LETTER • OPEN ACCESS

Global economic–biophysical assessment of midterm scenarios for agricultural markets—biofuel policies, dietary patterns, cropland expansion, and productivity growth

To cite this article: Ruth Delzeit *et al* 2018 *Environ. Res. Lett.* **13** 025003

View the article online for updates and enhancements.

Recent citations

Environmental Research Letters

LETTER

Global economic–biophysical assessment of midterm scenarios for agricultural markets—biofuel policies, dietary patterns, cropland expansion, and productivity growth

Ruth Delzeit[1,2] , Gernot Klepper[1], Florian Zabel[2] and Wolfram Mauser[2]

[1] Kiel Institute for the World Economy, Kiellinie 66, 24105 Kiel, Germany
[2] Ludwig-Maximilians-Universität München, Luisenstr. 37, 80333 Munich, Germany

E-mail: ruth.delzeit@ifw-kiel.de

Abstract

Land-use decisions are made at the local level. They are influenced both by local factors and by global drivers and trends. These will most likely change over time e.g. due to political shocks, market developments or climate change. Hence, their influence should be taken into account when analysing and projecting local land-use decisions. We provide a set of mid-term scenarios of global drivers (until 2030) for use in regional and local studies on agriculture and land-use. In a participatory process, four important drivers are identified by experts from globally distributed regional studies: biofuel policies, increase in preferences for meat and dairy products in Asia, cropland expansion into uncultivated areas, and changes in agricultural productivity growth. Their impact on possible future developments of global and regional agricultural markets are analysed with a modelling framework consisting of a global computable general equilibrium model and a crop growth model. The business as usual (BAU) scenario causes production and prices of crops to rise over time. It also leads to a conversion of pasture land to cropland. Under different scenarios, global price changes range between −42 and +4% in 2030 compared to the BAU. An abolishment of biofuel targets does not significantly improve food security while an increased agricultural productivity and cropland expansion have a stronger impact on changes in food production and prices.

1. Introduction

Land is a limited resource that can be used in different ways for the production of food, animal feed, fibre, and bioenergy, or for the protection and maintenance of ecosystems and its services (Foley *et al* 2011). Land-use decisions are made at the local level. Together with local environmental constraints, they also depend on a local cultural and legal framework that sets socio-economic boundaries determined by e.g. available capital resources and management practices (Tilman *et al* 2011, Václavík *et al* 2013, Mauser *et al* 2015).

A significant share of agricultural commodities is traded internationally (OECD/FAO 2016). The larger this share, the more local production conditions are codetermined by global socio-economic and environmental conditions and political interventions mainly through price signals from world markets (Porkka *et al* 2017, Golub *et al* 2012).

Global socio-economic changes are driven mainly by an increase of world population and expected higher incomes (Dellink *et al* 2017). As a result, global demand for agricultural commodities is estimated to increase, not only for food, but also for bioenergy and livestock-based products (Calzadilla *et al* 2016, Seppelt *et al* 2014, Foley *et al* 2011, Bruinsma 2011). Thus, pressure on land for intensification and expansion will increase with far-reaching environmental consequences (Foley *et al* 2011, Gerstner *et al* 2014, Newbold *et al* 2015).

Political decisions e.g. on agricultural policies, the demographic and technological development or environmental changes trigger feedbacks between the world market for agricultural commodities and local land-use decisions which again feed back on the world market and the other factors mentioned. These multi-facetted feedbacks have been studied by developing and analysing scenarios (Popp *et al* 2017, Dellink *et al* 2017, Valin *et al* 2014). Scenarios help to better understand complex cause-impact relations and identify alternative pathways into the future and their respective trade-offs.

Most scenarios cover the time frame from today towards 2050 or 2100. While this is the established timeframe for climate change studies it is largely impossible to agree on reasonable scenario assumptions for the socio-economic development until the middle, not to speak of the end of the 21st century. The mid-term integrated scenarios, which reach out until 2030, allow to establish a reasonable set of assumptions, which can form a solid basis to carefully analyse feedbacks between economic and biophysical factors in the development of land-use.

Appropriate modelling tools to study the feedbacks between economic and biophysical factors and land-use with integrated scenarios of global change are emerging. The studies combe partial/general computable equilibrium models (e.g. Baldos and Hertel 2014) or optimisation models (e.g. Popp *et al* 2017) with crop growth models. These studies feed changes in agricultural productivity into economic models. Usually no feedback exists from economic models to the simulation of crop yields and land-use changes. An approach that studies the feedback effects by iteratively coupling the socio-economic results of a computable general equilibrium (CGE) simulation of the global agricultural market and the biophysical simulations of global potential crop yields is followed by Mauser *et al* (2015). It shows that considering the feedback of economic and biophysical factors changes the spatial land-use patterns and results in larger potential yields compared to other studies.

Several scenario-based studies have looked into potential future developments of the agricultural sector as a whole (Odegard and van der Veat 2014, Schmitz *et al* 2014). A model exercise showed that most models agree on an increase of global cropland area between 10%–25% in 2050 compared to 2005 (Schmitz *et al* 2014). Nevertheless, after harmonising key assumptions significant differences in projections remain. The differences in key assumptions partly represent the uncertainty about major drivers of agricultural markets (von Lampe *et al* 2014). The diverging results of these studies suggest that in order to develop mid-term scenarios an expert based process should to be used which develops clearly defined storylines and scenario assumptions.

The objective of this paper is to develop and analyse a set of global integrated mid-term scenarios of the

likely development of socio-economic and environmental conditions until the year 2030. They are used to explore the range at which the world agricultural market and regional land-use decisions influence each other.

2. Methods

2.1. Co-design of storylines and scenarios[4]
The global scenarios were developed using a three-step participatory co-design approach according to Mauser *et al* (2013) in the course of several workshops (figure 1). First, we proposed a preliminary set of storylines (supplementary figure A.1.1, available at stacks.iop.org/ERL/13/025003/mmedia) to experts from globally distributed regional studies of the research program 'Sustainable Land Management' by the German Ministry for Education and Research.

The workshop participants discussed the preliminary storylines and suggested additional storylines. The storylines were then consolidated and further discussions concluded with a final set of six storylines (left part in figure 2). The storylines can be analysed with and without future climate change[5].

Data for quantifying the storylines with regard to sectoral developments and their aggregation in terms of the temporal and spatial resolution were then identified (column 2 in figure 1). The main outputs are changes in regional and global commodity prices and production, agricultural yield potentials, and changes in land-use.

Finally, each storyline was transformed into a scenario by formulating assumptions for model parameters representing the drivers and by assigning appropriate values (figure 1, right column, figure 2 and section 3). Under the two extreme scenarios, certain parameters sets of the other scenarios are combined. This was presented for discussion in a third workshop. The scenarios were then implemented in a modelling framework (see figure 1 and section 2.2).

2.2. Modelling framework
We apply a modelling framework that combines the global CGE model DART-BIO and the dynamic crop growth model PROMET. Results are simulated by either using the DART-BIO model alone or by linking it with PROMET.

2.2.1. DART-BIO
The Dynamic Applied Regional Trade (DART) model is a global multi-sectoral, multi-regional recursive-dynamic CGE model (e.g. Klepper and Peterson 2006).

---

[4] Details in supplement A.1.
[5] Due to space restrictions, we report only the impact of climate change on the 'business as might be usual' path. All scenarios have been simulated with climate change. Details are available upon request.
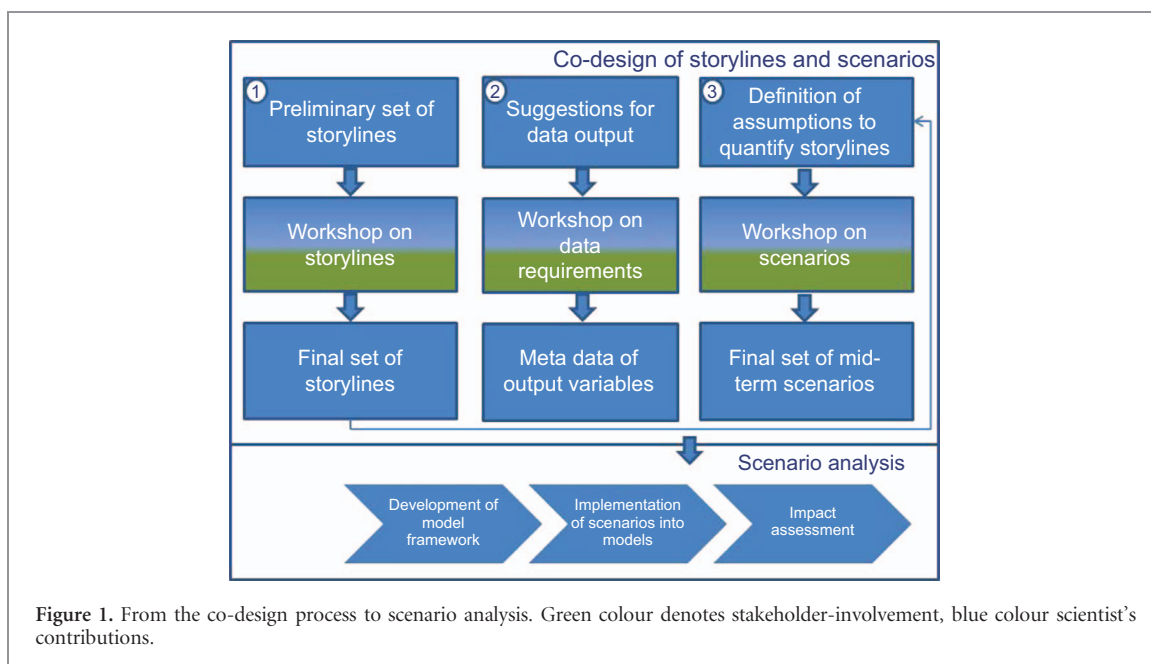
Figure 1. From the co-design process to scenario analysis. Green colour denotes stakeholder-involvement, blue colour scientist's contributions.

Figure 2. From storylines to scenarios.

The economy in each region is modelled as a competitive economy with flexible prices and market clearing conditions. The version DART-BIO is calibrated based on the GTAP8.1 database (Narayanan *et al* 2012)[6] which represents the global economy in 2007. DART-BIO has 23 regions (figure S1) subdivided into 18 so-called agro-ecological zones (AEZs) (figure S2), 38 sectors, 45 products (table S1) and 21 production factors (table S2). DART-BIO takes into account

economy wide repercussions of policies or changes in assumptions[7].

2.2.2. PROMET
PROMET is an integrated hydrological land surface process model, which includes a detailed dynamic simulation of crop growth for 18 different staple and bioenergy crops (table S3) (e.g. Mauser and Bach 2009, Mauser *et al* 2015). It takes into account the inter-dependency of net primary production, phenological

---

[6] Data on AEZs were not yet available for the new GTAP9 database when we did the analysis.

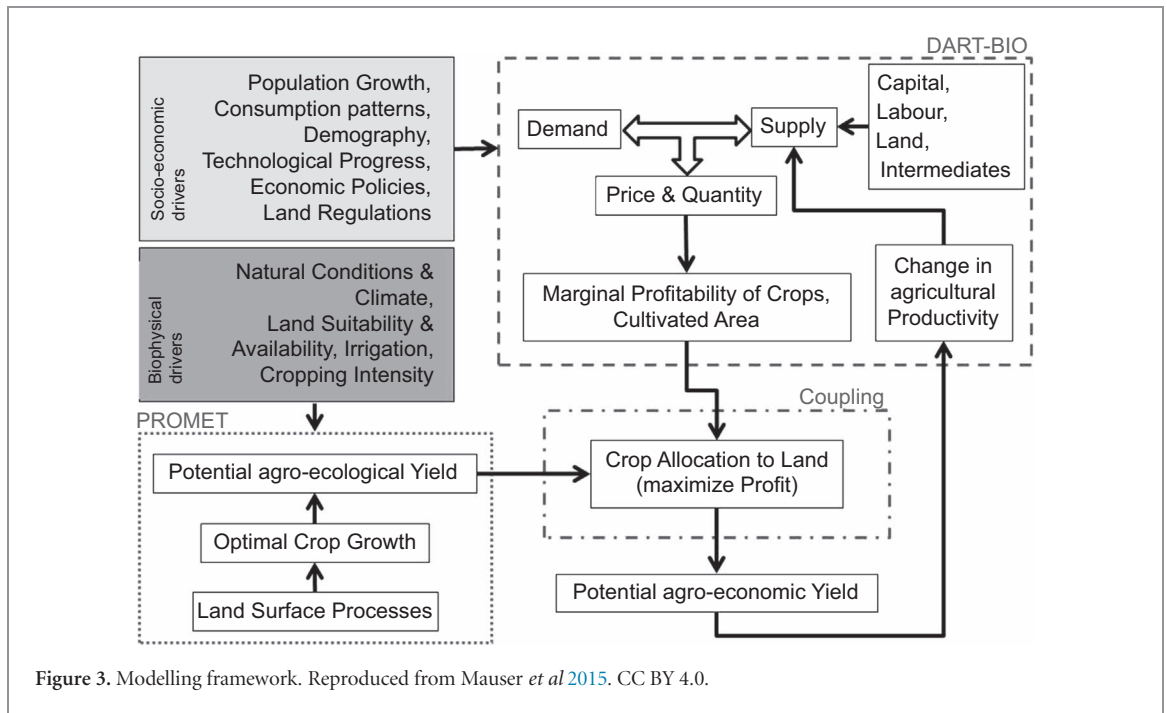[7] Detailed description in Calzadilla *et al* (2016).

Figure 3. Modelling framework. Reproduced from Mauser *et al* 2015. CC BY 4.0.

development, leaf temperature, water availability and environmental factors, including meteorology and CO_2 concentration for C3 and C4 pathways. For global application, 250 000 statistically representative samples are chosen randomly on the global agriculturally suitable area according to Zabel *et al* (2014). Management measures, such as irrigation and fertilisation are considered. This allows the simulation of potential yields presuming optimal crop management (no nutrient deficits, pests, diseases and yield losses), denoted as 'potential agro-ecological yields'.

2.2.3. The coupling approach
While in former assessments yield potentials are calculated on sample locations by taking the crop that is currently grown (Pugh *et al* 2016, Mueller *et al* 2012, IIASA and FAO 2012), our approach allows farmers to change the allocation of crops by choosing the crops with the highest profitability (Mauser *et al* 2015). The profitability (profit per hectare) is influenced by biophysical drivers that determine the agro-ecological yield, and by socio-economic drivers (figure 3) that influence the relative profitability of crops.

In a coupling procedure (figure 3), the agro-ecological potential yields of 18 crops as an output of PROMET are spatially aggregated to the 23 regions applied by DART-BIO and grouped into 10 crop categories (table S3) to match with the crop aggregates used in DART-BIO. Agro-ecological potential yields, harvested areas, and crops' marginal profitability to land determine an agro-economic potential yield in an iterative approach. The approach is performed within five steps (supplement A.2.2). It takes into account that land allocation to crops changes over time due to changing cropping decision of farmers driven by e.g. dietary preferences or climate change.

3. Defining mid-term scenarios[8]

3.1. Business as usual scenario (BAU)
The BAU scenario carries forward the present situation until 2030. Assumptions for important drivers such as population growth, trade policies, and information about the calibration of the BAU scenario are explained in the supplement A.3.1. Biofuel policies are taken from OECD/FAO (2016) and Beurskens *et al* (2011) (figure 4). We assume that these shares will not change between 2020 and 2030.

3.2. No biofuel policies scenario (NBQ)
Some countries have already decided or are discussing to reduce or abolish biofuel targets (e.g. the EU (EC 2016)). Therefore, we implement a scenario in which there are no biofuel policies while the other parameters remain at the BAU levels.

3.3. Meat scenario (MS)
It is expected that demand for meat and dairy products (MDP) will rise particularly in Asian regions (Chemnitz 2016, Alexandratos and Bruinsma 2012). In the MS scenario, we increase the preference of consumers for MDP by replacing the estimated income elasticities for meat consumption in Asian regions with the highest elasticities found in the respective demand functions (table 1). Thus, with rising incomes, a higher share of a consumers' budget is spent for MDPs[9].

---

[8] All data and scenario assumptions in supplement A.3 and table S4.
[9] Details on the implementation and data on the parameter choices in supplement A.3.2.
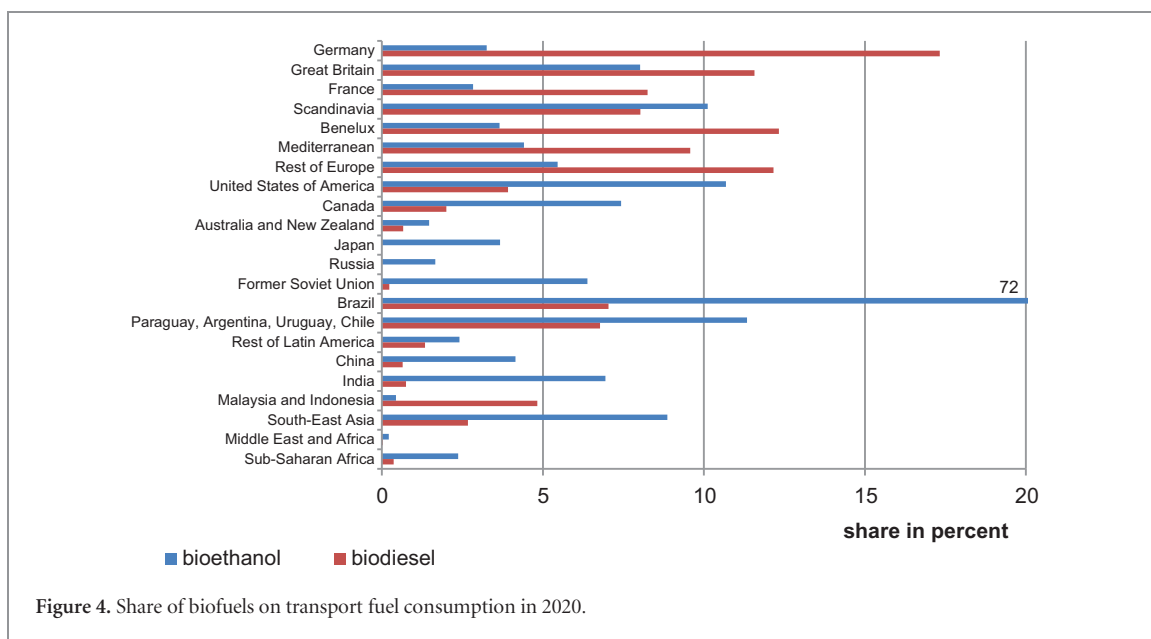
Figure 4. Share of biofuels on transport fuel consumption in 2020.

Table 1. Income elasticities of demand for indoor livestock and processed meat.

		India	Malaysia/Indonesia	South-East Asia
Business as usual	Indoor livestock	0.92	0.79	0.9
	Processed meat	0.92	0.77	0.77
Meat scenario	Indoor livestock	1.18	1.13	1.14
	Processed meat	1.18	1.13	1.14

Source: based on Narayanan *et al* (2012).

3.4. Land expansion/contraction scenario (LE)

The FAO outlook (Alexandratos and Bruinsma 2012) predicts an expansion of global crop areas by about 7%. We use this forecast to create the LE scenario by calculating annual growth rates of harvested area from the 2005/2007 base year to 2030 (figure 5).

3.5. Higher prices (HP)

This scenario combines aspects of the BAU with multiple supply and demand drivers leading to higher prices for agricultural products. Under this scenario biofuel policies and the other policies of the BAU scenario remain in place, and expansion of agriculture into uncultivated land is not possible. In addition, the MS assumptions are used. At the same time, lower productivity growth in the agricultural sector is implemented by reducing yield increases 0.2 percentage points below the BAU rates.

3.6. Lower prices (LP)

This scenario represents a combination of changes, now with a tendency towards larger agricultural supply and less demand to lowering future agricultural product prices. We combine the abolition of biofuel targets with keeping MDP consumption preferences as in the BAU scenario. We use assumption of the LE scenario and introduce a partial closing of regional yield gaps. Specifically, the regional yield gap ratio (figure 6), which is the potential agro-economic yield

divided by the statistical yield[10] is reduced by 5%. This reduction of yield gaps causes productivities to increase more strongly in regions with high yield gaps.

3.7. Climate change (CC)

To address climate change impacts on agriculture, we take the assumption of the BAU and add changes in yields under climate change. This is modelled by using results from the linking of PROMET and DART-BIO, where PROMET is driven by ECHAM5 climate data for A1B conditions[11]. Percentage changes in agro-economic yield potentials are gathered by comparing the agro-economic yields for the period 1981–2010 with those of 2011–2040.

4. Results[12]

4.1. Trends under the BAU scenario

The global production of agricultural primary products increases by between 30% and 83% between 2007 and 2030 (figure 7). The strong increase of soybeans and wheat is mainly caused by their use as feed in the livestock industry as increasing incomes lead to higher

---

[10] The statistical yield is derived from the underlying GTAP database (Baldos and Hertel 2014).
[11] Details in supplement A.3.3.
[12] The full set of results is available from the authors upon request.
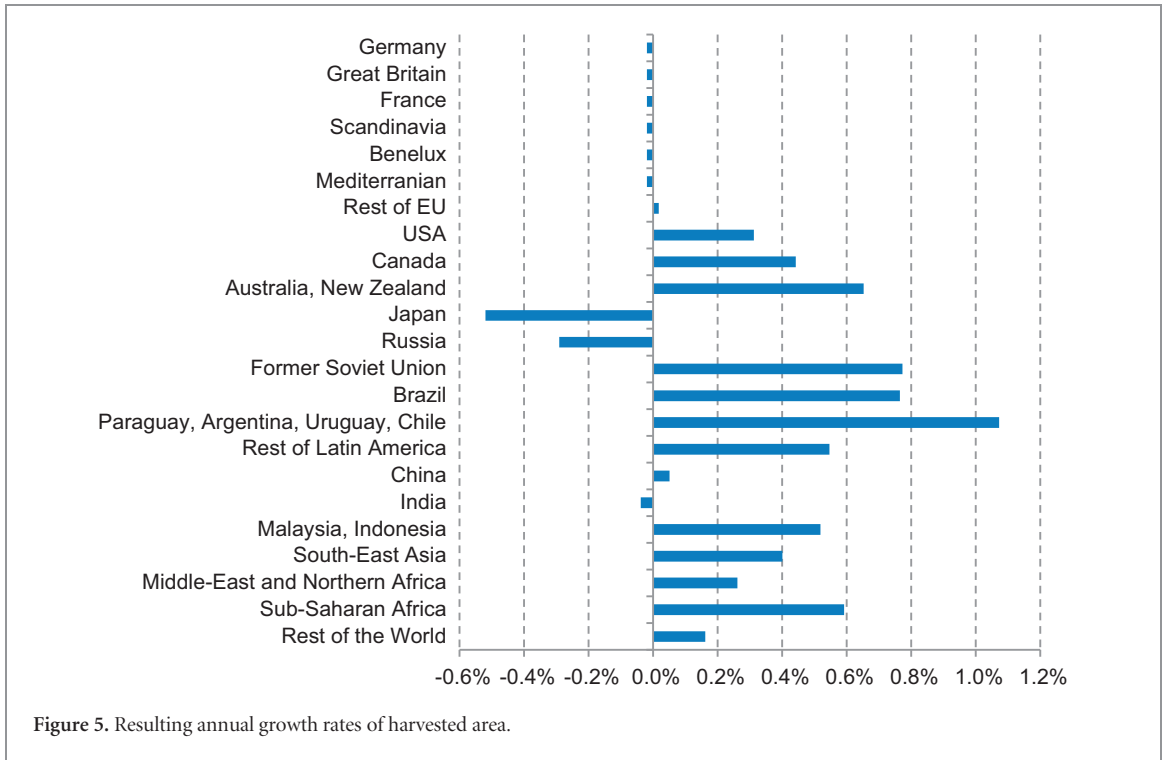
Figure 5. Resulting annual growth rates of harvested area.
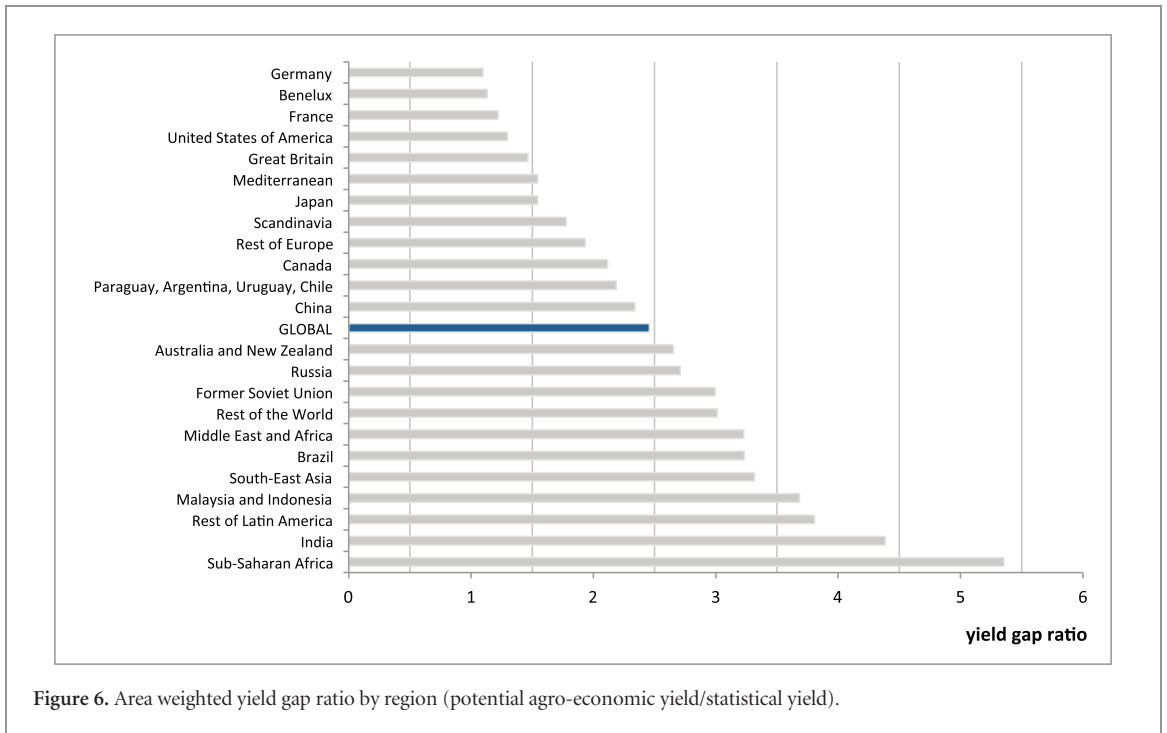
Figure 6. Area weighted yield gap ratio by region (potential agro-economic yield/statistical yield).

meat consumption. In addition, soybeans are used for biodiesel production for which demand increases threefold by 2030.

Global average prices increase more strongly for primary agricultural products than for processed agricultural goods since land price increase relative to the other factors of production, labour and capital. Prices of livestock bred on pasture land rise by 111% while production only increases by 23%. This result is driven by the increased competition for land leading to a reduction in pasture land, a rise in land prices

and consequently in the prices of land intensive meat products.

The harvested crop area expands by +5% until 2030 at the expense of pasture land (−9%). Within cropland, oil seeds and wheat show the largest increase in harvested area. Additional results are discussed in supplement A.4.1.

4.2. Comparison of scenarios with BAU

Results are presented in percentage differences in 2030 between BAU and a scenario to illustrate the relative

Figure 7. Change in production, prices and harvested area in 2030 compared to 2007 under BAU.

impact of the scenarios on production, prices and land-use[13]. At the global level, most scenarios do not show a large deviation from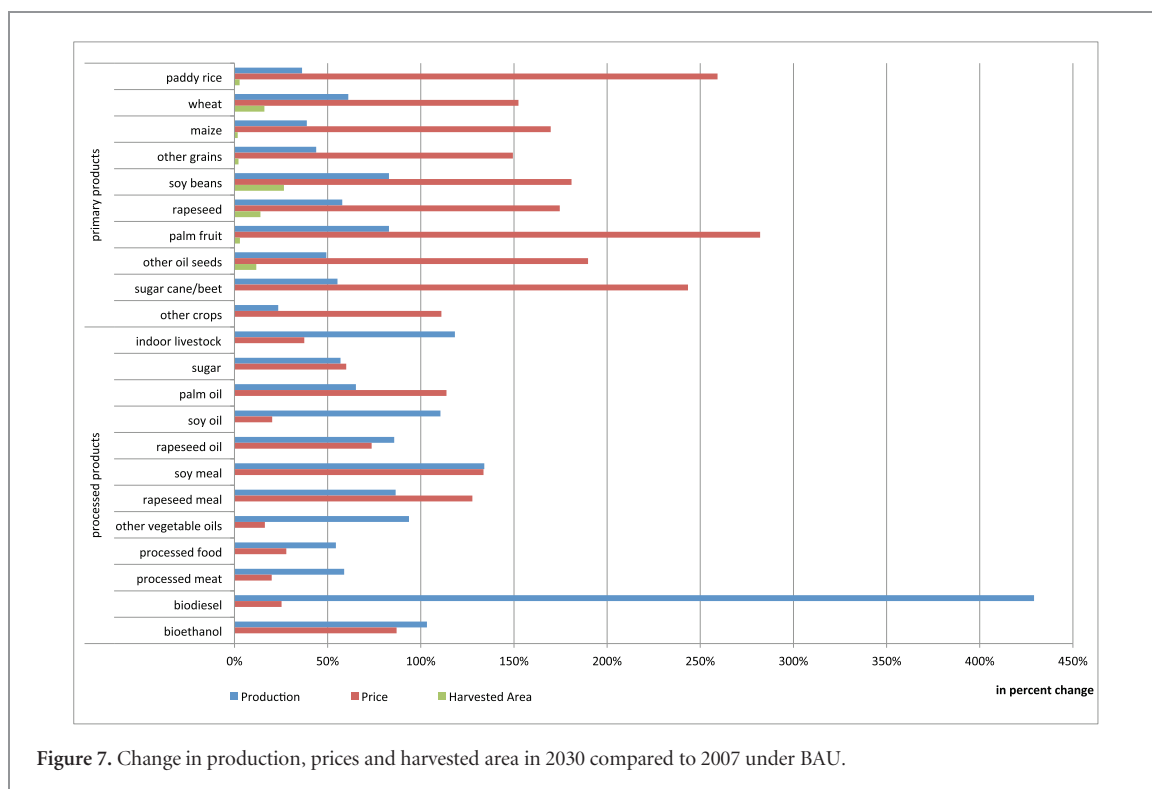 BAU. As illustrated in figure 8 for the case of wheat, the dominating overall trend is an increase in global crop production. The exception is the LP scenario where strong productivity growth strongly increases the global output of crops. Figure 9 summarises the impact of the six scenarios on agricultural products on a global scale.

The production and price changes in the different scenarios vary across crops and across regions. The results are discussed in detail in the following sections.

4.2.1. Impact of the no biofuel policy scenario (NBQ)
Less demand for oil seeds for biodiesel production and less demand for sugar cane, maize, and wheat for bioethanol production lowers their global production, trade flows and prices. The global average prices of annual crops drop by about 1%, only sugar cane shows a strong decline in prices by 8.7% (figure S3 and supplement A.4.2).

4.2.2. Impacts of the meat scenario (MS)
On the global level, additional demand for MDP in Asian countries causes only small changes in production, harvested area and prices[14]. To satisfy the increased MDP demand, the production of processed meat rises by 0.4%, and consequently the production

of the major feedstuff soy meal (and beans) increases by 0.3%. The area used for soy beans production increases at the costs of the area used for rapeseed (figure S4).

Most Asian countries are net-importers of crops. The higher demand for MDP causes imports to these countries and production of these products and their intermediates to rise.

4.2.3. Impact of the land expansion/contraction scenario (LE)
With changes in harvested area under the LE scenario (figure 5), global average crop production increases while prices decline. The impact on the global production of the different crops varies since they are produced in different regions with different growth rates in land endowment. Consequently, the global palm fruit, soy beans, and sugar cane production increases by up to 8.4% (figure 9).

Global average prices of crops fall by 6% to 20% (see figure S5). Regional prices of crops decrease most in regions with high land expansion (e.g. Latin American regions), while prices increase in regions where cropland area is reduced and trade restricted (Japan) (figure S6). Not only regions with high growth rates in land expansion experience decreasing food prices, but also net importers of crops benefit from lower world market prices for imported products[15].

4.2.4. Impacts of the higher prices scenario (HP)
The combined effects of smaller productivity increases and rising MDP demand cause the strongest increase

---

[13] Additional information for each scenario on the changes in trade flows, regional prices and production for each scenario in the supplement A.4.
[14] Results are discussed in supplement A.4.3.
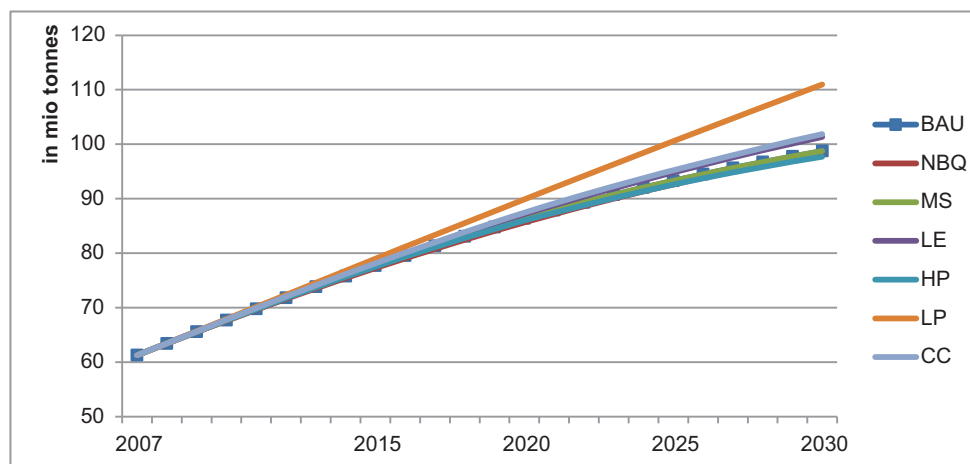
[15] Details in supplement A.4.4.

Figure 8. Growth of global wheat production under the selected scenarios. For abbreviations see figure 2.
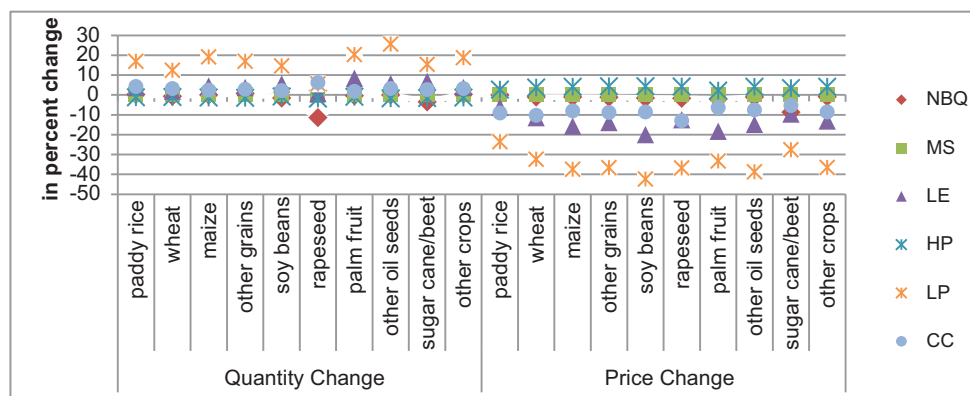

Figure 9. Summary of global quantity and prices changes in 2030 under different scenarios compared to BAU. For abbreviations see figure 2.

in global average prices among all scenarios (2.1% to 4.4% across crops), while the global production of crops decreases by 0.9% to 1.8% (figure 10). The reduced productivity gains obviously constrain the effect of higher MDP demand. Even the production of the main feedstocks does not increase relative to the BAU scenario, even though there is a shift of land towards these crops. One might expect an increase in crop production to satisfy higher demand for animal feed, but the lower productivity on the supply side has a stronger impact on production than the increase in MDP demand. Crop prices increase most in the EU, Africa and Middle East (figure S7). Surprisingly, price increases are lower in Asian regions, where more MDP is demanded under this scenario. The decrease in productivity growth is smaller in these regions compared to other regions (figure S8), such that regional prices increase less relative to the global average[16].

4.2.5. Impacts of the lower prices scenario (LP)
The abolishment of biofuel quotas causes less demand for crops, while cropland expansion and higher yields cause a higher production of crops. The results are strong market responses with lower global average prices of agricultural products.

Globally, the largest increases in production occur for palm fruit and 'other oil seeds' (figure 11). These are predominantly produced in countries with a large potential for increasing yields and a large predicted land expansion (Malaysia/Indonesia, Sub-Saharan Africa, Latin America). The production of rapeseed and wheat increases much less due to two competing factors: (1) the reduced demand for biofuels causes rapeseed and wheat production to decrease; (2) yield gaps of wheat are below the average (figure S9) such that wheat becomes less competitive relative to other crops.

Regions are affected very differently. Summed up over all crops, crop production increases by up to 42% in the South American regions, but also Malaysia/Indonesia and South-East Asia show strong increases in production (figure S10). This is caused by a combined effect of cropland expansion and increases in land productivity. Production increases less in e.g. India, since a high increase in productivity coincides with limited land expansion potentials[17].

---

[16] Details in supplement A.4.5.
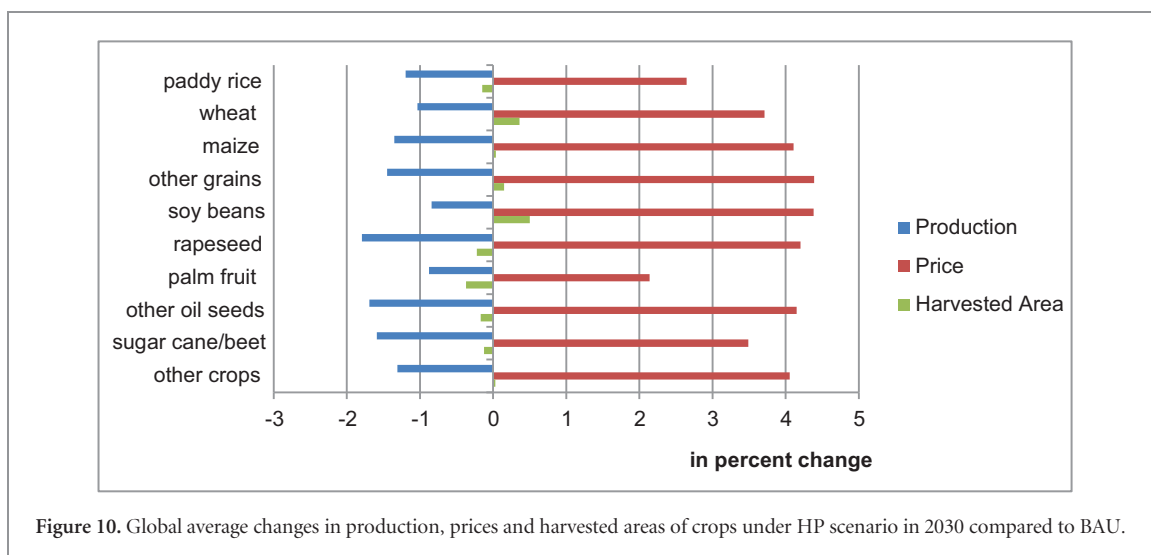[17] Details in supplement A.4.6.

Figure 10. Global average changes in production, prices and harvested areas of crops under HP scenario in 2030 compared to BAU.
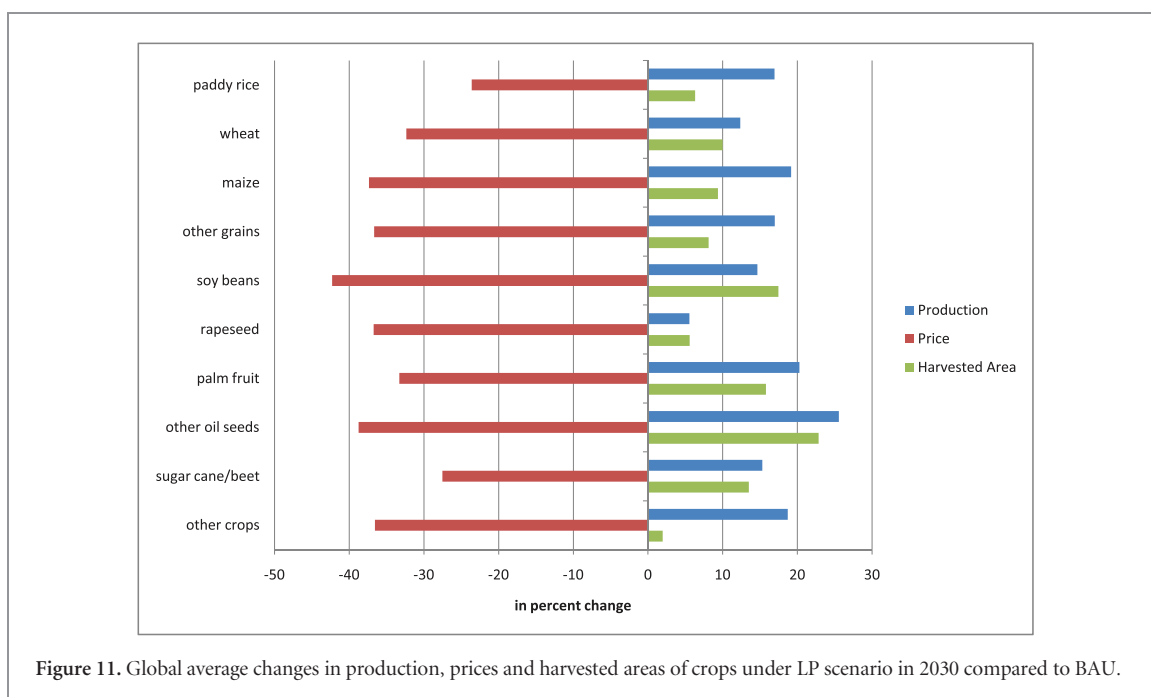

Figure 11. Global average changes in production, prices and harvested areas of crops under LP scenario in 2030 compared to BAU.

4.2.6. Impact of the climate change scenario (CC)

Climate change has globally a small positive impact on potential yields until 2030. The large productive agricultural areas in the higher latitudes experience a moderate temperature increase until 2030 resulting in longer growing seasons. In sum, global production increases for all crops between 1.7% and 6% until 2030, while crop prices decline (figure S11).

The regional effects are quite diverse. Crop production increases by 3% in the EU, by 8% in the USA, and 10% in Russia (figure S12). Prices of crops drop in all regions except Brazil, South-East Asia and Malaysia/Indonesia. Tropical regions mainly show a decline in potential yields and crop production, since temperature increase results in higher heat stress for plants[18].

---

[18] Details in supplement A.4.7.

5. Discussion

The results clearly show that that accounting for world market responses to regional economic developments such as demand, supply, and prices on world markets is highly important. Global trends as shown in the BAU scenario lead to an increasing scarcity of fertile land with rising prices for primary agricultural products. The trends are mainly driven by higher incomes combined with higher demand for meat products and to a lesser degree by the rising demand for biofuels. These trends cause production and prices of crops to rise and lead to a conversion of 228 Mha of pasture land to cropland. Compared to other studies (Schmitz *et al* 2014) that predict an expansion between 10% to 25% by 2050, we are at the lower range of cropland expansion.

The comparison of the scenario simulations with the BAU highlights the impact of specific policy as well
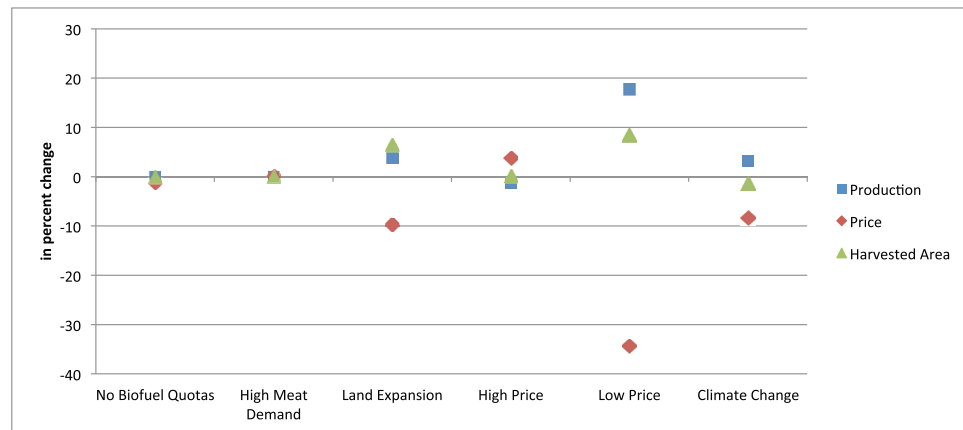
Figure 12. Change in global production, prices of crops (aggregated) and harvested area in 2030 compared to BAU.

as supply- and demand-side changes. It turns out that supply-side effects have a stronger impact than changes on the demand side. Figure 12 illustrates in an aggregated way how global production remains relatively stable. Exceptions are the scenarios with land expansion (LE scenario) and higher productivity (LP scenario).

Demand side effects in the MS and the NBQ scenario are small compared to the impacts on global quantities and prices in the other scenarios which indicates that the changes in dietary preferences do not have a large impact on global agricultural markets and land-use. However, the product- and region-specific adjustments show that substitution is taking place to accommodate the increased demand for meat. Adjustments show up in large changes in international trade and in regional adjustments[19].

Biofuel support is often made responsible for the increasing scarcity of food and thus a threat to food security (e.g. OECD 2008). This cannot be supported by the scenario analysis, since global food consumption rises by only 0.3% compared to the BAU when abolishing biofuel policies. Hence, a reduction in biofuel support does not significantly improve food security[20]. The international adjustments through trade and the integration of the joint production of oils or grains and feed are responsible for our result.

Under the HP scenario with all adjustments, global consumption of food is only 1% lower than in the BAU. But prices do not increase as much as expected which is mostly due to substitution effects towards other non-food consumption goods.

Much stronger effects occur in the LP scenario. Taking prices of agricultural goods and production quantities as indicators for food security, our results show that the LP scenario leads to an improvement of food security. This holds particularly in regions that face

problems in improving food security (Latin America, South-East Asia, Sub-Saharan Africa).

Land expansion and climate change have a stronger impact on prices than on production indicating that demand is more inelastic than the supply side.

6. Conclusions

The set of scenarios, developed in a co-design process, provides consistent information on the impact of different global developments. It also highlights by how much different supply and demand developments as well as policies influence the allocation of resources in future markets. Since local land-use decisions strongly depend on global market conditions using the same scenarios in regional studies increases the comparability and transferability of such studies.

The results indicate that world market effects are themselves the result of very diverse regional developments and adjustment processes to the drivers of the different scenarios. This diversity of responses underscores the advantage of using globally consistent scenarios when analysing the development in a region in detail as the regional development may have an impact on world markets but world markets also transmit the reactions of markets in other regions. These effects cannot be accounted for by regional studies alone.

Global markets attenuate the potentially large regional impacts of changes in policies or supply and demand conditions substantially. Therefore, issues with regional food security become less pressing, too. Contrary to concerns about the impact of biofuel policies or behavioural changes towards higher meat consumption, food security seems to be less of a concern because quantity and price effects remain small. The biggest opportunity for improving food security is productivity increases. The strong price decreases are particularly important since food security is to a large extent connected to the ability to afford food.

---

[19] Detailed results on the substitution effects in supplement A.4.2 and A.4.3.
[20] Detailed information in supplement A.4.1.

Acknowledgments

ORCID iDs

Ruth Delzeit ● https://orcid.org/0000-0003-1668-8009

References

Alexandratos N and Bruinsma J 2012 World agriculture towards 2030/2050: the 2012 revision *ESA Working Paper 12–03* vol 4 (Rome: FAO)

Baldos U L C and Hertel T W 2014 Global food security in 2050: the role of agricultural productivity and climate change *Aust. J. Agric. Resour. Econ.* **58** 554–70

Bruinsma J 2011 The resources outlook: by how much do land, water and crop yields need to increase by 2050? *Looking Ahead in World Food and Agriculture: Perspectives to 2050* ed P Conforti (Rome: FAO)

Beurskens L W M, Hekkenberg M and Vethman P 2011 Renewable Energy Projections (ECN-E—10-069) *National Renewable Energy Action Plans of the European Member States* (European Environmental Agency) (http://ec.europa.eu/energy/renewables/action_plan_en.htm)

Calzadilla A, Delzeit R and Klepper G 2016 Assessing the effects of biofuel quotas on agricultural markets *The WSPC Reference on Natural Resources and Environmental Policy in The Era of Global Change* vol 3 (Singapore: World Scientific) pp 399–442 (https://doi.org/10.1142/9789813208179_0013)

Chemnitz C 2016 *Fleischatlas 2016—Deutschland Regional* (Berlin: Heinrich-Böll-Stiftung und ihre Landesstiftungen in Zusammenarbeit mit dem BUND)

Dellink R, Chateau J, Lanzi E and Magné B 2017 Long-term economic growth projections in the shared socioeconomic pathways *Glob. Environ. Change* **42** 200–14

EC 2016 Proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast). COM(2016) 767 final/2, 2016/0382(COD) (Brussels)

Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42

Gerstner K, Dormann C F, Stein A, Manceur A M and Seppelt R 2014 Effects of land use on plant diversity–a global meta-analysis *J. Appl. Ecol.* **51** 1690–700

Golub A A, Henderson B B, Hertel T W, Gerber P J, Rose S K and Sohngen B 2012 Global climate policy impacts on livestock, land use, livelihoods, and food security *Proc. Natl Acad. Sci.* **110** 20894–9

IIASA and FAO 2012 *Global Agro-Ecological Zones (GAEZ v3.0)—Model Documentation* (Rome/Laxenburg: FAO/IIASA)

Klepper G and Peterson S 2006 Emissions trading, CDM, JI, and more: the climate strategy of the EU *Energy J.* **27** 1–26

Mauser W and Bach H 2009 PROMET–large scale distributed hydrological modelling to study the impact of climate change on the water flows of mountain watersheds *J. Hydrol.* **376** 362–77

Mauser W, Klepper G, Rice M, Schmalzbauer B, Hackmann H, Leemans R and Moore H 2013 Transdisciplinary global change research: the co-creation of knowledge for sustainability *COSUST* **5** 420–31

Mauser W, Klepper G, Zabel F, Delzeit R, Hank T, Putzenlechner B and Calzadilla A 2015 Global biomass production potentials exceed expected future demand without the need for cropland expansion *Nat. Commun.* **6** 8946

Mueller N D, Gerber J S, Johnston M, Ray D K, Ramankutty N and Foley J A 2012 Closing yield gaps through nutrient and water management *Nature* **490** 254–7

Narayanan G, Aguiar A and McDougall R 2012 *Global Trade, Assistance, and Production: The GTAP 8 Data Base* (Purdue, IN: Center for Global Trade Analysis, Purdue University)

Newbold T *et al* 2015 Global effects of land use on local terrestrial biodiversity *Nature* **520** 45–50

OECD/FAO 2016 *OECD-FAO Agricultural Outlook 2016−2025* (Paris: OECD)

OECD 2008 *Biofuel Support Policies: An Economic Assessment* (Paris: OECD)

Odegard I Y R and Van der Voet E 2014 The future of food-scenarios and the effect on natural resource use in agriculture in 2050 *Ecol. Econ.* **97** 51–9

Popp A *et al* 2017 Land-use futures in the shared socio-economic pathways *Glob. Environ. Change* **42** 331–45

Porkka M, Guillaume J H, Siebert S, Schaphoff S and Kummu M 2017 The use of food imports to overcome local limits to growth *Earth*'*s Future* **5** 393–407

Pugh T A M, Müller C, Elliott J, Deryng D, Folberth C, Olin S, Schmid E and Arneth A 2016 Climate analogues suggest limited potential for intensification of production on current croplands under climate change *Nat. Commun.* **7** 12608

Schmitz C *et al* 2014 Land-use change trajectories up to 2050: insights from a global agro-economic model comparison *Agric. Econ.* **45** 69–84

Seppelt R, Manceur A M, Liu J, Fenichel E P and Klotz S 2014 Synchronized peak-rate years of global resources use *Ecol. Soc.* **19** 50

Tilman D, Balzer C, Hill J and Befort B L 2011 Global food demand and the sustainable intensification of agriculture *Proc. Natl Acad. Sci.* **108** 20260–4

Václavík T, Lautenbach S, Kuemmerle T and Seppel R 2013 Mapping global land system archetypes *Glob. Environ. Change* **23** 1637–47

Valin H *et al* 2014 The future of food demand: understanding differences in global economic models *Agric. Econ.* **45** 51–67

von Lampe M *et al* 2014 Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison *Agric. Econ.* **45** 3–20

Zabel F, Putzenlechner B and Mauser W 2014 Global agricultural land resources-a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions *PLoS ONE* **9** e107522