The Importance of Analyzing Interdependencies to Build a Healthy, Nature-Positive, and Inclusive Food System

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Summary for Policymakers

Integrated Assessment Models (IAMs) can systematically incorporate potential interlinkages between different aspects of the food system transformation and are thus well equipped to inform policy makers about potential trade-offs and synergies between interventions. In the future, inclusion aspects need to be better integrated in IAMs.

Policy recommendations (trade-offs and solutions to overcome them), based on IAMs such as the MAgPIE model are:

Land productivity:

- *Trade-off:* Between 1961 and 2007, 86% of agricultural growth occurred due to increases in yield and intensification but current food production systems have negative implications on biodiversity, GHG emissions, as well as soil- and water quality.
- *Solution:* Fast advancements in technology and intensification on a global scale can lead to reduced future cropland expansion and can be a prerequisite for land sparing for conservation activities. Additionally, increased competition for land on agricultural prices may be substantially reduced.

Biodiversity protection through land sparing:

- *Trade-off:* Interventions to halt biodiversity loss must be designed to avoid negative effects on food security.
- *Solution:* Integrated interventions (demand-side measures or supply-side measures) are more effective than single measures in achieving the preservation of biodiversity: By integrating supply-side measures that increase crop yields and the trade of agricultural goods with demand-side measures that reduce food waste and lower the consumption of animal-based calories, the loss of biodiversity can be reversed by 2050, even as agricultural prices are reduced by as much as 20%.

Bioenergy production:

- *Trade-off*: Bioenergy and carbon capture and sequestration (BECCS) could simultaneously produce substantial amounts of energy and reduce the concentration of atmospheric CO_2 but requires land, water, and nutrients needed for food production.
- *Solution:* A portfolio of interventions can mitigate those trade-offs: Reducing deforestation, protecting freshwater ecosystems, and at the same time improving fertilization techniques and investing in technologies to increase agricultural productivity will keep agricultural prices constant.

Dietary change:

- *Trade-off:* Hundreds of millions of people obtain significant portions of their protein/calories from animal-sourced proteins to be food secure but over-reliance on animal-sourced proteins and empty calories has led the food system to increasingly exceed environmental limits, leading to further deforestation, GHG pollution, and regional water stress.

- *Solution:* Reducing consumption of livestock products in regions with over-consumption has the potential to substantially reduce deforestation (47-55%) and cumulative carbon pollution (34-57%). Furthermore, reducing waste and animal products would lower agricultural prices and thus fight undernutrition.

Livestock production:

- *Trade-off:* Future demand for livestock is expected to rise. Intensification of extensive livestock systems will lead to a substantially lower increase of total agricultural water use in 2050 compared to 2010 (12% increase vs. 23% increase) but – through a shift from pasture to cropland- leads to higher irrigation water demand which can lead to water scarcity in regions such as Sub-Saharan Africa and South Asia.
- *Solutions:* Intensification of low-intensity livestock systems, e.g. by substituting residues, food waste and grazed biomass as feed source with higher quality and nutrient-rich feed, can mitigate some of the consequences of an increasing livestock demand that is currently responsible for over 80% of all agricultural non-CO2 emissions. Highly intensive livestock systems, on the other hand, need to be de-intensified to improve animal welfare and reduce negative environmental impacts such a nitrogen pollution.

Abstract

Many technological and behavioral measures have been proposed to transition the food system to be healthier, nature-positive, and inclusive. In targeting one specific sustainability goal, these measures often have positive or negative side-effects on the other sustainability targets. Global integrated assessment models (IAMs) of the food and land system are often used to assess the quantitative direction and magnitude of these side-effects. Within this brief, we synthesize the findings of multiple analyses using the land system model MAgPIE to study the effects and side-effects of different measures taken within the land system, such as improving agricultural productivity, land-sparing for biodiversity protection, bioenergy cultivation, and changing food consumption patterns. We find that side-effects of measures are widespread and often impact multiple SDGs. We conclude that measures must be bundled to achieve a sustainable outcome; due to their interrelatedness, any implemented measure should be accompanied by as many measures as there are sustainability targets that are affected by side-effects. While we found large literature on the impact of measures, their side-effects, and their allocative efficiency, we identified few studies that also considered the policies that would lead to the implementation of these measures. This research gap warrants more research, because the type of policy instrument has a major effect on the distributional outcomes and likelihood of success.

1. Introduction

Shifting the food system onto a trajectory that guarantees the world's population healthy food, equitable livelihoods, and a thriving environment is one of the most pressing challenges of the 21st century (IPCC 2014; Steffen et al. 2015; FAO 2020). This importance is reflected in the UN's declaration of the Sustainable Development Goals (SDGs) for 2030. While synergies among many of the goals exist, measures intervening in the food system to achieve one of these goals often result in trade-offs with other SDGs (Pradhan et al. 2017; Herrero et al. 2021). These trade-offs often generate high-dimensional impact pathways that may lead to unforeseen consequences for other SDGs (Pradhan et al. 2017), especially when these interventions are chosen solely based on their first-order effects (Fesenfeld et al. 2020). Foreseeing and mitigating these trade-offs are a vital task for scientists in supporting governments.

To illustrate these multidimensional impact pathways, consider the case study of Herrero et al. (2021), who explore the potential consequences of further advances in automation and robotics in agriculture. These technologies are already being increasingly adopted in the agricultural context (Roldán et al. 2018; Sparrow and Howard 2021), and their impacts will be felt at every level of the food system. Their first-order impacts are far-reaching: Improvements in resource-use efficiency result in less environmental pollution (SDG 12, 14, 15), and decoupling agricultural production from labor could boost the resilience of supply chains to disruptions such as pandemics and aging populations (SDG 2). However, a shift away from labor may dramatically increase economic and social inequality (SDG 10), as many of the world’s most vulnerable workers are dependent on agricultural labor for their income. This may, in turn, shift populations towards cities, leading to more urbanization, greater urban unemployment, and potentially more social conflict. Understanding these complexities is critical to properly aligning interventions to maximize their positive impacts without unforeseen negative consequences.

Integrated assessment modeling (IAM) has emerged as one of the key methodologies employed to explore these complex system interactions by the scientific community and has thus become one of the primary tools researchers use to explore possible scenarios of the Earth's future (e.g., O'Neill et al. 2017; Frieler et al. 2018). By integrating models of the biogeophysical system with quantitative projections of potential future human societal development, these models enable scientists to trace the interactions and feedbacks between anthropogenic changes to the earth system, the biosphere, and our economic system. Importantly, these models have played a critical role in quantifying the potential of different measures to contribute to a sustainable development pathway (Sörgel et al. *in press*) and potentially keep global warming below 1.5° C (IPCC 2018).

In this brief, we review recent literature specific to the MAgPIE modeling framework (Model of Agricultural Production and its Impact on the Environment, Dietrich et al. 2019; Lotze-Campen et al. 2008), modular open-source framework for modeling global land-systems developed at the Potsdam Institute for Climate Impact Research in Potsdam, Germany, and often used for integrated assessment analyses (van Meijl et al. 2018). Specifically, we demonstrate the complex interrelations between different interventions in the food system and quantitatively illustrate how interventions – measures – intended to achieve one SDG can often backfire and hinder progress towards another. We highlight specific measures that tend to have large positive impacts and relatively few negative knock-on effects. Further, we describe how combining measures may be integral to mitigating their negative secondary consequences when in isolation. We further discuss the implications of this review for policy design, specifically arguing for the generation of policy bundles to mitigate the negative consequences of isolated interventions. Finally, we end by calling for IAMs to better represent inclusion – the equitable distribution of resources – in their analyses.

2. Methods

This brief focuses on recent studies carried out with MAgPIE (Dietrich et al. 2019). MAgPIE is a global partial-equilibrium model used to analyze potential developments in the land system given different scenarios of socio-economic development (Popp et al. 2017) and climate change (Stevanović et al. 2016). As a spatially explicit model, it minimizes the total costs of the agricultural sector (production, investment, and transportation) under regional biogeophysical constraints (e.g., agricultural area, water availability) while meeting demand for regional and globally-traded agricultural goods. Apart from allocating agricultural land to grow different crops to meet demand, the model may, for example, invest in technological change to increase crop yields (Dietrich et al. 2012) or simply expand the total land area used for crops. For an overview of the model structure, see Figure 1.

Within MAgPIE, interventions are modeled by either setting exogenous constraints on the optimization or by exogenously changing the parameters of a specific equation (e.g., increasing nitrogen efficiency). Adding constraints could take many forms, for example specifying that half of the global land area should be spared from cropland expansion (the "Half-Earth Project," Wilson 2016), and may reflect the successful implementation of policies or gradual cultural change. A common mode of analysis using this methodology is to inspect, given a particular set of interventions, how MAgPIE projects the land system (which is composed of not only cropping patterns, but agricultural prices, resultant environmental pollution, and endogenous technological investment) to internally respond to these new constraints. For example, if half of the earth is unavailable for cropland expansion, agricultural prices may rise, but agricultural intensification and technological innovation could potentially increase to compensate, and a substantial amount of carbon dioxide may become sequestered in newly-forested areas (Doelman et al. *in review*; Folberth et al. 2020).

In the scope of this brief, we reviewed recent literature using MAgPIE to explore the impact of different interventions on the land system. We focus on five interventions central to the food system: Increases in agricultural productivity, biodiversity protection, bioenergy production, intensification in the livestock sector, and shift in food consumption patterns. In particular, we elaborate on these measures' direct and indirect effects. With these case studies, we illustrate the complex interdependencies within the land-use sector and highlight key insights generated from the model that are relevant to a policy context.

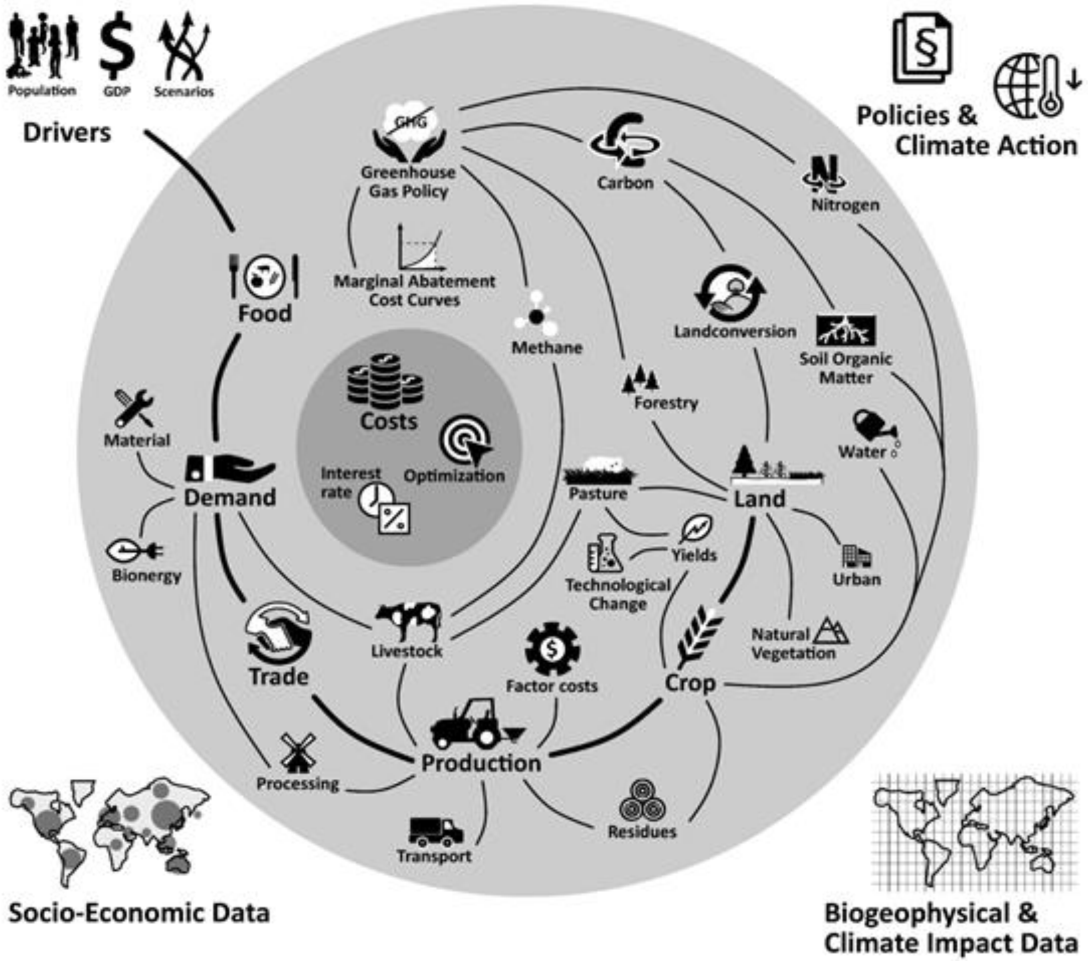

Figure 1. Simplified overview of the MAgPIE framework (Dietrich et al 2019; Lotze-Campen et al 2008). Different parts of the land system are implemented as separate sub-modules (e.g. trade, livestock production, land conversion) which interact (e.g. the total demand directly depends on food, material and bioenergy demand), as shown in the light-gray shaded area. Main drivers in the model are projections of the population size and the Gross Domestic Product (GDP), both directly affecting the food demand, as well as scenarios to analyze interventions such as protecting half of the global land area. Biophysical data such as crop yield potentials and water availability are derived from the global dynamic vegetation model LPJmL (Lund-Potsdam-Jena managed Land, Bondeau et al. 2007; Müller and Robertson 2014).

3. Measures

Improving agricultural productivity satisfies future food demand and spares land for conservation: As a supplier of sufficient food to satisfy global demand, agricultural production is the heart of food systems. Further, the sector can contribute to several SDGs, namely SDG 1 *(No poverty)*, SDG 2 (*Zero hunger*), SDG 12 (*Responsible consumption and production*), SDG 13 (*Climate action*), and SDG 15 (*Life on land*). Increasing demand and the resulting need to increase agricultural production are associated with intensification and increasing productivity or cropland expansion. Historically, the sector achieved most growth through intensification. Stehfest et al. (2019) estimate an increase of 60% in agricultural production but only 5% in cropland expansion in the last 40 years. Projections of yield and productivity can help to understand the future development of potential growth rates and trade-offs related to resource and land use.

Van Zeist et al. (2020) evaluate the progress of yields of the most important cereals using MAgPIE in combination with other IAMs, such as AIM, GLOBIOM, GCAM, IMAGE-MAGNET, and IMPACT. While in developed regions (e.g., OECD countries), yields are already close to the attainable yields with decreasing growth rates, substantial yield gaps remain in sub-Saharan African countries. These gaps can be closed by increasing productivity through improved crop management and the adoption of new technologies (e.g., new varieties, genetic improvements). Supporting the result of a continuation in productivity growth, Wang et al. (2020) emphasize differences in the growth rates relying on variations in socioeconomic conditions. They stress, for example, that technological progress depends on governance and the institutional environment in a country. However, fast advancements in technology and intensification on a global scale can lead to reduced future cropland expansion and can be a prerequisite for land sparing for conservation activities. On a regional scale, it is likely to recognize the opposite effect. Comparative advantages due to technological progress can lead to increasing land expansion.

The projections show that yield improvement rates similar to those observed in the past are sufficient to satisfy future demand. However, they built on investments in research and development (R&D) of technology and broad adoption of them. This can have positive effects on the production potential, agricultural prices, and various SDGs. However, these innovations can have negative or unintended side-effects, which need to be considered when analyzing trade-offs (Herrero et al. 2021).

Higher yields may need higher nutrient inputs. In MAgPIE, nutrient requirements scale with production, implying higher nutrient loads per area but not higher nutrient loads in total. This is in line with historical observations (Lassaletta et al. 2014) where nitrogen use efficiency (NUE) remained rather constant in most world regions between 1961 and 2009. However, it implies that technological progress is achieved by an improvement in total factor productivity, and not primarily via the increase of an individual production factor like fertilizer. In the latter case, the expected outcome would be increasing nutrient requirements per unit of production

(Bodirsky et al. 2014). The higher nutrient requirements per area may still be environmentally problematic as they may lead to an exceedance of spatial critical loads (Gerten et al. 2020).

Both intensification and cropland expansion depend on the use of water and the adoption of irrigation technologies. Wang et al. (2020) report that cropland expansion combined with rainfed production leads to a decrease in average yields. In their paper on livestock production, Weindl et al. (2017b) argue that the total agricultural water consumption in developing countries can be reduced by growth in production and the usage of irrigation technology. However, water consumption in agriculture is projected to increase, even though people would change their diets away from water-intensive livestock products.

High rates of agricultural R&D may also increase production costs (Wang et al. 2020); how far they will translate into increased agricultural prices likely depends on the way they are financed (see section *Implications for the design of policy*). High R&D costs occur primarily in the context of poor governance (Wang et al. 2020) but may be needed to satisfy the demands for a growing population, more affluent lifestyles, or for the use of bioenergy or afforestation for climate change mitigation.

Land sparing for biodiversity protection can be accomplished without increasing agricultural prices: Agricultural intensification, if unsustainably managed, significantly threatens biodiversity (Simons and Weisser 2017; Raven and Wagner 2021). Protecting biodiversity is critical to maintaining a functioning biosphere as well as the health of the agricultural system (Cardinale et al. 2012; Steffen et al. 2015; IPBES 2019). Therefore, conserving large tracts of land – especially in biodiversity hotspots, such as South America and Sub-Saharan Africa – is a promising measure to achieve this goal (Van Vuuren et al. 2015; Mace et al. 2018). Critically, however, in the MAgPIE model, conserved land cannot be used to grow food. Given that many of the most biodiverse regions on earth are still developing, a tension emerges between SDG 15 (*Life on land*) and SDG 2 (*Zero hunger*), between the long-term viability of our biosphere and the necessity of feeding a growing population (Mehrabi et al. 2018). Therefore, interventions to halt biodiversity loss must be designed to mitigate these potential effects.

Although trade-offs exist between the preservation of biodiversity and agricultural prices (but see Tamburini et al. 2020; Dasgupta et al. 2021), Leclère et al. (2020) demonstrate that integrated interventions approaching this challenge from multiple perspectives – based on conservation and principles of sustainable economics – can stem more than two-thirds of future biodiversity loss without increasing the price of food. Using MAgPIE in combination with several other IAMs (AIM, GLOBIOM, and IMAGE), the authors implemented a series of future scenarios, depicting several potential futures. First, they described one in which society conserves biodiversity without relieving the underlying economic factors that drive biodiversity loss (e.g., increasing demand for animal-source calories), or attempting to mitigate the economic consequences of sparing arable land. They contrasted this scenario with one depicting a society that employs either demand- or supply-side economic interventions (e.g., increasing crop yields) as well as one in which society integrates all of these measures together.

Comparing the interventions, they show that those conserving and restoring land alone will indeed achieve their purpose (avoiding over 50% of the potential biodiversity losses accrued in the baseline, no interventions, scenario). However, by integrating supply-side measures that increase crop yields and the trade of agricultural goods with demand-side measures that reduce food waste and lower the consumption of animal-based calories, the loss of biodiversity can be reversed by 2050, even as agricultural prices are reduced by as much as 20%. Although demand-side measures or supply-side measures in isolation also mitigate biodiversity loss, these positive effects are also dwarfed by the integrated-action portfolio. Integrated measures are more effective than single measures in achieving the preservation of biodiversity.

Bioenergy production needs a comprehensive integration framework: Bioenergy and carbon capture and sequestration (BECCS) is one of the key strategies currently being discussed to mitigate climate change (Azar et al. 2013; Hanssen et al. 2020), and thus achieve SDG 13 (*Climate action*). If widely employed, this measure could simultaneously produce substantial amounts of energy and reduce the concentration of atmospheric CO_2 (Schleussner et al. 2016; Rose et al. 2014). However, the production of bioenergy crops requires land, water, and nutrients (DeFries et al. 2004; Popp et al. 2011). This drives a trade-off with other aspects of the food-system transition: Do we grow bioenergy crops on existing agricultural land, therefore reducing food production (and thereby threatening SDG 1, *No poverty*, and SDG 2, *No hunger*, among others)? Or do we allow further cropland expansion, and therefore amplify deforestation, fertilizer use, and water use? Is there a pathway towards the implementation of BECCS that does not undermine food security and environmental health?

Humpenöder et al. (2018) approach this multidimensional trade-off through a scenario analysis using the MAgPIE model. They compare simulated futures wherein society decides to implement bioenergy without regard to its potential downsides for food security and the environment, as well as futures wherein society decides to implement a portfolio of different strategies to mitigate its negative knock-on effects, ranging from protecting forests or water to technological innovations and agricultural intensification. Their analysis demonstrates that single-sector interventions often induce difficult trade-offs. However, a portfolio of interventions substantially reduces the negative side-effects of single interventions. When used together, measures such as forest protection, improving nitrogen efficiency, water protection and sustainable agricultural intensification enable society to use bioenergy and combat climate change without sacrificing the well-being of its peoples, or the health of its environment.

Delving into their analysis, they find that bioenergy production without other interventions will lead to a 90% increase in cropland expansion compared to no bioenergy production by 2030. Indeed, without protecting pastures and forests, cropland expansion leads to a 145% increase in the destruction of natural vegetation by 2030 (with bioenergy, there is a 147 Mha reduction in pastures and forests, compared to only 60 Mha without bioenergy production). Importantly, because the model predicts Sub-Saharan Africa and Latin America together will account for more than 50% of future global bioenergy production, these developing regions will be subject to substantial negative environmental impacts: Forest losses, nitrogen pollution, unsustainable water withdrawals, and above all higher agricultural prices. Implementing single interventions, such as those reducing deforestation, or protecting freshwater ecosystems, will likely raise agricultural prices. Counterintuitively, protecting freshwater ecosystems by limiting water withdrawals may even lead to more deforestation, as croplands expand because there is less water available for irrigation (see also Bonsch et al. 2014). Improving fertilization techniques and investing in technologies to increase agricultural productivity will decrease agricultural prices and nitrogen losses, but do little to combat deforestation and water use. It is only when all of the measures were implemented together that forests, pastures, and freshwater systems were spared while agricultural prices remained constant. The safest path towards sustainable, equitable production of bioenergy crops is through a comprehensive, integrated portfolio of interventions that reduce negative environmental externalities even as they increase the production of agricultural commodities.

Livestock intensification provides opportunities to reduce negative environmental impacts: The consumption of livestock products and the associated feed demand is one of the main drivers in agricultural land use, accounting for 80% of agricultural land either directly or through feed production (Steinfeld et al. 2006). Thereby, the livestock sector is also responsible for over 80% of all agricultural non-CO2 emissions (Tubiello et al. 2013), and 42% of total agricultural water use (Heinke et al. 2020). Future demand for livestock is expected to rise (Alexandratos and Bruinsma 2012; Bodirsky et al. 2015), putting additional pressure on the land system and impeding the achievement of several SDGs, including SDG 6 (*Clean water and sanitation*), SDG 12 (*Responsible consumption and production*), SDG 13 (*Climate action*), SDG14 (*Life below water*) and SDG15 (*Life on land*). However, livestock products are an important source of protein in current diets, and providing an increased number of people with a healthy amount of animal-sourced protein can help to fight undernutrition and achieve SDG 2 (*Zero hunger*) (Bodirsky et al. 2020).

Intensification of low-intensity livestock systems, e.g., by substituting residues, food waste, and grazed biomass as feed sources with higher quality and nutrient-rich feed, can be a way to mitigate some of the consequences of meeting an increasing demand for livestock products (Havlík et al. 2014; Weindl et al. 2015). Weindl et al. (2017a) estimate that intensification of extensive livestock systems can reduce future deforestation until 2050 by 50-58% compared to a scenario following current productivity trends, as reductions in pasture area will outpace the increasing demand for cropland to produce feed. Furthermore, Weindl et al. (2017b) project the increase of total agricultural water-use in 2050 compared to 2010 to be substantially lower in the intensification scenario (12% increase vs. 23% increase). However, they also show that the shift from pasture to cropland for feed production goes hand in hand with a shift from green water (naturally infiltrated soil water formed by precipitation) to blue water (liquid water from rivers, lakes, and reservoirs) used for irrigation of cropland. This leads to a higher increase in blue water use in the intensification scenario, which can increase regional water scarcity in areas as Sub-Saharan Africa and South Asia. Attention should also be given to regional and socio-economic differences and difficulties in transforming livestock systems, as especially low-income producers often lack the resources for sustainable development (Garnett et al. 2013).

Concerns are also raised about the consequences of highly intensive livestock systems (Garnett et al. 2013; Lemaire et al. 2014). Weindl et al. (2017a, b) estimate no substantial impact of de-intensification of highly intensive livestock systems on water use or future land-use dynamics, giving the opportunity to improve animal welfare and reduce environmental impacts such as nitrogen pollution of aquatic ecosystems without environmental trade-offs.

A further, more explorative mitigation measure is the use of microbial protein to replace feed protein (Pikaar et al. 2017). Microbes could be either cultivated on sugar, biogas, or syngas from cropland origin or even completely landless based on inorganic fertilizers and hydrogen. Pikaar et al. (2017) show the potential for a strong reduction of cropland, water demand, nitrogen, and greenhouse gases, in particular for the landless production of microbial protein, but also when using sugar and syngas. The application is however limited to protein feed components, and the landless production requires large amounts of energy.

Next to improved feeding practice, also a higher circularity of animal wastes can reduce the negative environmental impact of the livestock system, as currently large amounts of nitrogen are lost in the form of ammonia and denitrification. Increased recycling rates could substitute inorganic fertilizers and reduce nitrogen emissions. Bodirsky et al. (2014) estimated that improved feeding and higher manure recycling rates could reduce agricultural nitrogen losses by 12%.

Dietary shifts are critical to a sustainable and healthy global food system: Diets – and their underlying nutrition – are a fundamental determinant of public health outcomes and global change. Historically, improvements in crop yields and production techniques have enabled global food production to meet the caloric demands of a growing population and reduce malnourishment. However, lack of sufficient food still leads to approximately 820 million deaths globally, with many more affected by undernutrition (Willet et al. 2019). The State of Food Security and Nutrition in the World (SOFI) report shows that the main constraint to achieving the UN's Sustainable Development Goals related to nutrition remains the high cost of healthy diets (FAO 2020). Indeed, an estimated 3 billion people remain unable to afford the least costly but nutritionally complete diet that is recommended by the findings of the EAT-Lancet Commission (Willett et al. 2019). At the same time, population growth, as well as an over-reliance on animal-sourced proteins and empty calories by an increasing share of the population, has led the food system to increasingly exceed environmental limits, leading to further deforestation, GHG pollution, and regional water stress (FAO 2020).

Dietary change touches almost every SDG, for example, from SDG 2 (*Zero hunger)* to biodiversity as in SDG 14 (*Life below water*) and SDG 15 (*Life on land*), SDG 3 (*Good health and well-being)*, and SDG 10 (*Reducing inequalities)*. Achieving these and other critical targets will require the food system to provide affordable, sustainably sourced healthy diets. In their global assessment of the ongoing nutrition transition, Bodirsky et al. (2020) evaluate the links between global health, food systems, and environmental change. They demonstrate that a broad-based dietary change is a fundamental prerequisite in our search to alleviate the current epidemics of under- and overweight diets, food waste, and environmental degradation.

However, dietary change varies greatly on a global level. While high-income countries need to reduce their consumption of animal products substantially, healthy people in low-income regions would likely benefit from increasing meat consumption (Willet et al. 2019).

Their results reveal that our goal to achieve SDG 2 (*Zero hunger*) will fail under a business-as-usual scenario, as undernourishment will persist (528 million people, or 6% of the global population, in 2050) (Bodirsky et al. 2020). Further, high population growth will continue to correlate with increasing food demand and the share of animal-source calories is predicted to rise (Bodirsky et al. 2020). Without dietary changes, this will impose even greater pressures on the environment. Several MAgPIE studies analyze the impacts of a change in consumption patterns. Specifically, they study a scenario with a gradual shift towards a demitarian diet consisting of no more than 15% animal-sourced calories. Quantifying the impacts of changing human diets and livestock productivity on land dynamics and carbon depletion, Weindl et al. (2017a) conclude that reducing consumption of livestock products has the potential to substantially reduce deforestation (47-55%) and cumulative carbon pollution (34-57%). Furthermore, Weindl et al. (2017b) expect the future increase in agricultural water use to be substantially lower in case the demand for livestock products is reduced. Bodirsky et al. (2014) estimate that the change in consumption patterns can reduce requirements for reactive nitrogen by 30 Tg, by lowering field losses due to reduced feed demand, and by reducing losses in animal waste management. Furthermore, reducing food waste and animal products would lower agricultural prices and thus fight undernutrition (Stevanovic et al. 2017).

Summarizing, a dietary shift away from a high share of animal-source and empty calories has multiple benefits on the environment and health, without any apparent trade-offs (Bodirsky et al. 2020; Clark et al. 2019; Weindl et al. 2017a; Weindl et al. 2017b; Stevanovic et al. 2017; Springmann et al. 2016). Therefore, reducing demand for unhealthy, environmentally damaging food will be a key avenue of progress in the 21st century, with the potential to facilitate progress towards a sustainable, healthy food system (Springmann 2020). Future research must elucidate policies that reduce this demand.

	Crops	Pasture	GHG	Water	Nitrogen	Biodiversity	Bioenergy	Livestock	Food	Forests/Protected areas	Poverty	Trade	Health
Bodirsky et al. (2014)					M, I			M	M				
Bodirsky et al. (2020)									M, I				M, I
Humpenöder et al (2018)	M, I	I	I	M, I	M, I		M	M	I	M, I			
Leclère et al (2020)	M					I			M	M		M	
Pikaar et al. (2017)			I	I	I	I		M					
Sörgel et al. (2021)			M								I		
Stehfest et al. (2019)	M, I	I							I			I	
Stevanovic et al. (2017)			M, I						M, I				
van Zeist et al. (2020)	M, I							M					
Wang et al. (2020)	M, I			I					I			I	
Weindl et al. (2017a)				I				M	M				
Weindl et al. (2017b)	I	I	I					M	M	I		M	

Table 1. Overview on analysed effects and side-effects of measures within MAgIE modelling studies. M indicates a measure in this sphere, I indicates quantified impact indicators in this sphere.

4. Discussion

Interventions in the land system often generate multidimensional impacts on the biogeophysical and economic system, differentially influencing progress towards the UN's 17 Sustainable Development Goals for 2030. While there are many opportunities for synergy between the goals (Pradhan et al. 2017), our results demonstrate that trade-offs are common when studying measures independently and that different measures often compete for the same resources. This is especially pertinent for land, which is at the intersection of three competing priorities: Food production, bioenergy production, and biodiversity protection. Therefore, deepening our understanding of these interdependencies – and their trade-offs – and developing a framework for designing science-driven interventions is an urgent task for researchers going forward. Here, we first synthesize our results and propose several key insights for the design of measures going forward. When possible, we must embrace measures that induce few trade-offs, and otherwise, bundling measures together often mitigates the negative side-effects of single measures alone. Second, we discuss an important caveat within the MAgPIE literature, and other IAMs generally: Inclusion dynamics are underrepresented within these models, suggesting that important side-effects may be unaccounted for. Finally, we discuss the nexus of measure and policy design, reviewing their conceptual difference and translating our insights – based on a measure paradigm – into one useful for policymakers.

4.1 Principles of measure design

Our review reveals several critical lessons that pervade analyses using MAgPIE. Broadly, almost all measures taken to achieve specific Sustainable Development Goals will have direct and indirect consequences for other goals. To manage these trade-offs and synergies, we propose two principles: First, when possible, low risk–high reward measures should be a central focus. Second, when "easy win" measures are scarce, bundling measures is a powerful strategy for managing trade-offs.

Some measures within the economic and social system are low-risk interventions that do not induce trade-offs between the SDGs. A dietary transition is one such measure that may reduce the negative health, environmental, and social costs of our food system. As shown in Bodirsky et al. (2020), unhealthy diets rich in animal proteins increasingly endanger world health and the stability of the earth system. While a dietary transition away from animal-sourced protein must ensure that the world's poor are still able to access enough protein for a healthy life (FAO 2020; Willet et al. 2019), the second-order benefits of reducing animal protein and empty calories are enormous (see *Results: Dietary Shift)*. Therefore, when possible, policies promoting the EAT-Lancet diet (Willet et al. 2019) should be vigorously pursued.

However, easy-win measures are often the exception. Commonly, measures taken to promote one goal have negative side-effects for others. When these situations emerge, measure bundling (Peters et al. 2018; Fesenfeld et al. 2020) is a promising methodology to reduce these negative side-effects. By incorporating one measure for each dimension of a trade-off, bundling measures allows for each negative side-effect to be tuned independently and therefore more easily ameliorated (Daly 1991, citing Tinbergen 1952). Humpenöder et al. (2018) demonstrate the power of measure bundles in their analysis of bioenergy and its trade-offs. In their analysis, they found that wide-scale bioenergy adoption (SDG 7, 13) would increase pressure on food crop production (SDG 1, 2), regional water supplies (SDG 6), and biodiversity (SDG 14, 15). Measures intended to ameliorate single side-effects, such as protecting biodiversity areas from cropland expansion, endangered progress towards the other SDGs. Only by bundling measures, such that each side-effect is accompanied by a corresponding measure, could they increase bioenergy production without substantial negative side-effects on the other SDGs.

4.2 The necessity of embedding inclusion into IAMs

Integrated assessment models are designed to project the future of the biogeophysical and economic system, and how various interventions – measures – may shape this future. This functionality has cemented them as a primary tool researchers use to explore the allocation of limited resources within the land system and advise policymakers on how to minimize the negative side-effects and trade-offs inherent in making policy decisions. As models, they are in continuous development as their detail is enhanced and scope is expanded to encompass more facets of the biogeophysical and economic system. The processes and trade-offs modeled within MAgPIE are accordingly in continuous development. The distributional effects of measures taken within the land system are especially important to consider within analyses of the land system and are one such process that is currently underdeveloped within the MAgPIE framework, which will be critical for transitioning the land system on a healthy, just, and sustainable path.

These distributional effects (Kehlbacher et al. 2016; Coudouel and Paternostro 2006, 2005) reflect the differential effects of interventions in the land and agricultural system on peoples' health and livelihoods and can serve as a proxy for inequality. For instance, these effects are especially salient when considering the affordability of a healthy diet. Measures taken to achieve some SDGs, e.g., bioenergy production (SDG 7, 13) or biodiversity protection (SDG 14, 15), often indirectly increase agricultural prices by increasing the competition for available land (Wang et al. 2020; Stevanović et al. 2017; Humpenöder et al. 2018; Leclère et al. 2020**)**. However, the unequal impact that rising agricultural prices have on different segments of the population has rarely been integrated into an IAM. Sörgel et al. (2020) is the first of such analyses using MAgPIE to approach this omission. In their study, they analyzed the impact of a GHG tax on global poverty rates, finding that redistributive taxation dramatically reduces the negative effects of taxation on the poor. As food prices and the price of energy is higher, low-income households would have to spend disproportionately more of their income on food (OECD 2021; Kehlbacher et al. 2016). By modelling an equal-per-capita climate dividend, Soergel et al. (2020) find that the poor are compensated and poverty actually decreases over time.

This example demonstrates the necessity of including the unintended side-effects of interventions on marginalized groups. For this reason, IAMs should emphasize more aspects of inclusion. For example, with 2.5 billion livelihoods depending on agriculture (FAO 2016), changes in production, productivity, or demand patterns directly affect rural employment and the involvement of women in production (FAO 2020; IFPRI 2020). Further, changing agricultural food prices do not only affect consumers but also the income of producers. As Herrero et al. (2021) emphasize, all trade-offs need to be foreseen and addressed to achieve sustainability in food systems. Therefore, modeling studies need to avoid a myopic focus on single indicators such as average income or agricultural price, and more fully consider the effect of interventions on the inclusivity of the food system going forward.

4.3 Implications for the design of policy

Within this brief, we reviewed recent literature using the land system model MAgPIE. In particular, we documented the interaction pathways generated by different measures taken in support of the UN's Sustainable Development Goals. In the MAgPIE framework, measures are defined by either constraining the model's optimization or by exogenously fixing parameters (*see Methods*). This process does not directly reflect the role of policies in steering our economic system. For instance, to understand the role of dietary shift in achieving climate and health targets in the MAgPIE model, the global intake of meat and dairy products can be exogenously reduced to its target levels (Weindl et al. 2017a; Bodirsky et al. 2020). The policies necessary to steer this dietary shift in real-world societies - such as a tax on animal products, or the change of public provision in school cafeterias, however, are not explicitly modeled. Depending on the mechanism by which these policies are implemented (e.g., enabling, persuading, nudging, economic incentivizing, commanding), and depending on the actual policy configuration, the consequences – in particular the distributional outcomes – can strongly differ (OECD 2021; Barrett et al. 2020; Givoni et al. 2012). The implementation of policies moreover is subject to transaction costs for administration, monitoring, implementation, evaluating, and sanctioning that also influence outcomes. Integrated assessment models are unable to model these vital effects. Therefore, significant future research is needed on policy development and effectiveness, especially including multi-dimensional evaluations (Peng et al. 2021).

Recent research using MAgPIE has begun to more mechanistically integrate a policy framework. For instance, Sörgel et al. (2021), as discussed in the previous section, attempt to assess and mitigate the potential distributional side-effects of a carbon tax by introducing a progressive redistribution taxation scheme. While still highly stylized, this policy assessment already more closely follows potential policy implementations than previous work and is, therefore, more likely to capture the nuanced consequences of carbon taxation on real people. The work strongly suggests that policymakers should consider these redistributive taxation schemes as they design taxation policy for greenhouse gases.

As researchers begin to connect measures and policies more concretely, policymakers should consider the literature revealing the consequences of measures taken within the land system as idealized effects of policy implementations. A resulting key insight is the need to bundle measures – and similarly bundle policies – to maximize positive impacts while limiting overall trade-offs.

5. Conclusion

Within this brief, we reviewed several recent studies that have employed the MAgPIE model for analyses of global land use in the 21st century. We focus throughout on the interactions present between different facets of the land system, and describe how interventions aimed at progressing towards one Sustainable Development Goal often have complex systemic effects on the others. It is the responsibility of researchers to communicate these complexities, and identify potential avenues, such as focusing on "easy wins" and bundles, for minimizing trade-offs. While integrated assessment models will be vital to this task, they should further integrate distributional effects, because the only durable transformation of our food system will be an inclusive one (Peng et al. 2021).

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