LETTER

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

Jonathan C Doelman1,2,* , Felicitas D Beier3,4 , Elke Stehfest1 , Benjamin L Bodirsky3,7 , Arthur H W Beusen2,4, Florian Humpenöder5 , Abhijeet Mishra4,4 , Alexander Popp3,7 , Detlef P van Vuuren1,2 , Lotte de Vos5 , Isabelle Weindl3 , Willem-Jan van Zeist6 and Tom Kram1

1 PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands
2 Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, The Netherlands
3 Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
4 Department of Agricultural Economics, Humboldt-Universität zu Berlin, Berlin, Germany
5 Wageningen Environmental Research, Wageningen University & Research, Wageningen, The Netherlands
6 Wageningen Economic Research, Wageningen University & Research, The Hague, The Netherlands
7 World Vegetable Center, Tainan, Taiwan
8 Department of Earth Sciences-Geochemistry, Utrecht University, Utrecht, The Netherlands
* Author to whom any correspondence should be addressed.
E-mail: jonathan.doelman@pbl.nl

Keywords: nexus, integrated assessment, climate change mitigation, food security, biodiversity, nitrogen budget, water use

Supplementary material for this article is available online

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-food-climate nexus at the global scale. For this purpose, a set of six harmonized scenarios is simulated with the MAgPIE and IMAGE 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, Humppenöder 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 framework7 (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 crop- or pastureland as well as from livestock and crop-land production. N₂O 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 framework8 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/magpiemod/magpie. The code is comprehensively documented under https://tse.pik-potsdam.de/doc/magpie/4.3/ and a model description is available in the model description article published in Geoscl. 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 Smakhtin et al. (2004) that derives the baselows (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.

| 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$/tCO₂ 2050: 87 US$/tCO₂ | GHG price for 2 °C climate mitigation 2030: 55 US$/tCO₂ 2050: 87 US$/tCO₂ |
| 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 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$_2$O 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$^2$ 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$_2$O) 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 km$^3$ yr$^{-1}$ compared to REF in 2050) and even lead to lower water withdrawals than in 2015 (−260 km3 yr$^{-1}$ compared to 2015).
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 CO₂, CH₄, and N₂O 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 GtCO₂-eq., resp.). The LAND scenario, on the other hand, shows substantial reductions in CO₂ 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-CO₂ 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-CO₂ GHG emissions. Emission reductions vary widely between regions, with the largest reductions in land-use change CO₂ emissions in SSA and CSA and major reductions in agricultural non-CO₂ 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 GtCO₂-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
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
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 CO₂ 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 hydro-power, 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 CO₂ emissions are lower in MAgPIE than in IMAGE (1.9 GtCO₂ and 4.1 GtCO₂ 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 GtCO₂ 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 km³ and 2010 km³, 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.

Acknowledgments

The research benefited from funding under the European Union’s Horizon 2020 research and innovation programme, under Grant agreement no 689150 SIM4NEXUS. In addition, it received funding from the SHAPE project which is part of AXIS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (SE), FFG/BMWF (AT), DLR/MBF (DE, Grant No. 01LS1907A-B-C), NWO (NL) and RCN (NO) with co-funding by the European Union (Grant No. 776608). It also received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement Nos. 776479 (COACCH), and 031B0787B (FOCUS). We acknowledge the support by the German Federal Environmental Foundation (DBU) through a scholarship for FB.

ORCID iDs

Jonathan C Doelman  https://orcid.org/0000-0002-6842-573X
Felicitas D Beier  https://orcid.org/0000-0002-8725-7663
Elke Stehfest  https://orcid.org/0000-0003-3016-2679
Benjamin L Bodirsky  https://orcid.org/0000-0002-8242-6712
Arthur H W Beusen  https://orcid.org/0000-0003-0104-8615
Florian Humpenöder  https://orcid.org/0000-0003-2927-9407
Abhijeet Mishra  https://orcid.org/0000-0002-8287-9922
Alexander Popp  https://orcid.org/0000-0001-9500-1986
Dietlef P van Vuuren  https://orcid.org/0000-0003-0398-2831
Lotte de Vos  https://orcid.org/0000-0001-5841-9873
Isabelle Weindl  https://orcid.org/0000-0002-7651-6930
Willem-Jan van Zeist  https://orcid.org/0000-0002-6371-8509
References

Albrecht T R, Crooth A and Scott C A 2018 The water-energy-food nexus: a systematic review of methods for nexus assessment Environ. Res. Lett. 13 043002
Barbarossa V, Bosmans J, Wanders N, King H, Bierkens M F P, Huijbregts M A J and Schipper A M 2021 Threats of global warming to the world’s freshwater fishes Nat. Commun. 12 1701
Beusen A H W, Van Beek L P H, Bouwman A F, Mogollon J M and Middelburg J J 2013 Coupling global models for hydrology and nutrient loading to simulate nitrogen and phosphorus retention in surface water—description of IMAGE-GNN and analysis of performance Geosci. Model Dev. 8 4045–67
Biemans H, Siderius C, Mishra A and Ahmad B 2016 Crop-specific seasonal estimates of irrigation-water demand in South Asia Hydrol. Earth Syst. Sci. 20 1971–82
Bijl D L, Biemans H, Bogaert P W, Dekker S C, Doelman J C, Stehfest E and van Vuuren D P 2018 A global analysis of future water deficit based on different allocation mechanisms Water Resour. Res. 54 8083–24
Bijl D L, Bogaert P W, Kram T, de Vries B J and van Vuuren D P 2016 Long-term water demand for electricity, industry and households Environ. Sci. Policy 55 75–86
Bobrink R et al 2010 Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis Ecol. Appl. 20 30–59
Bodirsky B L et al 2014 Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution Nat. Commun. 5 3838
Bodirsky B L, Dietrich J P, Martinielli E, Stenstad A, Pradhan P, Gabrysch S, Mishra A, Weindl I, Le Mouël C and Rolinski S 2020 The ongoing nutrition transition thrwarts long-term targets for food security, public health and environmental protection Sci. Rep. 10 1–14
Bodirsky B L, Popp A, Weindl I, Dietrich J, Rolinski S, Scheifele L, Schmitz C and Lotze-Campen H 2012 Current state and future scenarios of the global agricultural nitrogen cycle Biogeosci. Discuss. 9 2753–821
Bondeau A et al 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance Glob. Change Biol. 13 679–739
Bonsch M et al 2015 Environmental flow provision: implications for agricultural water and land-use at the global scale Glob. Environ. Change 30 113–32
Dagnachew A G, Lucas P L, Hof A F and van Vuuren D P 2018 Trade-offs and synergies between universal electricity access and climate change mitigation in Sub-Saharan Africa Energy Policy 114 355–66
Daigoulo V, Doelman J C, Wicke B, Faaij A and van Vuuren D P 2021 Climate change impacts on renewable energy supply Nat. Clim. Change 11 119–25
Deng T, Hoff H, Rockström J, Jägermeyer J, Kummu M and Pastor A V 2013 Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements Curr. Opin. Environ. Sustain. 5 551–8
Gustavsson J, Cederberg C, Sonesson U, Van Otterdijk R and Meybeck A 2012 Global Food Losses and Food Waste (Rome: FAO)
Harmsen J H M, van Vuuren D P, Nakay D R, Hoff A F, Höglund-Isaksson L, Lucas P L, Nielsen J B, Smith P and Stehfest E 2018 Long-term marginal abatement cost curves of non-CO2 greenhouse gases Environ. Sci. Policy 99 136–49
Hasegawa T et al 2018 Risk of increased food insecurity under stringent global climate change mitigation policy Nat. Clim. Change 8 699–703
Hasegawa T, Fujimori S, Shin Y, Tanaka A, Takahashi K and Masui T 2015 Consequence of climate mitigation on the risk of hunger Environ. Sci. Technol. 49 7245–53
Hausfather Z and Peters G P 2020 Emissions—‘the Business as Usual’ Story is Misleading Nature 577–779 618–20
Hayman G D 2021 Regional variation in the effectiveness of methane-based and land-based climate mitigation options Earth Syst. Dyn. Discuss. 12 513–44
Hoff H 2011 Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus Stockholm Stockholm Environment Institute
Howarth R, Chan F, Conley D J, Garnier J, Doney S C, Marino R and Billen G 2011 Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems Front. Ecol. Environ. 9 18–26
Huppmönder F et al 2018 Large-scale bioenergy production: how to resolve sustainability trade-offs? Environ. Res. Lett. 13 024011
IEA 2017 World Energy Balances 2017 (Paris: OECD Publishing) (https://doi.org/10.1787/world_energy_bal-2017-en)
IPBES 2019 Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services ed S Diaz et al (Bonn: IPBES Secretariat)
IPCC 2014 Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change IPCC Geneva, Switzerland
IPCC 2019 Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems ed P R Shukla IPCC
Jägermeyer J et al 2021 Climate impacts on global agriculture emerge earlier in new generation of climate and crop models Nat. Food 2 873–85

land-use change and land-based climate change mitigation Glob. Environ. Change 48 119–35
FAO 2018 The Future of Food and agriculture—Alternative Pathways to 2050 (Rome)
Frank S et al 2019 Agricultural non-CO2 emission reduction potential in the context of the 1.5 °C target Nat. Clim. Change 9 66–72
Friedlingstein P, Jones M, O’Neill M, Andrew R, Hauck J, Peters G, Wongsrat J, Sitch S and Le Quéré C 2019 Global carbon budget 2019 Earth Syst. Sci. Data 11 1783–838
Frieler K et al 2017 Assessing the impacts of 1.5 °C global warming—simulation protocol of the inter-sectoral impact model intercomparison project (ISIMIP2b) Geosci. Model Dev. 10 4321–45
Fujimori S et al 2019 A multi-model assessment of food security implications of climate change mitigation Nat. Sustain. 2 386–96
Gernaert D E, de Boer H S, Daigoulo V, Valey S G, Müller C and van Vuuren D P 2021 Climate change impacts on renewable energy supply Nat. Clim. Change 11 119–25
Hugues C, Frank S, Peters G, Peters W, Pongratz J, Sitch S and Le Quéré C 2018 Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of

IOP Publishing Environ. Res. Lett. 17 (2022) 045004 J C Doelman et al

16
Johnson N, Burke P, Byers E, Falchetta G, Flørke M, Fujimori S, Havlik P, Hejazi M, Hunt J and Krey V 2019 Integrated solutions for the water-energy-land nexus: are global models rising to the challenge? Water 11 2223
Karlb erg L, Hoff H, Amsalu T, Andersson K, Binnington T, Flores-López E, de Bruin A, Gebrehiwot S G, Gedef B and Johnson O 2015 Tackling complexity: understanding the food-energy-environment nexus in Ethiopia’s Lake Tana Sub-basin Water Altern. 8 710–34
Klein D et al 2014 The value of bioenergy in low carbon scenarios: an assessment using REMIND–MagpiE Clim. Change 123 705–18
Kolk M T J et al 2020 Assessing ambitious nature conservation strategies within a 2 degree warmer and food-secure world bioRxiv Preprint (https://doi.org/10.1101/2020.08.04.236489)
Krieger E et al 2017 Fossil-fuel development (SSPS): an energy and resource intensive scenario for the 21st century Glob. Environ. Change 42 297–315
Latka C et al 2021 Paying the price for environmentally sustainable and healthy EU diets Glob. Food Secur. 28 100437
Leclère D et al 2020 Bending the curve of terrestrial biodiversity needs an integrated strategy Nature 585 551–6
Liu J, You L, Amini M, Obersteiner M, Herrero M, Zeidhammer A J B and Yang H 2010 A high-resolution assessment on global nitrogen fluxes Proc. Natl. Acad. Sci. 107 8035–40
Lotze-Campen H, Müller C, Bondeau A, Rost S, Popp A and Lucht W 2008 Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical and water approach Agric. Econ. 39 325–58
Meinshausen M, Raper S C B and Wigley T M L 2011 Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC-6—Part 1: model description and calibration Atmos. Chem. Phys. 11 4147–56
Müller C and Robertson R D 2014 Projecting future crop productivity for global economic modeling Agric. Econ. 45 37–50
Müller C, Stehfest E, van Minnen J G, Strefer J, Hasegawa T and Marangoni G 2018 Scenarios towards limiting global mean temperature increase below 1.5◦ C Nat. Clim. Change 8 325
Rosenzweig C et al 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison Proc. Natl Acad. Sci. USA 111 3268–73
Sandbag 2021 Tracking the European union emissions trading system carbon market price day-by-day
Scapello S, von Bloh W, Ramming A, Thonnieke B, Biersch H, Forkel M, Gerten D, Heinke J, Jägermeyer J and Knauper J G 2018 LPJmL-a dynamic global vegetation model with managed land-use part 1: model description Geosci. Model. Dev. 11 1343–75
Schmitz C, Biewald A, Lotze-Campen H, Popp A, Dietrich J P, Bodirsky B, Krause M and Weindl I 2012 Trading more food: implications for land use, greenhouse gas emissions, and the food system Glob. Environ. Change 22 189–209
Smitkink V, Reveenga C and Döll P 2004 A pilot global assessment of environmental water requirements and scarcity Water Int. 29 307–17
Smith P, Davis S J, Creutzig F, Fuss S, Minx J, Gabrielle B, Kato E, Jackson R B, Cowie A and Krieger E 2016 Biophysical and economic limits to negative CO2 emissions Nat. Clim. Change 6 42–50
Soergel B et al 2021 A sustainable development pathway for climate action within the UN 2030 agenda Nat. Clim. Change 11 636–64
Springmann M et al 2018 Options for keeping the food system within environmental limits Nature 562 519–25
Steffen W, Richardson K, Rockström J, Cornell S E, Fetzer I, Bennett E M, Biggs R, Carpenter S R, De Vries W and De Wit C A 2015 Planetary boundaries: guiding human development on a changing planet Science 347 6223 736
Stehfest E et al 2014 Integrated Assessment of Global Environmental Change with IMAGE 3.8. Model Description and Policy Application Glob. Environ. Change 42 169–80
Stober M, Waltz B, Frank S, Havlik P, Cantele M, Liu J, Palazzo A, Herrero M, Ru A and Mosnier A 2016 Assessing the land resource-food price nexus of the sustainable development goals Sci. Adv. 2 e1501499
OECD 2017 The Land-Water-Energy Nexus: Biophysical and Economic Consequences (Paris: OECD Publishing) (https://doi.org/10.1787/9789264279360-en)
Orlove A, Daloza A S, Sillmann J, Thiery W, Douzal C, Lejeune Q and Schleussner C 2021 Global economic responses to heat stress impacts on worker productivity in crop production Econ. Disasters Clim. Change 8 45–60
Pastor A, Ludwig F, Biemans H, Hoff H and Kabat P 2014 Accounting for environmental flow requirements in global water assessments Hydrol. Earth Syst. Sci. 18 5041–59
Pimm S L, Jenkins C N and Li B V 2018 How to protect half of Earth to ensure it protects sufficient biodiversity Sci. Adv. 4 eaat2616
Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E, Bodirsky B L, Dietrich J P, Doelman J C and Gusti M 2017 Land-use futures in the shared socio-economic pathways Glob. Environ. Change 42 331–45
Pop A, Dietrich J P, Lotze-Campen H, Klein D, Bauer N, Krause M, Beringer T, Gerten D and Edenhofer O 2011 The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system Environ. Res. Lett. 6 035017
Popp A, Humpenöder F, Weindl I, Bodirsky B L, Bonisch M, Lotze-Campen H, Müller C, Biewald A, Rolinski S and Stevanovic M 2014 Land-use protection for climate change mitigation Nat. Clim. Change 4 1095–8
Rockström J et al 2009 A safe operating space for humanity Nature 461 472–5
Rogelj J, Popp A, Calvin K V, Luderer G, Emmerling J, Gerna D, Fujimori S, Strefer J, Hasegawa T and Marangoni G 2018 Scenarios towards limiting global mean temperature increase below 1.5◦ C Nat. Clim. Change 8 325
UN 2019 World Population Prospects 2019: Highlights ST/ESA/SER.A/423 United Nations, Department of Economic and Social Affairs, Population Division
UNCCD 2017 Global Land Outlook—First Edition (Bonn: Secretariat of the United Nations Convention to Combat Desertification)
UN Environment 2019 Global Environment Outlook—GEO-6: Healthy Planet, Healthy People (Nairobi: UN Environment) (https://doi.org/10.1081/086171461)
UNFCCC 2015 Paris Agreement United Nations Framework Convention on Climate Change

van Meijl H, Havlik P, Lotze-Campen H, Stehfest E, Witzke P, Dominguez I P, Bodirsky B L, van Dijk M, Doelman J and Fellmann T 2018 Comparing impacts of climate change and mitigation on global agriculture by 2050 Environ. Res. Lett. 13 064021

van Meijl H, Havlik P, Lotze-Campen H, Stehfest E, Doelman J and Lucas P 2020 How food secure are the green, rocky and middle roads: food security effects in different world development paths Environ. Res. Commun. 2 031002

van Soest H L, van Vuuren D P, Hilaire J, Minx J C, Harmsen M J, Krey V, Popp A, Riahi K and Luderer G 2019 Analysing interactions among sustainable development goals with integrated assessment models Glob. Transiat. 1 210–25

van Vliet M T H, Jones E R, Flörke M, Franssen W H P, Hanasaki N, Wada Y and Yearsley J R 2021 Global water scarcity including surface water quality and expansions of clean water technologies Environ. Res. Lett. 16 024020

van Vliet M T H, Wigberg D, Leduc S and Riahi K 2016 Power-generation system vulnerability and adaptation to changes in climate and water resources Nat. Clim. Change 6 575–80

van Vuuren D P et al 2011 The representative concentration pathways: an overview Clim. Change 109 5–31

Van Vuuren D P, Bijl D L, Bogaart P, Stehfest E, Biemans H, Dekker S C, Doelman J C, Gernaey D E and Harmans M 2019 Integrated scenarios to support analysis of the food–energy–water nexus Nat. Sustain. 2 1132–41

Van Vuuren D, Stehfest E, Gernaey D, de Boer H-S, Daioglou V, Doelman J, Edelenbosch O, Harmans M, van Zeist W-J and van den Berg M 2021 The 2021 SSP scenarios of the IMAGE 3.2 model 4740 Netherlands Environmental Assessment Agency (PBL)

Vörösmarty C J, McIntyre P B, Gessner M O, Dudgeon D, Prusseit A, Green P, Glidden S, Bunn S E, Sullivan C A and Liermann C R 2010 Global threats to human water security and river biodiversity Nature 467 555–61

Wada Y et al 2013 Multimodel projections and uncertainties of irrigation water demand under climate change Geophys. Res. Lett. 40 4626–32

Wada Y, van Beek L P H, van Kempen C M, Reckman J W T M, Vasak S and Bierkens M F P 2010 Global depletion of groundwater resources Geophys. Res. Lett. 37 L24002

Weindl I et al 2017a Livestock production and the water challenge of future food supply: implications of agricultural management and dietary choices Glob. Environ. Change 47 121–32

Weindl I, Popp A, Bodirsky B L, Rolinski S, Lotze-Campen H, Biewald A, Humpe, nöder F, Dietrich J P and Stevanović M 2017b Livestock and human use of land: productivity trends and dietary choices as drivers of future land and carbon dynamics Glob. Planet. Change 159 1–10

Willett W et al 2019 Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems Lancet 393.10170 447–92

Wilson E O 2016 Half-earth: Our Planet’s Fight for Life (New York: WW Norton & Company)

Wisser D, Froliking S, Douglas E M, Fekete B M, Vörösmarty C J and Schumann A H 2008 Global irrigation water demand: variability and uncertainties arising from agricultural and climate data sets Geophys. Res. Lett. 35 L24408

Woltjer G B, Kuiper M, Kavallari A, van Meijl H, Powell J, Rutten M, Shutes L and Tabeau A 2014 The MAGNET Model: Module Description LEI Report 14-057 LEI Wageningen University & Research centre

Yang Y E, Ringler C, Brown C and Mondal M A H 2016 Modeling the agricultural water–energy–food nexus in the indus river basin, Pakistan Water Resour. Plan. Manage. 142 04016062

Zhang X, Davidson E A, Mauzerall D L, Searchinger T D, Dumas P and Shen Y 2015 Managing nitrogen for sustainable development Nature 528 51–59