and MAgPIE between the REF scenario and the nexus scenarios in 2050. Colour indication shows where strong synergies occur in green, weak synergies in light green, strong trade-offs in red, weak trade-offs in light red, indicators specifically targeted by measures in a particular scenario in blue, and no substantial change in grey.

Model	MAgPIE					IMAGE				
Scenario	WATER	LAND	FOOD	CLIMATE	TOTAL	WATER	LAND	FOOD	CLIMATE	TOTAL
Water Withdrawal Irrigation	−26%	+10%	−24%	+31%	−25%	−28%	0%	−3%	+5%	−26%
Natural Land Area	0%	+2%	+4%	+2%	+6%	−1%	+4%	+8%	+2%	+8%
Nitrogen Surplus Agriculture	−27%	−27%	−35%	−8%	−61%	−30%	−32%	−23%	−24%	−51%
Food Price	+1%	+1%	−18%	+7%	−11%	+9%	+20%	−46%	+11%	−34%
AFOLU Emissions	−3%	−14%	−58%	−43%	−83%	0%	−27%	−45%	−30%	−53%

almost all increases take place in the low income regions.

The implemented measures lead to substantial decreases in nitrogen surpluses in nearly all scenarios. The only exception is the CLIMATE scenario in MAgPIE that only shows a relatively small reduction as the surplus reduction gained from higher fertilizer use efficiency is cancelled out by higher total fertilizer input for large-scale bioenergy production. The FOOD scenario also leads to lower nitrogen surpluses even though fertilizer use efficiency rates are assumed to be the same as in the REF scenario. This is because of lower total crop production due to less food waste and reduced feed production, and lower losses in animal waste management due to the reduction in livestock product consumption. The TOTAL scenario shows very strong reductions in nitrogen surplus in both models, even below historical levels (−58 and −43 Mt N yr^{-1} compared to 2015 in MAgPIE and IMAGE, resp.), due to the combination of dietary change and strong increases in fertilizer use efficiency.

3.6. Trade-offs and synergies

Here we compare the relative change of all indicators across scenarios, models, and regions by calculating the percentage difference in 2050 between the REF scenario and all other scenarios. These results are used to identify synergies and trade-offs, differences between regions, and robustness of these findings across models (table 2 and figure 6). Synergies and trade-offs are defined as, respectively, positive or negative effects on certain processes, as a consequence of measures that are not specifically targeted at these

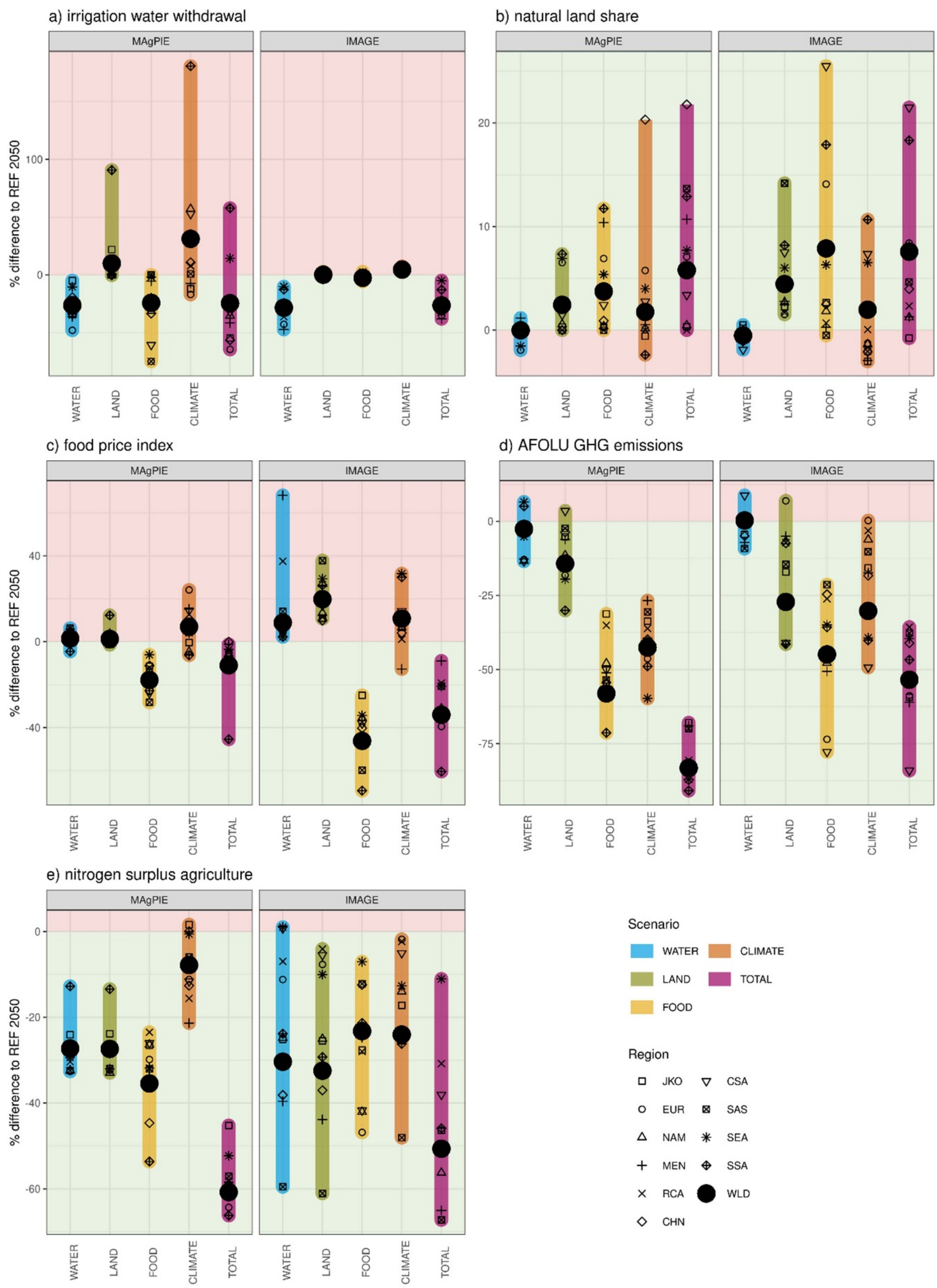

Figure 6. Percentage difference of scenario indicators in IMAGE and MAgPIE between the REF scenario and the nexus scenarios in 2050 for the global total/average and regional variation: (a) irrigation water withdrawal, (b) natural land share, (c) food price index, (d) AFOLU GHG emissions, (e) nitrogen surplus agriculture. The red shaded areas show in which cases the scenario projects a worsening performance compared to REF, the green shaded areas show in which cases the scenario projects an improved performance compared to REF. The graph also shows the regional results and their divergence, in case regional trends differ the bars in the graph become extended.

processes. In the scenarios considered in this study, this is represented by the indicators in each nexus scenario that represent a nexus component that is not the main focus of this particular scenario: For example, AFOLU emissions in the WATER scenario, or irrigation water withdrawal in the CLIMATE scenario.

In the WATER scenario, irrigation water withdrawal and nitrogen surplus in agriculture are specifically targeted by measures and therefore show substantial reductions both in MAgPIE and IMAGE. Food prices show a trade-off compared to REF (+9%) in IMAGE due to lower yields in irrigated agriculture as a result of environmental flow requirements, with a large regional variation as food prices increase much more in the Middle East (+68%) and Russia and Central Asia (+38%) because irrigation plays such an important role in food production in these regions. In MAgPIE the trade-off with food prices due to environmental flow requirements is much lower (+1%) because of the compensating effect of improved nitrogen use efficiencies reducing the costs of agricultural production.

In the LAND scenario, natural land area increases and the nitrogen surplus decreases as intended by the measures. In addition, both IMAGE and MAgPIE show synergies with AFOLU emissions (−14% to −27%) due to reduced deforestation and conversion of other agricultural lands. A trade-off is found in MAgPIE with irrigation water withdrawal (+10%) due to intensification of agriculture involving expansion of irrigation due to increased pressure in the food system. IMAGE shows a trade-off in food prices (+9%), also due to pressure in the food system.

The FOOD scenario shows substantial reductions in food prices (−18% to −46%) indicating positive trends in food security. In addition, synergies are found in both models with all other indicators: Irrigation water withdrawal (−3% to −24%), natural land area (+4% to +8%), nitrogen surplus in agriculture (−23% to −35%) and AFOLU emissions (−45% to −58%). Especially the reduction in meat consumption and reduced food waste results in less animal waste leading to nitrogen surpluses and GHG emissions, lower requirements for intensive irrigation and reduced agricultural area requirements increasing natural land area and strongly reducing CO_2 emissions from land-use change.

In the CLIMATE scenario, AFOLU emissions show strong decreases (−30% to −43%), although the FOOD scenario actually has larger decreases highlighting the potential for climate change mitigation from dietary change. The CLIMATE scenario involves a synergy with natural land share (+2%) in both models as a result of forest protection limiting land-use change. There is, however, a substantial regional variation with some regions showing a reduction in natural land due to expansion of bioenergy and reallocation of global agricultural production: E.g. in Sub-Saharan Africa in MAgPIE (−2.4%) or in IMAGE in Japan, Korea and Oceania (−3.0%) and Middle East and Northern Africa (−2.9%). Trade-offs are found with food prices (+7% to +11%) and irrigation water withdrawal (+5% to +31%) due to increased pressure on the land system from forest protection and increased demand for bioenergy production.

The TOTAL scenario combines all measures from the different nexus scenarios. This implies that all indicators are targeted and therefore no synergies or trade-offs can be analysed. It is interesting however to observe how some measures reinforce each other while others counteract one another. For example, the combined effect of improved nitrogen use efficiency and lower levels of livestock production results in a major decrease in the nitrogen surplus in agriculture (−51% to −61%). Similarly, the combined effects of lower livestock numbers with technical mitigation measures in agriculture results in large reductions in AFOLU emissions (−53% to −83%). On the other hand, the reduction in food prices due to dietary change is counteracted by higher pressure in the land system from land protection measures and increased bioenergy demand: Consequently, food prices still go down in the TOTAL scenario (−11% to −34%), but not as much as in the FOOD scenario (−18% to −46%).

4. Discussion

The synergies and trade-offs analysis presented in this study generally finds similar results in both models providing more confidence in the results than in the case of a single model study. The trade-offs found between climate mitigation measures, increased pressure in the land use system from land protection and higher food prices are found in both models and are confirmed by the literature (Hasegawa *et al* 2018, Fujimori *et al* 2019). The trade-off of climate mitigation measures (most notably bioenergy production) with water use is most clear in MAgPIE and less commonly considered in scenario studies on climate mitigation but also a known issue that warrants attention (Hayman *et al* 2021, Stenzel *et al* 2021). The strong synergy between diet change, climate change mitigation, excessive water use and nitrogen input into the environment is also a clear result from both models and confirmed in the literature (Obersteiner *et al* 2016, Springmann *et al* 2018, Soergel *et al* 2021). The notion that a combined portfolio of measures in multiple dimensions of the nexus as shown in both models in the TOTAL scenario could lead to the best results for biodiversity (as implied by improvements in natural land share, water withdrawals and nitrogen surplus) is also shown by Leclère *et al* (2020).

Given our goal to assess different dimensions of the WLFC nexus in two models at the same time, we choose to focus on the nexus components that are well represented in both models. Both models have a good representation of the nexus, but the focus on nexus dimensions related to the land system limits the study's scope somewhat. The nexus' energy component is taken into account by considering the impact of bioenergy use for climate mitigation. However, impacts of water availability on the energy system, such as for thermoelectric power generation or hydropower, or the effects of climate change on renewable energy supply (van Vliet *et al* 2016, Gernaat *et al*

2021), are not considered. Also, the water dimension of the nexus is considered only from the volumetric water quantity perspective as the metric of environmental flow requirements implies restrictions on human use volume to protect aquatic ecosystems by providing sufficient high and low flow quantities (Gerten *et al* 2013), while both water quantity and water quality are also of crucial importance for human wellbeing (Vörösmarty *et al* 2010, Bijl *et al* 2018, van Vliet *et al* 2021). Water quality is indirectly covered by the nitrogen surplus indicator.

For this study, five indicators were selected to simplify the comparison between models and scenarios. More indicators could have been added: For example, food price is a fairly simple indicator that does not reflect consumers' eventual purchasing power, which changes with increasing income. Other dimensions of food security, such as nutritional value or undernourishment, can provide additional interesting insights (van Meijl *et al* 2020). Similarly, the natural land share and nitrogen budget only provide indirect indications of biodiversity impacts, while specialized biodiversity models have more direct indicators (Leclère *et al* 2020). While irrigation water withdrawals represent about 70% of anthropogenic water use, it does not represent dynamics in the water use for energy, industry and households—which is substantial—that might have more direct impact on communities (de Vos *et al* 2021). In IMAGE these other uses are taken into account based on population, GDP and energy and industry system dynamics (Bijl *et al* 2016). In MAgPIE an exogenously assumed fraction of water use is reserved for other uses.

Some key differences in individual scenario results between the two models result from differences in model setup. In IMAGE, irrigated cropland area is set exogenously (Doelman *et al* 2018). It does not vary between the scenarios producing different irrigation water withdrawal dynamics compared to MAgPIE, where irrigated area is responsive to the agricultural intensification trends (Bonsch *et al* 2015). Also, the nitrogen use efficiency assumptions play out differently in the models: In MAgPIE, the efficiency assumption makes it cheaper to intensify agriculture resulting in reduced food prices, while in IMAGE, nitrogen use efficiency is assumed not to affect food prices. In the integrated assessment modelling community several multi-model studies exist on GHG emissions, land-use change dynamics, and food security indicators (Popp *et al* 2017, Hasegawa *et al* 2018, Frank *et al* 2019). For the water and nitrogen dimensions, such comparison studies have not been conducted yet, indicating an important direction of future research and model development.

Other indicators do show similar dynamics in both models across the scenarios, but still show interesting differences: AFOLU CO_2 emissions are lower in MAgPIE than in IMAGE (1.9 $GtCO_2$ and 4.1 $GtCO_2$ in 2015, respectively). The majority of these emissions result from land-use change which is notoriously uncertain as illustrated by the 2.9–8.1 $GtCO_2$ range reported by Friedlingstein *et al* (2019). Part of the difference can be explained as IMAGE takes emissions from forestry and degraded peatlands into account whereas MAgPIE does not. Total irrigation water withdrawal is similar in MAgPIE and IMAGE (1850 km^3 and 2010 km^3, respectively). However, compared to the literature these estimates are on the low end of the range (Wisser *et al* 2008, Wada *et al* 2013). IMAGE and MAgPIE use the LPJmL model for irrigation estimates that (in this version) does not take into account unsustainable groundwater use from deep aquifers and multiple cropping cycles explaining part of this low estimate (Wada *et al* 2010, Biemans *et al* 2016).

Both models take climate impacts into account following either the RCP 6.0 or RCP 2.6 climate change trajectories. It should be noted though that the two trajectories start only to diverge strongly after the year 2050 (which is the focus of this assessment). Climate change impacts predominantly influence the results through changes in the biophysical system as modelled by LPJmL. Key processes that are affected are crop productivity, water availability and growth rates of natural vegetation. Various other climate impacts that might affect the WLFC nexus are excluded due to model or data limitations, e.g. the effect of heat stress on labour productivity (Orlov *et al* 2021) or the effect of increasing water temperatures on aquatic biodiversity (Barbarossa *et al* 2021). The effects on crops are central to the food system modelling in this study and involve substantial uncertainty. Generally, global gridded crop models simulate crop yield improvements in temperate and boreal regions and for C3 crops such as wheat, while reductions in crop yields are predominantly found in more tropical regions and in C4 crops such as maize (Rosenzweig *et al* 2014, Jägermeyr *et al* 2021). The LPJmL model used in this study also shows these patterns but is on the optimistic side of the model range. More empirically based studies typically find larger climate change impacts on crop yields indicating that our study might underestimate the effects of climate change on the food system (IPCC 2019). Moreover, the MAgPIE and IMAGE models do not consider climate-change induced extreme events such as storm or droughts. Due to the additional use of land for mitigation (e.g. reforestation and bio-energy) our study finds higher food prices in the CLIMATE scenario (RCP2.6) than in the REF scenario (RCP6.0), implying that mitigation measures (without looking at other objectives) lead to stronger impacts on food security than climate change in the baseline. Some earlier studies have also reached this conclusion (Hasegawa *et al* 2018, van Meijl *et al* 2018). These impacts can be prevented by smarter design of mitigation scenarios or using a part of GHG tax revenues to compensate food insecure households (Fujimori *et al* 2019, Soergel *et al* 2021).

In this study we explicitly choose to implement measures instead of policies. Especially at the global scale, designing and implementing policies capable of achieving the measures assumed here is a major challenge. For example, in our FOOD and TOTAL scenarios very ambitious changes in diets and food waste are assumed. Previous studies with similar dietary scenarios (Stehfest *et al* 2009, Bodirsky *et al* 2014, Stevanović *et al* 2017, Springmann *et al* 2018) also showed the high impacts of such changes. Given that diets high in livestock protein and high food waste only appeared within the last decades (Bodirsky *et al* 2020), a transformation to healthy diets and low food waste seems technically possible. It is however on open research question how such a large-scale behavioural change can be achieved. If diet change shall be incentivized via the price, extremely high prices would be required to achieve this transformation within current elasticities (Latka *et al* 2021). It seems therefore evident, that price-based measures cannot achieve this transformation alone, but also food environments and food preferences need to be addressed, e.g. through healthy food options in canteens and awareness raising campaigns. The step from measures to policies is beyond the scope of this study but should be a key direction of follow-up research.

5. Conclusions

This article presents a model comparison study with harmonized scenarios quantifying dynamics in all components of the WLFC nexus. Broadly, the models find similar results for the synergies and trade-offs that are quantified. Trade-offs are identified resulting from climate mitigation measures and land protection for biodiversity purposes, affecting irrigation water withdrawals (+5% to +30%) and food prices (+1% to +20%) indicating excessive freshwater use and food security risks. A clear synergy is found between food measures and all other nexus dimensions: Dietary change including reduced meat consumption and less food waste results in lower irrigation water withdrawal (−3% to −24%), higher natural land areas (+4% to +8%), reduced AFOLU GHG emissions (−45% to −58%), and lower nitrogen surpluses (−23% to −35%). This reaffirms the potential of changes in the food system, although it is recognized that the feasibility of measures at the scale implemented in this study is difficult to assess and crucial questions remain how to design and implement policies that can achieve the implementation of these ambitious measures. While the models agree in broad terms, some substantial variations are present: The most considerable differences are found in the water and nitrogen indicators, signifying that model development and future research should focus on these components. In conclusion, this study provides an example of a nexus approach to scenario development where all dimensions are considered providing input to the next generation of pathways aiming to achieve multiple dimensions of sustainable development in line with the PBs and the SDGs.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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