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Meeting the food security challenge for nine billion people in 2050: What impact on forests?

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1. Introduction

Agricultural activities on croplands and pastures occupy 11% and 26% of earth surfaces, respectively, while forests comprise 31% of the earth's surface (FAOSTAT, 2016). Global cropland and pasture areas have increased by 110% and 59%, respectively, from 1850 to 2015, while the area of global forest decreased by 17% (Houghton and Nassikas, 2017). Native lands and non-forest ecosystems (e.g. grasslands or shrub lands) were also cleared at the expense of agricultural lands over this period (Houghton and Nassikas, 2017). Agricultural land use and expansion have been identified as primary drivers of forest loss and degradation throughout the globe, ranging from subtle modification of natural forest to extensive deforestation (Clark et al., 2012) particularly in tropical regions (Gibbs et al., 2010; Keenan et al., 2015; Song et al., 2018). In addition to agricultural activities, timber and fuelwood extraction contribute to forest loss and degradation. Natural forests are increasingly converted to managed forests which amount to 278 million ha worldwide, out of 3999 million ha of the total global forest area in 2015 (FAO, 2015; Keenan et al., 2015). Managed forestry may replace natural forests but will also encroach on abandoned agricultural land, leading to competition with other land uses.

With increasing global population and incomes, the global demands for food and forest products are rising (FAO, 2017; Buongiorno et al., 2012; Alexander et al., 2015). In the future, it is unclear how global agricultural land will respond to the anticipated increase in demand for agricultural products. The FAO projects a 69 million ha increase in cropland is needed between 2005 and 2050 (Alexandratos and Bruinsma, 2012), an estimate that falls within the range reported by other modelling studies (Le Mouël and Forslund, 2017; Hertel et al., 2016; Tilman et al., 2011). This expected agricultural expansion stems from the theory that global agricultural production needs to rapidly expand, e.g. to double by 2050 (Ray et al., 2013; Tilman et al., 2011), due to a combination of population increase and dietary transitions. Such statistics have come to shape the policy debate on global food security, support industry and research agendas and influence decision making at multiple levels (Tomlinson, 2013). However, there has been some criticism regarding the uncertainties and assumptions of the fundamental drivers of global agricultural consumption and production growth (Pardey et al., 2014; Hunter et al., 2017; Wise, 2013). Many key driving forces such as population, increasing affluence, diets, waste, yield, climate and the global biophysical cycle are continuously changing (FAO, 2017), posing great uncertainties in estimation of future demand for agricultural and forestry products. Nevertheless, the ‘production-at-all-cost’ narrative is the dominant strategy in achieving global food security, despite its inherent environmental costs. Agriculture is now a dominant force behind the degradation of land and freshwater which has led to exceeding the ‘planetary boundaries’, reaching levels that jeopardize Earth's safe operating space (Steffen et al., 2015; Jaramillo and Destouni, 2015; Springmann et al., 2018). The expansion of agriculture into forests and natural ecosystems has contributed significantly to the loss of forest's ecosystem services including carbon storage, energy and water regulation and biodiversity (Houghton and Nassikas, 2017).

Forests were, until recently, rarely featured in food security discussions, other than being perceived mainly as a space or reserve for further agricultural expansion or a threatened resource to be protected because of expansion (Sunderland et al., 2013). Consequently, the important role of forest in food production/provisioning is yet to be accounted and mainstreamed in both agricultural and forestry models. It is now understood that there are important linkages between forests and trees and food security and nutrition, both as a means of direct (food) and indirect provisioning ecosystem services (pollination, climate/water regulation, soil protection) (Vira et al., 2015; The High Level Panel of Experts on Food Security and Nutrition, 2017; Sunderland et al., 2019). Forests directly contribute to several dimensions of food security, most notably in securing food availability (i.e. the supply of food through production, distribution and exchange) and stability (i.e. the ability to obtain food over time). Animal- and plant-

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based forest foods contribute to 0.6% of global food supply (FAO, 2014), although the percentage is thought to be underestimated due to lack of information. A variety of forest foods is consumed on a regular or occasional basis (Powell et al., 2015), meeting the seasonal food and nutritional gaps (Shackleton and Pullanikkatil, 2019; Jamnadass et al., 2015; Rowland et al., 2016). There is also a body of evidence to suggest that rural dwellers living in close proximity to forests and tree formations have more diverse and nutritious diets than more distal communities (Ickowitz et al., 2014; Galway et al., 2018). Further, agroforestry and tree-based agricultural systems contribute to securing food via increases in yield and livelihood resilience (Reed et al., 2017; Angelsen et al., 2014; Waldron et al., 2017).

Human land use changes contribute to a 10–15% increase in greenhouse gas fluxes and 40% of the total radiative forcing (Mahowald et al., 2017). Considering the contribution of agriculture and forestry to global greenhouse gas emissions and climate change, these two sectors are critical for climate mitigation and carbon sequestration, and the ability to meet climate goals, such as the UN Framework Convention on Climate Change 'Paris Agreement'. Climate mitigation activities in agriculture and forestry are available from the technical supply-side such as changes in land management (bioenergy plantations, avoided deforestation through REDD and reforestation of degraded forest areas, sustainable intensification) as well as through demand-side actions, such as waste reduction and dietary change toward less greenhouse gas-intensive products (less meat and livestock products) (Springmann et al., 2018; Smith et al., 2013; Searchinger et al., 2018). Demand-side and supply-side actions may result in very different feedbacks, with different synergies and trade-offs. All of these feedbacks are influenced by climate change, through its impact on key drivers such as temperature, atmospheric CO_2 and water availability (Smith et al., 2013; Martinich et al., 2017). Meeting the growing global demand for food and forest products, while preserving natural ecosystems will require widespread actions by land users, governments, civil society organizations, donors and market actors (Agrawal et al., 2014; TEEB, 2018).

Global agricultural, forestry and land use models are useful for trying to understand the socioeconomic and environmental challenges of the future (FAO, 2017; Hurmekoski and Hetemäki, 2013). Projections of future demand for agricultural and forestry products matter, because they drive public discourse, policy and research (Tomlinson, 2013; Wise, 2013; Keenan et al., 2015). Similarly, policy decisions when embedded in models could have substantial effects on predicting food production, forest conservation and climate mitigation in the future (Rose et al., 2012; Thomson et al., 2010) which can then in turn be used to justify particular policies. Thus, an informed perspective on projections of food and forest demands and land use may help to prioritize policy decisions and vice versa. Importantly, the value of such projections relies on the credibility of the underlying models and their assumptions (Wise, 2013; Hunter et al., 2017; Hurmekoski and Hetemäki, 2013). In addition, most models are built to serve sector-specific objectives. For instances, agricultural models are constructed within the framework of securing future food production with increasing environmental pressures whilst forestry models are traditionally developed to project future supply and demand of wood and fibre products. Similarly, past reviews on agriculture (Hertel et al., 2016; Reilly and Willenbockel, 2010; Le Mouël and Forslund, 2017), forest (Hurmekoski and Hetemäki, 2013; Latta et al., 2013), bioenergy (Searle and Malins, 2015; Creutzig et al., 2015) and land use change models (Magliocca et al., 2015; Smith et al., 2010) often have sector-specific focus and objectives; these reviews influence and reinforce the existing narrative within individual sector.

The first aim of this review is to summarize the extent of changes in land types predicted by the middle (and end) of this century by capturing diverse agriculture, forest, bioenergy and land use models, regardless of the objective(s) and structure of individual model. Our review is not limited to economic models; other types including Earth system models, mass flow models, biomass models, and biogeochemical process models are included to provide a wide range of coverage. Secondly, we evaluate scenario outcomes to assess the extent of prevailing narratives in the agricultural and forestry sectors, which are often rooted in food/ forest scarcity and crisis frameworks (Tomlinson, 2013; Meyfroidt and Lambin, 2011; Benton and Bailey, 2019). In addition to the evaluation of scenario outcomes (in term of the extent of changes in land types) across multiple models, we explore the tendency of models to support or reinforce sector-specific narratives. Finally, we assess the pathways and options that are embedded in multiple scenarios, focusing on food and forestry sectors. As such, our study highlights the forestry sector and its associated services to re-balance the current asymmetric focus on cropland (Alexander et al., 2017). Our assessment involves appraisal of the merit and demerits of proposed actions to achieve food security and forest conservation under a changing climate.

2. Methods

A scoping exercise for relevant key terms, developed by the authors, was performed in September 2017 using Google Scholar and Web of Science. This preliminary scoping was conducted to develop the framing and coverage of research aims, to test the sensitivity and appropriateness of search terms and to determine the final search terms. The search strategy was formulated to gather relevant literatures that consist all components of 1) food and its variation, 2) forest and its variation, 3) global coverage, and 4) projections of future scenarios. A list of relevant literature identified during scoping exercise ($n = 16$) is provided in Supplementary Table 1.

Various combinations of search terms were tested in the search engines and the number of hits was recorded. The final search terms were divided into five components:

> "food produc*" OR "agri* produc*" OR "crop produc*" OR "food demand*" OR "crop demand*" OR "crop yield*" OR "nutrition" OR "food secur*" OR "agri*" OR "feed*" OR "livestock*" OR "biomass" OR "crop*" OR "food*"
> AND "global" OR "world"
> AND "2025″ OR "2030″ OR "2050″ OR "2070″ OR "2100″
> AND "model*" OR "project*" OR "forecast*" OR "trend*" OR "possibilit*" OR "scenario*"
> AND "*forest*" OR "tree*"

After consultation with the author group regarding the selection of search engine and search terms, the final search terms were applied to three search engines: Scopus, Web of Science and PubMed in October 2017. To assess the sensitivity and appropriateness of search terms, the returned hits from the search engines were compared with the list of highly relevant literature that was obtained from a preliminary scoping exercise (Supplementary Table 1).

All searches were conducted in English and covered all years available in the literature databases. Scopus, Web of Science and PubMed returned 437, 356 and 104 hits, respectively. These hits were downloaded into Endnote and duplicates were manually removed to yield a total of 579 studies. The remaining studies were screened for relevant titles, abstracts and full text. The list of studies that were deemed relevant during abstract screening ($n = 169$) is provided in Supplementary Table 2.

The following inclusion criteria were used:

(a) Relevant study subject: studies needed to include models that estimate future food production AND its impact on forest via agricultural land expansion or vice versa (forest expansion/afforestation on abandoned agricultural lands etc.) at global scale
(b) Relevant study design: studies needed to represent food and forest in the model components

(c) Relevant study outcomes: studies needed to report forest (area) gain or loss, data presented such that changes or values could be obtained
(d) Primary data: studies needed to report primary data in table or graph formats to allow extraction of projected values at year 2100 and/or 2050. Reviews, conceptual frameworks, non-empirical studies, methodology papers, and policy briefs were excluded from analysis

The search terms were effective in capturing most of the relevant literature. The search engines, using the final search terms, captured twelve out of sixteen studies that were identified by scoping exercise (highlighted in Supplementary Table 1). In addition to using the search engines, we also obtained more relevant studies from a snowball search. The snowball search was carried out by identifying new, relevant papers cited in the reference lists and citing papers, as well as identifying related papers suggested by Google Scholar. The full text of these papers (Supplementary Table 1) were screened using the inclusion criteria described above.

All the papers accepted at the full-text review stage and met the inclusion criteria were analysed by extracting the relevant data to a tabular spreadsheet with the appropriate variables and grouped according to themes (Table 1). The variables of relevance were grouped into the following categories: model, objective(s), temporal horizon, baseline areas, model scenario(s), underlying assumptions associated with each scenario and primary and secondary model outputs (Table 2). Most studies establish a reference or business-as-usual (BAU) scenario (hereinafter referred to as reference) and simulate alternative scenario (s) based on a set of assumptions to answer their objectives.

A total of 63 scenarios from 17 modelling studies (illustrated in Fig. 1) are included in our main analysis. There are additional seven studies that met the inclusion criteria (see Table 2), however these studies are excluded from Fig. 1 due to incompatible format. The key themes that are covered in these scenarios are listed in Table 1. Carbon pricing/tax, reforestation/plantation, no deforestation, yield improvement and livestock feed are identified as recurring themes under the supply side. Waste reduction and diet are key actions on the demand side.

In addition to summarizing the changes in land types using primary data, the projections from four model intercomparison studies were extracted (Fig. 2). The model intercomparison studies draw together the outcomes of many different modelling approaches, thus enable us to compare and contrast our findings. It is important to note that many model-intercomparison studies require harmonization of data input to allow standardization of different representation and parameterization of biogeochemical, biophysical and socio-economic processes (e.g. Hurtt et al., 2011, Lotze-Campen et al., 2014, Schmitz et al., 2014, Popp et al., 2014b). Thus, model intercomparison studies are limited in terms of their versatility to integrate models beyond the domains of intercomparison exercises.

3. Results

3.1. Assessment of scenarios

The majority of scenarios (37 out of 63) expect cropland expansion to feed the world's population in 2050 and a reduction in global forest and pastureland (Figs. 1 and 2a). Out of the 37 scenarios showing cropland expansion and forest loss, 10 scenarios are the reference scenarios. In 30 scenarios, forest loss is accompanied with crop gain, although the magnitude of changes differs in each scenario. Studies show diverging trends as high variance exists in the extent of land use changes, ranging from −890 to +1000 million ha (cropland), −3000 to +500 million ha (pastureland) and −800 to +2800 million ha (forest) in 2050. The largest changes in cropland (−890 million ha), pastureland (−3000 million ha) and forest (+2800 million ha) are modelled according to an 'extreme mitigation' scenario involving substantial reduction in meat consumption and extremely high increases in crop and livestock yields to achieve +1.6 °C in 2050 (Strapasson et al., 2017; no. 6 in Table 2).

Only two scenarios demonstrate a similar magnitude of forest loss and cropland gain [0% food competing feedstuffs with climate change (Schader et al., 2015) and BAU economic, population and productivity growth and renewable fuel mandates (Winchester and Reilly, 2015)]. In 12 scenarios, conversion of *both* pastureland and forest is required to meet future demand for cropland [see scenarios modelled by Steinbuks and Hertel (2016), Popp et al. (2017), 'no land carbon pricing' scenario by Humpenöder et al. (2015) and BAU scenario by Stevanovic et al. (2017)].

By contrast, a total of 20 scenarios estimate a 20–2800 million ha increase in forest, with nine of these 20 scenarios predicting an increase in commercial/planted/managed forest i.e. 'other forest' types in Fig. 1. Eleven scenarios show no change in forest area by 2050. Constant forest area from baseline to 2050 is achieved either by setting aside areas presently dominated by forest i.e. zero deforestation (Pardey et al., 2014; Bouwman et al., 2010; Erb et al., 2016) or by applying a penalty on released greenhouse gas emission in combination with 50% reduction in food waste (Stevanovic et al., 2017).

Increase in forest is made possible by applying a variety of interventions in alternative scenarios (Fig. 3), which include: 1) large scale reforestation of formerly agricultural areas (Sonntag et al., 2016) including REDD-Reducing Emissions from Deforestation & Degradation (van Vuuren et al., 2017); 2) land carbon pricing (Humpenöder et al., 2015; Winchester and Reilly, 2015); 3) mitigation in land, food and bioenergy (Strapasson et al., 2017; van Vuuren et al., 2017; Sands et al., 2014; Walsh et al., 2015); 4) a combination of sustainable intensification and 50% reduction in food/agricultural waste and healthy diets (Bajželj et al., 2014); 5) high agricultural productivity growth (Wise et al., 2014); and 6) conservation of protected areas/ nature parks (Kubiszewski et al., 2017). Forest gain is accompanied by loss in crop and/or pastureland in 13 scenarios.

In scenarios where deforestation is inevitable, the extent of forest loss could be reduced via 1) 50% reduction in food/agricultural waste (Stevanovic et al., 2017; Bajželj et al., 2014); 2) healthy/low meat diet (Stevanovic et al., 2017; Bajželj et al., 2014); 3) feeding livestock only from grassland and by-products of food production (Schader et al., 2015); 4) higher agricultural yield and productivity (Humpenöder et al., 2015; Wise et al., 2014; Bajželj et al., 2014); 5) constraints in greenhouse gas emission (Steinbuks and Hertel, 2016), including universal carbon tax and REDD (Popp et al., 2014a; Winchester and Reilly, 2015); and 6) limiting the expansion of bioenergy crops (Winchester and Reilly, 2015). These mitigation actions, often being applied in combination (see the combination provided with Fig. 3), have been shown to ease the pressure on forest and resulted in lower forest loss in comparison to reference (i.e. in absence of mitigation actions) for individual model.

Alternative scenarios that are designed according to a set of mitigation actions (carbon pricing/tax, reforestation/plantation, yield improvement, waste reduction, changing diet; Table 1 and Fig. 3) generally lead to significant reduction in greenhouse gas (GHG) emissions and increase in carbon sequestration (refer to secondary outputs in Table 2). These environmental outcomes are coupled with either forest gain (Walsh et al., 2015; Sands et al., 2014; Wise et al., 2014; Bajželj et al., 2014; van Vuuren et al., 2017; Strapasson et al., 2017; Winchester and Reilly, 2015; Humpenöder et al., 2015; Sonntag et al., 2016) or a lower rate of deforestation (Stevanovic et al., 2017; Schader et al., 2015; Popp et al., 2014a; Steinbuks and Hertel, 2016). Hence, forest gain or less deforestation are prerequisites to reducing GHG emissions and increasing carbon sequestration, as well as achieving a reduction in global temperature in the next decade (Sonntag et al., 2016; Walsh et al., 2015; Strapasson et al., 2017; van Vuuren et al., 2017).

Table 1

The themes covered by multiple scenarios.

Themes	Papers	Notes
Supply side		
Carbon pricing/tax	(Stevanovic et al., 2017; Humpenoder et al., 2015; Winchester and Reilly, 2015; Popp et al., 2014a; Bouwman et al., 2010)	Varying carbon price: - 30 \$US/tCO$_2$eq and annual tax growth rate of 5% (Stevanovic et al., 2017) - 24 \$US/tCO$_2$eq (Humpenoder et al., 2015) - 25 \$US/tCO$_2$eq in 2015, rising at 4% per year (Winchester and Reilly, 2015) - 25 \$US/tCO$_2$eq and increase by 2.4% per year (Bouwman et al., 2010) - 30 \$US/tCO$_2$eq in 2020, starts in 2015 and increases nonlinearly at a rate of 5% per year (Popp et al., 2014a)- carbon tax applies on land emission or universally across all sector.
Reforestation/ conservation/ plantation	(Sonntag et al., 2016; Winchester and Reilly, 2015; Strapasson et al., 2017; van Vuuren et al., 2017; Popp et al., 2014a)	- Lower, medium and higher REDD protection levels were simulated by protecting forests with carbon densities higher than 200, 150 and 100 tC/ha, respectively. Two reforestation levels imply that either reforestation is implemented on 50% or 100% of the degraded forest land (van Vuuren et al., 2017).
No deforestation	(Erb et al., 2016; Pardey et al., 2014; Bouwman et al., 2010)	- Cropland expands only into grazing land of the highest productivity (i.e. no deforestation) (Erb et al., 2016). - Projected global consumption is met even after setting aside forest areas suitable for crop production (an additional 571 million hectares) (Pardey et al., 2014). - Direct deforestation for bioenergy production is not possible, however second-generation energy crop cultivation expands into savannah areas (Bouwman et al., 2010).
Crop yield improvement	(Humpenoder et al., 2015; Winchester and Reilly, 2015; Strapasson et al., 2017; Erb et al., 2016; van Vuuren et al., 2017; Bajželj et al., 2014; Wise et al., 2014)	- 1.36% increase in average annual yield from 1995 until 2100 (Humpenoder et al., 2015) - 0.75% to 1% per year for all crops (including food crops) (Winchester and Reilly, 2015). - Crop yield increases as a function of GDP (van Vuuren et al., 2017). - Two-fold increase in yield improvement rates; average yield from 1.8 to 2.3 tC/ha (C27%) (Bajželj et al., 2014). - Increase in crop productivity around the world at twice the annual rate of reference scenario (Wise et al., 2014).
Livestock feed	(Schader et al., 2015; Walsh et al., 2015)	- By-products from food production (brans, oilseed cake, whey, etc.) are fed to animals (Schader et al., 2015). - 32.5 tDM/ha/year of algaculture output to meet 40% of global feedstock demand (Walsh et al., 2015).
Demand side		
Waste reduction	(Stevanovic et al., 2017; van Vuuren et al., 2017)	- Reduction of food waste by 1/3 (van Vuuren et al., 2017). - 50% reduction in food and agricultural waste (Bajželj et al., 2014).
Dietary change	(Stevanovic et al., 2017; Strapasson et al., 2017; Erb et al., 2016; van Vuuren et al., 2017; Bajželj et al., 2014)	- Substantial reduction in meat consumption (Strapasson et al., 2017; van Vuuren et al., 2017), all providing sufficient energy and protein of meat (2636 – 3546 kcal per cap per day). - Average consumption of sugar, oil, meat and dairy is limited to expert health recommendations (Bajželj et al., 2014).
Others		
Bioenergy	(Humpenoder et al., 2015; Winchester and Reilly, 2015; Bouwman et al., 2010; Strapasson et al., 2017; Steinbuks and Hertel, 2016; Walsh et al., 2015; Sands et al., 2014)	- 18EJ in 2009 to about 150 EJ in 2050 (Winchester and Reilly, 2015). - Bioenergy providing 170 EJ - 250 EJ by 2050 from 54 EJ in the model's 2011 base-year (Strapasson et al., 2017). - The projected annual output of 50 million ha of algaculture generates 65 EJ per year (Walsh et al., 2015).

3.2. *Assessment of models*

We identified seven models that are prone to yield significant forest loss in the majority of their scenario outputs, which are: MAgPIE (Humpenoder et al., 2015), bottom-up mass-flow modelling (Schader et al., 2015), EPPA (Winchester and Reilly, 2015), FABLE (Steinbuks and Hertel, 2016), statistical data driven scenario analysis (Bajželj et al., 2014), GCAM (Wise et al., 2014) and an ArcGIS Model (Kubiszewski et al., 2017). Out of these seven models, only the MAgPIE (Humpenoder et al., 2015) and EPPA (Winchester and Reilly, 2015) show a significant potential of forest gain (>500 mil ha) when land carbon pricing is implemented in its alternative scenarios (Figs. 1 and 3). This suggests that policy providing economic incentives for carbon stock (i.e. forest) conservation and enhancement is the only option to reverse the trend of forest loss within the scenarios captured by these models.

Contrary to those of the other models examined, IMAGE (van Vuuren et al., 2017), FeliX (Walsh et al., 2015) and FARM (Sands et al., 2014) demonstrate forest gain in all scenarios including their reference scenario (Fig. 1). These models were constructed within the climate adaptation and mitigation framework to achieve certain climate targets. IMAGE follows the SSP1 (Shared Socio-economic Pathway) of green growth strategy, assuming use of environmentally friendly technologies, a (modest) transition towards less resource intensive lifestyles and global cooperation to achieve < 3°C temperature increase in 2100 (van Vuuren et al., 2017). FeliX incorporates the mitigation potential of microalgae as alternative livestock feed, thus freeing 2 billion ha of land for forest plantation which translates to 544 ± 107 PgC emission mitigation by 2100 (Walsh et al., 2015). FARM explores alternative mitigation technologies such as bioelectricity to maintain 550 ppm CO$_2$-eq in 2100 (Sands et al., 2014).

Three models deliberately set constant forest area over the temporal horizon as its input parameter and consequently, yield no change in forest area. BioBaM, a biophysical accounting model (Erb et al., 2016) assumes a hypothetical zero-deforestation boundary condition for agricultural production, iAP (Pardey et al., 2014) sets aside areas presently dominated by forests that are also deemed suitable for crop production (i.e. 571 million ha) and IMAGE (Bouwman et al., 2010) implements no deforestation for bioenergy production. While these models provide compelling evidence that deforestation is not a precondition for supplying the world with sufficient food in terms of quantity and quality in 2050 (Erb et al., 2016; Pardey et al., 2014), they highlight the risk of crop and bioenergy expansion into other types of land such as savanna and grazing land (Bouwman et al., 2010; Erb et al., 2016).

Table 2

Summary of models, scenarios and changes in land types included in the analysis. * correspond to models obtained from snowball search.

Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
1) Stevanovic et al. (2017) Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices. Environmental Science & Technology 51, 365–374. **temperate cereals, maize, tropical cereals, rice, soy bean, rapeseed, groundnuts, sunflower, oil palm, pulses, potato, cassava, sugar cane, sugar beet, fruits and vegetables, and cotton, ruminant meat, monogastric meat, poultry meat, milk, egg**	MAgPIE (Model of Agricultural Production and its Impacts on the Environment) *Analyse the impacts on food prices under mitigation policies targeting either incentives for producers or consumer preferences.*	2010–2100 *1580 mil ha cropland. 3100 mil ha pastureland. 4100 mil ha forest.*	BAU (SSP2)	9.5 million people in 2070, moderate income growth except for emerging economies	320 million ha increase in cropland area, 300 million ha decrease in pasture area. 100 million ha decrease in forest area.	3 Gt CO_2eq decrease in net total GHG emissions
			Incentive-based mitigation	A penalty on released GHG emission, starting at 30 US$/t CO_2eq in 2020 with an annual tax growth rate of 5%	No change in cropland area, 20 million ha decrease in pasture area. No change in forest area.	6.5 Gt CO_2eq decrease in net total GHG emissions
			Preference-based mitigation	50% reduction of food waste, converging to 2750 kcal/cap/day with maximum of 15% food intake from livestock products	80 million ha decrease in cropland area, 150 million ha decrease in pasture area. 50 million ha decrease in forest area.	7.6 Gt CO_2eq decrease in net total GHG emissions
			Combined mitigation	Coupled both incentive- and preference-based mitigation strategies	180 million ha decrease in cropland area, 10 million ha decrease in pasture area. No change in forest area.	9.3 Gt CO_2eq decrease in net total GHG emissions
2) Sonntag et al. (2016) Reforestation in a high-CO_2 world—Higher mitigation potential than expected, lower adaptation potential than hoped for. Geophysical Research Letters 43, 6546–6553. **Plant Functional Types (PFTs)**	Max Planck Institute Earth System Model (MPI-ESM) *Assess the potential and possible consequences for the global climate of a strong reforestation scenario for this century.*	2006–2100 *41.7 mil km^2 cropland and pastureland. 39.5 mil km^2 forest.*	RCP8.5 (reference)	No mitigation or climate engineering options resulting in a strong global warming	8 million km^2 increase in cropland and pastureland. 1 million km^2 decrease in forest area	0.27 K lower global annual mean temperature, 85 ppm decrease in atmospheric CO_2 and 215 Gt increase in terrestrial carbon content compared to reference
			RCP4.5	Large-scale reforestation of formerly agricultural areas	7 million km^2 decline in cropland and pastureland. 8 million km^2 increase in forest area	
3) Humpenoder et al. (2015) Land-Use and carbon cycle responses to moderate climate change: implications for land-based mitigation? Environmental Science & Technology 49, 6731–6739.. **temperate cereals, maize, tropical cereals, rice, soy bean, rapeseed, groundnuts, sunflower, oil palm, pulses, potato, cassava, sugar cane, sugar beet, cotton, bioenergy grasses, bioenergy trees**	MAgPIE *Estimate the mitigation potential of a climate policy that provides economic incentives for carbon stock conservation and enhancement*	1995–2100 *1438 mil ha cropland. 2913 mil ha pasture. 4235 mil ha forest. 4321 mil ha other land.*	No LCP & no CC (reference)	No land carbon pricing (LCP). Biophysical crop yields and carbon densities are assumed to be static (no CC). Second generation bioenergy crop production.	+698 million ha cropland −1212 million ha pasture −511 million ha forest +1025 million ha other land	−90 Gt C stock, 0 Gt C of mitigation
			LCP & no CC	Land carbon pricing (24 $/t$CO_2$). Biophysical crop yields and carbon densities are assumed to be static (no CC).	−319 million ha cropland −1390 million ha pasture +1489 million ha forest +220 million ha other land	+101 Gt C stock, 191 Gt C of mitigation
			No LCP & RCP2.6	No land carbon pricing. Moderate climate change (radiative forcing of 2.6 W/m^2 in 2100).	+579 million ha cropland −1423 million ha pasture −449 million ha forest +1293 million ha other land	−12 Gt C stock, 78 Gt C of mitigation
			LCP & RCP2.6	Land carbon pricing (24 $/t$CO_2$). Moderate climate change (radiative forcing of 2.6 W/m^2 in 2100).	−452 million ha cropland −1524 million ha pasture +1724 million ha forest +253 million ha other land	+185 Gt C stock, 275 Gt C of mitigation
4) Schader et al. (2015) Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. Journal of the Royal Society Interface 12: 113 **grains, starchy roots, oil crops, legumes, vegetables, fruits, sugar and sweeteners, tree**	Bottom-up mass-flow model of the agricultural and food sector *Explore the room for sustainable livestock production by modelling the impacts and constraints of a third strategy in which livestock feed components that*	2005–2050 *1540 mil ha cropland. 8.2 mil ha annual deforestation.*	Reference scenario 2050	Reference year with 100% food competing feedstuffs (FCF)	+6% / 106% cropland, 90% annual deforestation	118% of GHG emissions, 134% N-surplus, 110% soil erosion from water
			Reference scenario 2050 + climate change	Reference year with 100% food competing feedstuffs and climate change	155% cropland, 120% annual deforestation	128% of GHG emissions, 130% N-surplus, 145% soil erosion from water
			0% FCFs 2050	0% food competing feedstuffs in 2050	80% cropland, 80% annual deforestation	95% of GHG emissions, 80% N-surplus,

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Table 2 (*continued*)

Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
nuts, stimulants, spices, milk, meat, fish, eggs	*compete with direct human food crop production are reduced.*					95% soil erosion from water
			0% FCFs 2050 + climate change	0% food competing feedstuffs in 2050 with climate change	120% cropland, 100% annual deforestation	100% of GHG emissions, 68% N-surplus, 130% soil erosion from water
5) Winchester & Reilly (2015) The feasibility, costs, and environmental implications of large-scale biomass energy. Energy Economics 51, 188–203. **corn, wheat, energy beet, soybean, rapeseed, sugarcane, oil palms, energy grass, woody crop, livestock**	Economic Projection and Policy Analysis (EPPA) model *Evaluate the role of bioenergy under a combination of current and additional policy incentives.*	2004–2050 *1550 mil. ha cropland. 4200 mil. ha natural forest*	Reference	BAU assumptions about economic, population, and productivity growth and renewable fuel mandates	1765 million ha cropland, 3994 million ha natural forest, 13 million ha bioenergy land	74,131 MMt CO_2e emission
			Base policy	Global carbon price on GHG emissions except those from land-use change beginning in 2015, rising by 4% p.a.	1634 million ha cropland, 3828 million ha natural forest, 158 million ha bioenergy land	43,180 MMt CO_2e emission
			Low ethanol blending	Global carbon price with tighter ethanol blending constraints	1674 million ha cropland, 3817 million ha natural forest, 97 million ha bioenergy land	44,466 MMt CO_2e emission
			Expensive LC ethanol	Global carbon price with 50% more expensive LC ethanol costs	1681 million ha cropland, 3815 million ha natural forest, 76 million ha bioenergy land	45,828 MMt CO_2e emission
			Low crop yield	Global carbon price with exogenous crop yield improvements of 0.75% per year (compared to 1% per year in the base case)	1726 million ha cropland, 3775 million ha natural forest, 160 million ha bioenergy land	43,124 MMt CO_2e emission
			Land carbon	Global carbon price extended to emissions from land-use change, including changes in emissions due to soil carbon accumulation and reforestation.	1609 million ha cropland, 4883 million ha natural forest, 361 million ha bioenergy land	35,627 MMt CO_2e emission
6) Strapasson et al. (2017) On the global limits of bioenergy and land use for climate change mitigation. GCB Bioenergy **cereals, grains, sugar, fruit and vegetables, pulses and vegetable oil, beef, sheeps & goats, pigs, poultry, eggs**	Global Calculator Land Use Change (GCLUC) *Probe the potential global sustainability limits of bioenergy over time for energy provision and climate change mitigation*	2010–2050 *1498 mil ha cropland. 3358 mil ha pastureland. 3762 mil ha forest. 271 mil ha commercial forest. 97 mil ha energy cropland.*	BAU	Total energy use grows by two-thirds by 2050. Rising total GHG emissions. Increasing per capita food and meat consumption. Minimal bioenergy expansion.	+119 mil ha cropland., +131 mil ha pastureland., −597 mil ha forest., +228 mil ha commercial forest. +1 mil ha energy cropland.	+36.3 Gt CO_2e/yr, +2.4 °C
			High mitigation	BAU for all sectors, but high mitigation effort in land/food/bioenergy sectors.	−354 mil ha cropland. −564 mil ha pastureland. +274 mil ha forest. +219 mil ha commercial forest. +219 mil ha energy cropland.	−32.2 Gt CO_2e/yr, +1.7 °C
			Extreme mitigation	BAU for all sectors, but extreme mitigation pathway for land/food/bioenergy including reforestation. Substantial reduction in meat consumption. Extremely high increase in crop and livestock yields.	−891 mil ha cropland. −3000 mil ha pastureland. +2573 mil ha forest. +228 mil ha commercial forest. +469 mil ha energy cropland.	−35.1 Gt CO_2e/yr, +1.6 °C
7) Erb et al. (2016) Exploring the biophysical option space for feeding the world without deforestation. Nat Commun 7, 11382.	BioBaM (biomass accounting model) *Explore the options and constraints*	2000–2050 *15 mil km^2 cropland. 48 mil km^2 pastureland.*	BAU	In line with FAO forecast for 2050; 2947 kcal per cap per day with large regional	15 million km^2 cropland. 48 mil km^2 pastureland. Zero deforestation.	–

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Table 2 (*continued*)

Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
Cereals, roots, sugarcrops, pulses, oilcrops, vegetables and fruits, other crops, meat (ruminants), pig, poultry, eggs, milk, butter, dairy, fish	*resulting from a hypothetical zero-deforestation boundary condition for agricultural production, thereby explicitly assessing limitations to grazing.*			differences. 16% of animal products.		
			RICH	The diet of North America in 2000 to prevail globally in 2050; 3546 kcal per cap per day. 25% of animal products.	20 million km^2 cropland. 43 mil km^2 pastureland. Zero deforestation.	–
			MEAT	A reduced meat diet; 2648 kcal per cap per day. 25% of animal products.	15 million km^2 cropland. 48 mil km^2 pastureland. Zero deforestation.	–
			VEGETARIAN	An ovo-lacto vegetarian; 2636 kcal per cap per day. 13% of animal products.	12 million km^2 cropland. 51 mil km^2 pastureland. Zero deforestation.	–
			VEGAN	Exclusively plant-based; 2636 kcal per cap per day.	10 million km^2 cropland. 53 mil km^2 pastureland. Zero deforestation.	–
8) Pardey et al. (2014) A bounds analysis of world food futures: global agriculture through to 2050. Australian Journal of Agricultural and Resource Economics 58, 571–589. **barley, cereals, fruit (excluding melons), maize, millet, pulses, rapeseed, rice (paddy), roots & tubers, seed cotton, sorghum, soybeans, sugarcane, sunflower seed, vegetables & melons, and wheat**	International Agricultural Prospects (iAP) Model *Project global agricultural consumption and production.*	2010–2050 *1130 mil ha cropland. 571 million ha forest suitable for crop.*	Low population	8.3 billion people. Set aside forest areas.	−83.5 million ha cropland. Zero deforestation.	–
			Medium population	9.6 billion people. Set aside forest areas.	+111.5 million ha cropland. Zero deforestation.	–
			High population	11.1 billion people. Set aside forest areas.	+311.5 million ha cropland. Zero deforestation.	–
9) Bouwman et al. (2010) Consequences of the cultivation of energy crops for the global nitrogen cycle. Ecological Applications 20, 101–109. **Seven different food crops, and three energy crop types (first generation [sugar cane, maize] and second generation [woody energy crops])**	Integrated model for the assessment of the global environment (IMAGE) 2.4 *Assess the consequences of implementing first- and second-generation bioenergy, focusing on the nitrogen cycle*	2000–2050 *1540 mil ha cropland. 3338 mil pastureland. 8 mil energy cropland.*	Climate mitigation scenario from OECD	Global cooperation for environmental policy. Energy crops on marginal lands. No deforestation. Global agricultural liberalization; subsidies and tariffs are phased out and reduced by 50% by 2030: starting in year 2010, decreasing by 3% p/y. Carbon tax starts at US$25/ton CO$_2$ and increase by 2.4% per year.	1912 million ha cropland (+372 million ha), 3622 million ha pastureland, (+284 million ha), 268 million ha energy cropland (+260 million ha)	+2.5 Tg/yr of nitrous oxide +0.6 Tg/yr of nitrogen oxide +15.5 Tg/yr of ammonia
10) *van Vuuren et al. (2017) Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environmental Change 42, 237–250. N/A	IMAGE 3.0 integrated assessment model *Describe the possible developments in global energy use and production, land use, emissions and climate changes following the SSP1 storyline.*	2010–2100 *1600 mil. ha cropland. 3300 mil. ha pastureland. 3750 mil. ha forest. 4400 mil. ha other land.*	SSP1 (reference)	Green growth; adaptation and mitigation to climate change is relatively easy. Crop yield increase as a function of GDP. Low consumption of animal products. Reduction of food waste by 1/3. Radiative forcing of 5.0 W m^{-2}	−120 million ha cropland. −910 million ha pastureland. +280 million ha forest. +125 million ha energy cropland. +425 million ha other land.	−12.5 Gt CO$_2$eq/year decrease in emissions, 3 °C temperature change in 2100
			4.5	Similar with reference, with radiative forcing of 4.5 W m^{-2}. Low REDD (Reducing Emissions from Deforestation &	−170 million ha cropland. −970 million ha pastureland. +480 million ha forest. +180 million ha energy	−33 Gt CO$_2$eq/year decrease in emissions, 2.7 °C temperature change in 2100

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Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
				Degradation), half reforestation	cropland. +280 million ha other land.	
			2.6	Similar with reference, with radiative forcing of 2.6 W m^{-2}. High REDD, full reforestation	−210 million ha cropland. −970 million ha pastureland. +560 million ha forest. +280 million ha energy cropland. +140 million ha other land.	−54 Gt CO_2eq decrease in emissions, 1.8 °C temperature change in 2100
11) *Steinbuks & Hertel (2016) Confronting the Food–Energy–Environment Trilemma: Global Land Use in the Long Run. Environmental and Resource Economics 63, 545–570. N/A	FABLE (forest, agriculture, and biofuels in a land use model with environmental services) *Determine the optimal profile for global land use in the context of growing demands for food and forest products, and more stringent greenhouse gas mitigation targets*	2004–2100 *1533 mil. ha cropland. 2730 mil. ha pastureland. 1620 mil. ha commercial forest. 2470 mil. ha unmanaged forest. 207 mil. ha protected forest. 0.1 mil. ha biofuel cropland.*	Reference	Strong economic growth, global population that grows quickly until mid-century and slows thereafter, the rapid introduction of new and more efficient technologies, and balanced energy use across all sources	+463 million ha cropland. −400 million ha pastureland. −4 million ha commercial forest. −675 million ha unmanaged forest. +471 million ha protected forest. +143 million ha biofuel cropland.	11.8 Gt CO_2eq accumulated GHG emissions
			Declining yield (A)	Permanent decline in potential food crop yields due to adverse effects of climate change.	+490 million ha cropland. −410 million ha pastureland. −9 million ha commercial forest. −680 million ha unmanaged forest. +467 million ha protected forest. +140 million ha biofuel cropland.	4.8 Gt CO_2eq accumulated GHG emissions
			Increasing growth of fossil fuel cost (E)	Permanent increase in growth of liquid fossil fuel costs over the medium term. The extent to which the energy prices can grow in the long term is limited by induced innovation and available backstop technologies.	+476 million ha cropland. −406 million ha pastureland. −6 million ha commercial forest. −686 million ha unmanaged forest. +466 million ha protected forest. +155 million ha biofuel cropland.	−15.4 Gt CO_2eq accumulated GHG emissions
			GHG emissions constraint (T)	60% reduction in baseline GHG emissions from petroleum products, crop production and terrestrial carbon fluxes by 2100.	+350 million ha cropland. −516 million ha pastureland. +167 million ha commercial forest. −636 million ha unmanaged forest. +459 million ha protected forest. +172 million ha biofuel cropland.	−34.2 Gt CO_2eq accumulated GHG emissions
			Declining yield + increasing growth of fossil fuel cost (*A* + *E*)	See assumptions above	+503 million ha cropland. −417 million ha pastureland. −11 million ha commercial forest. −690 million ha unmanaged forest. +462 million ha protected forest. +152 million ha biofuel cropland.	−15.7 Gt CO_2eq accumulated GHG emissions
			Declining yield + increasing growth of fossil fuel cost + GHG emissions constraint (*A* + *E* + *T*)	See assumptions above	+391 million ha cropland. −528 million ha pastureland. +146 million ha commercial forest. −643 million ha unmanaged forest. +452 million ha protected	−18.2 Gt CO_2eq accumulated GHG emissions

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Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
					forest. +179 million ha biofuel cropland.	
12) *Popp et al. (2014a) Land-use protection for climate change mitigation. Nature Climate Change 4, 1095. **temperate cereals, maize, tropical cereals, rice, soybeans, rapeseed, groundnut, sunflower, oilpalm, pulses, potatoes, tropical roots, sugar cane, sugar beet, fodder crops, fibres, others ruminant livestock, non-ruminant livestock, poultry, eggs, milk**	MAgPIE *Estimate land-use and associated carbon dynamics for different global terrestrial carbon policies*	2010–2100 *1454 mil. ha cropland. 3079 mil. ha pastureland. 4144 mil. ha forest. 4229 mil. ha other land.*	SSP2 (ref)	Intermediate socio-economic challenges for adaptation and mitigation. No climate mitigation policies.	+239 million ha cropland −212 million ha pastureland −181 million ha forest +154 million ha other land (abandoned agricultural land)	89 Gt CO_2 cumulative uptake
			REDD	Policy on carbon emissions from deforestation only	+204 million ha cropland −263 million ha pastureland −0.1 million ha forest +60 million ha other land	136 Gt CO_2 cumulative uptake
			All	Universal carbon tax on GHG emissions from all terrestrial systems	+35 million ha cropland −22 million ha pastureland −5 million ha forest −2 million ha other land	191 Gt CO_2 cumulative uptake
13) *Bajželj et al. (2014) Importance of food-demand management for climate mitigation. Nature Climate Change 4, 924. **vegetables, fruits, sugar & sweeteners, vegetable oils, red meat, poultry, eggs, dairy, fish, wheat products, rice, maize, other grains, roots, pulses, other crops**	Statistical data driven scenario analysis. *Estimate the environmental consequences of the increasing food demand by 2050, quantify the extent to which sustainable intensification and demand reduction measures could reduce them.*	2009–2050 *1560 mil. ha cropland. 3280 mil. ha pastureland. 2610 mil. ha forest.*	Current yield trend	Current trends in yields	2220 million ha cropland. 3710 million ha pastureland. 2260 million ha forest.	20.4 Gt CO_2eq annual emissions (+9 Gt CO_2eq)
			Current yield trend + waste reduction	Current trends in yields. 50% reduction in food and agricultural waste.	1920 million ha cropland. 3370 million ha pastureland. 2390 million ha forest.	15.9 Gt CO_2eq annual emissions (+4.4 Gt CO_2eq)
			Current yield trend + waste reduction + healthy diets	Current trends in yields. 50% reduction in food and agricultural waste. Average consumption of sugar, oil, meat and dairy is limited to expert health recommendations.	1820 million ha cropland. 2540 million ha pastureland. 2600 million ha forest.	9.3 Gt CO_2eq annual emissions (−2.2 Gt CO_2eq)
			Yield gap	Sustainable intensification closes yield gap in all regions.	1640 million ha cropland. 3770 million ha pastureland. 2400 million ha forest.	16.4 Gt CO_2eq annual emissions (+4.9 Gt CO_2eq)
			Yield gap + waste reduction	Sustainable intensification closes yield gap in all regions. 50% reduction in food and agricultural waste.	1420 million ha cropland. 3390 million ha pastureland. 2590 million ha forest.	11.9 Gt CO_2eq annual emissions (+0.4 Gt CO_2eq)
			Yield gap + waste reduction + healthy diets	(See assumptions above)	1370 million ha cropland. 2580 million ha pastureland. 2720 million ha forest.	6 Gt CO_2eq annual emissions (−5.5 Gt CO_2eq)
14) *Wise et al. (2014) Economic and physical modelling of land use in GCAM 3.0 and an application to agricultural productivity, land, and terrestrial carbon. Climate Change Economics 05, 1,450,003. N/A	Global Change Assessment Model (GCAM) version 3.0 *Explore the impact of changes in agricultural crop yields on global land use and terrestrial carbon.*	2005–2050 *1070 mil. ha cropland. 4100 mil. ha forest.*	Reference	Agricultural productivity growth adapted from Briunsma (2009) for the first few decades, followed by modest changes thereafter.	+210 million ha cropland. −100 million ha forest.	0.55 Gt annual C emissions (−0.2 Gt C)
			No agricultural productivity growth	No improvement in agricultural productivity from current levels	+570 million ha cropland. −250 million ha forest.	1.27 Gt annual C emissions (+0.5 Gt C)
			High agricultural productivity growth	Crop productivity increases twice the annual rate than in the reference scenario	−100 million ha cropland. +40 million ha forest.	0.05 Gt annual C emissions (−0.7 Gt C)
15) *Kubiszewski et al. (2017) The future value of ecosystem services: Global scenarios and national implications. Ecosystem Services 26, 289–301.	ArcGIS Model *Estimate the future value of ecosystem services in monetary units for four*	2011–2050 *1664 mil. ha cropland. 4414 mil. ha pastureland. 4225 mil. ha forest.*	Market forces	Free enterprise. Focus on market growth.	+85 mil. ha cropland. −428 mil. ha pastureland. −799 mil. ha forest.	–
			Fortress world	Strong individualism. Maintain current practices.	+113 mil. ha cropland. −719 mil. ha pastureland. −651 mil. ha forest.	–

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Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
N/A	*alternative global land use and management scenarios.*		Policy reform	Coordinated action. Green and pleasant land.	+46 mil. ha cropland. −213 mil. ha pastureland. −188 mil. ha forest.	–
			Great transition	Community wellbeing. Conservation fully implemented.	+6 mil. ha cropland. −64 mil. ha pastureland. +44 mil. ha forest.	–
Managed/planted forest:						
16) Walsh et al. (2015) New feed sources key to ambitious climate targets. Carbon Balance and Management 10:26 N/A	Functional Enviro-economic Linkages Integrated nexus (FeliX) *Quantify emissions pathways when microalgae is used as a feedstock to free up to 2 billion hectares of land currently used for pasture and feed crops.*	2000–2100 *1500 mil ha cropland. 3300 mil ha pastureland. 50 mil ha forest plantations.*	BAU	Future global population growth, dietary patterns, energy profiles, and agricultural yields develop along historical trends.	+300 million ha cropland +600 million ha pastureland +790 million ha forest plantations	+4.9 Pg C/yr net emissions, +2 °C change relative to preindustrial level
			Algae-Fuel	Microalgae as a source of biomass for energy	+300 million ha cropland +600 million ha pastureland +740 million ha forest plantations	+0.5 Pg C/yr net emissions, +1.7 °C change relative to preindustrial level
			Algae-Feed	Microalgae as a feedstock (40% of global demand for feed)	−100 million ha cropland −800 million ha pastureland +1990 million ha forest plantations	−3 Pg C/yr net emissions, +1.3 °C change relative to preindustrial level
			BioEnergy	Expansion of biomass, wind, and solar energy is accelerated exogenously to match more aggressive climate action Scenarios	+300 million ha cropland +600 million ha pastureland +690 million ha forest plantations	+2.5 Pg C/yr net emissions, +1.8 °C change relative to preindustrial level
17) Sands et al. (2014) Bio-electricity and land use in the Future Agricultural Resources Model (FARM). Climatic Change 123, 719–730. **wheat, rice, coarse grains, oil seeds, and sugar, vegetables and fruit, plant-based fibers, other crops**	Future Agricultural Resources Model (FARM) *Explore the economics of alternative mitigation technologies.*	2004–2104 *1400 mil ha cropland. 2700 mil ha pastureland. <1 million ha biomass land. 1600 mil ha managed forest.*	G17 550 ppm CO$_2$eq mitigation scenario	Reference energy intensity. Carbon capture & storage available at break-even cost. Nuclear is fully available. Wind/solar power capital cost declines by 2.5% per year. Biomass crop yield increases by 1%/y.	300 million ha reduction in cropland. 600 million ha reduction in pastureland. 900 million ha increase in biomass land. No change in managed forest.	–
			G18 550 ppm CO$_2$eq mitigation scenario	Low energy intensity. Carbon capture & storage available at break-even cost. Nuclear is fully available. Wind/solar power capital cost declines by 2.5% per year. Biomass crop yield increases by 1%/y.	150 million ha reduction in cropland. 600 million ha reduction in pastureland. 250 million ha increase in biomass land. 500 million ha increase in managed forest.	650 million tonnes decrease in CO$_2$ emissions from bio-electricity compared to reference (G17)
Model intercomparison studies:						
18) Hurtt et al. (2011) Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Climatic Change 109, 117–161. N/A	Global Land-use Model (GLM), MESSAGE, AIM, GCAM, IMAGE *Harmonize land-use information from multiple Integrated Assessment Models into a single set of land-use change scenarios*	2005–2100 *1560 mil ha cropland. 3340 mil ha pastureland. 2500 mil ha primary forest. 1400 mil ha secondary forest.*	RCP8.5-MESSAGE	A radiative forcing of 8.5 W m^{-2} and rising in 2100.	+280 million ha cropland +370 million ha pastureland −950 million ha primary forest +700 million ha secondary forest	–
			RCP6-AIM	Stabilize radiative forcing at 6 W m^{-2} after 2100. Med-high emission pathway with mitigation actions taken late in the century.	+370 million ha cropland −1550 million ha pastureland −560 million ha primary forest +680 million ha secondary forest	–
			RCP4.5-GCAM			–

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Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
				Stabilize radiative forcing at 4.5 W m^{-2} (~650 ppm CO_2-equivalent) before 2100.	−430 million ha cropland −470 million ha pastureland −980 million ha primary forest +1600 million ha secondary forest	
			RCP2.6-IMAGE	Limiting climate change to less than 2 °C by limiting radiative forcing to a peak of 3 W m^{-2} in mid-century, declining to 2.6 W m^{-2} in 2100. A very low emission scenario.	+540 million ha cropland −70 million ha pastureland −1000 million ha primary forest +820 million ha secondary forest	–
19) Lotze-Campen et al. (2014) Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. Agricultural Economics 45, 103–116. **wheat, coarse grains, rice, sugar crops, oilseeds**	AIM, MAGNET, GCAM, GLOBIOM, MAgPIE *Analyse a future scenario with strongly rising bioenergy demand until the year 2050.*	2005–2050	AIM (the Asia-Pacific Integrated Model)	Natural forest and grassland are available for agricultural use.	−14 million ha cropland +22 million ha pastureland +241 million ha bioenergy land −248 million ha unmanaged land	–
			MAGNET	Land and natural resources are heterogeneous production factors.	−18 million ha cropland −40 million ha pastureland +259 million ha bioenergy land −201 million ha unmanaged land	–
			GCAM	Land use is allocated amongst different uses according to relative land profit rates.	+21 million ha cropland −108 million ha pastureland +431 million ha bioenergy land −344 million ha unmanaged land	–
			MAgPIE	Agricultural production increase at additional costs: agricultural land expansion, spatial crop re-allocation, and endogenous mode for intensification.	−253 million ha cropland 0 million ha pastureland +267 million ha bioenergy land −13 million ha unmanaged land	–
			GLOBIOM (Global Biosphere Management Model)	One land cover type switched to another depending on relative profitability of individual activities and on inertia constraints.	−31 million ha cropland −34 million ha pastureland +188 million ha bioenergy land −124 million ha unmanaged land	–
20) *Popp et al. (2017) Land-use futures in the shared socio-economic pathways. Global Environmental Change 42, 331–345. N/A	AIM, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND/MAgPIE *Describe possible future pathways of land use, including the resulting GHG emissions and food prices, under different shared socio-economic pathways (SSPs)*	2005–2100 1500 mil. ha cropland.	Baseline	SSP1: taking the green road	−80 million ha cropland +300 million ha forest	
				SSP2: middle of the road	+200 million ha cropland −35 million ha forest	
				SSP3: regional rivalry- a rocky road	+640 million ha cropland −570 million ha forest	
				SSP4: inequality- a road divided	+100 million ha cropland −180 million ha forest	
				SSP5: fossil-fuelled development-taking the highway	+300 million ha cropland −220 million ha forest	
			RCP4.5	SSP1: taking the green road	−100 million ha cropland +450 million ha forest	
				SSP2: middle of the road	+35 million ha cropland +290 million ha forest	
				SSP3: regional rivalry- a rocky road	+ 390 million ha cropland −370 million ha forest	
				SSP4: inequality- a road divided	0 million ha cropland +120 million ha forest	
				SSP5: fossil-fuelled development-taking the highway	+40 million ha cropland −30 million ha forest	

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Table 2 (*continued*)

Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
21) *Alexander et al. (2017) Assessing uncertainties in land cover projections. Global Change Biology 23, 767–781. N/A	13 models: CAPS, FABLE, FARM, GLOBIOM, LandSHIFT, MAgPIE, AIM, CLUMondo, FALAFEL, GCAM, IMAGE, MAGNET, PLUM *Identify and quantify uncertainties in global land cover projections over a diverse range of model types and scenarios*	2010–2100 *1290–1650 mil. ha cropland. 1700–4100 mil. ha pastureland 3670–4400 mil. ha forest.*	54 scenarios	Unidentified	930–2670 million ha cropland 2000–3960 million ha pastureland 3500–4400 million ha forest	–
Others (excluded from Fig. 1):						
22) Boysen et al. (2017) Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. Global Change Biology 23, 4303–4317. **12 crop functional types, pastures and other non-nutritious plant type**	Biogeochemical process model LPJmL *Analyse three prioritizations that could severely restrict large-scale land availability for terrestrial* CO_2 *removal*	2005–2100	Food first	Biomass plantation on abandoned agricultural land, 50% conversion efficiency of carbon extraction potential. 7.5 billion population. 10% yield gap reduction. No increase in global kcal production.	3300 million ha agricultural land, reduces from 4200 million ha in 2005. 1009 million ha biomass plantation (in 2020)	53 Gt C removal potential from 2020 until 2100
			Food first + climate	As above, but biomass plantation is not allowed on areas with unfavourable albedo decreases	817 million ha biomass plantation (in 2020)	35 Gt C removal potential from 2020 until 2100
			Conservation first	Biomass plantation outside forests. 50% conversion efficiency of carbon extraction potential	4856 million ha forest, 3818 million ha biomass plantation, 17% loss of protected areas (in 2020)	613 Gt C stored in forest, 336 Gt C removal potential from 2020 until 2100
23) Davies-Barnard et al. (2014) Climatic impacts of land-use change due to crop yield increases and a universal carbon tax from a scenario model. Journal of Climate 27, 1413–1424. **Five PFTs (broadleaf tree, needleleaf tree, C3 and C4 grasses, and shrubs)**	Hadley Centre Global Environment Model, version 2–Earth System (HadGEM2-ES) *Investigate the biogeophysical climatic impact of combinations of agricultural crop yield increases and carbon pricing mitigation*	2005–2100	No land use change (reference)	No change in land use	0% crop and pastureland +2% forest area	+293 Pg C sequestered in land, +1.87 K of mean annual global temperature
			RCP4.5	Normal agricultural productivity growth (FAO 2005). Tax on GHG emissions	−15% crop and pastureland +11% forest area	+334 Pg C sequestered in land, +2 K of mean annual global temperature
			BAU	Normal agricultural productivity growth (FAO 2005). No tax on GHG emissions	+21% crop and pastureland −12% forest area	+250 Pg C sequestered in land, +1.7 K of mean annual global temperature
			No yield increase	No growth in agricultural productivity. Tax on GHG emissions	−6% crop and pastureland −5% forest area	+284 Pg C sequestered in land, +1.8 K of mean annual global temperature
			No yield increase No carbon mitigation	No growth in agricultural productivity. No tax on GHG emissions	+50% crop and pastureland −40% forest area	+106 Pg C sequestered in land, +1.4 K of mean annual global temperature
24) *Kreidenweis et al. (2016) Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. Environmental	MAgPIE *Assess global and regional food price impacts of large-scale afforestation*	2010–2100	BAU	No afforestation. No CO_2 pricing.	+2.8% cropland (+360 mil ha) −2.1% pastureland (−275 mil ha) −0.6% forest (−85 mil ha). No change in afforested area	91 Gt CO_2 cumulative emissions

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Table 2 (*continued*)

Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
Research Letters 11, 085001. **17 different crop groups and 5 livestock commodities**			Avoided deforestation	No afforestation. CO_2 price that starts at 30 US$/tonne CO_2 in 2020, with 5% annual increase.	+0.5% cropland (+77 mil ha) −0.2% pastureland. No change in forest/ afforested area	2 Gt CO_2 cumulative emissions
			Unrestricted afforestation	Global afforestation. CO_2 price (as above).	−5.4% cropland −12.9% pastureland −0.3% forest +20.5% (2577 million ha) afforested area	−860 Gt CO_2 cumulative emissions
			No boreal afforestation	Afforestation not allowed in the boreal zone north of 50°N. CO_2 price (as above).	−4.7% cropland −11.3% pastureland −0.1% forest +17.8% (2240 million ha) afforested area	−791 Gt CO_2 cumulative emissions
			Tropical afforestation	Afforestation limited to the tropical zone between 20°S and 20°N. CO_2 price (as above).	−1.3% cropland −7.0% pastureland −0.1% forest +9.7% (1235 million ha) afforested area	−525 Gt CO_2 cumulative emissions
25) Warner et al. (2013) Modelling biofuel expansion effects on land use change dynamics. Environmental Research Letters 8, 10. **cow/sheep/goat-like meat, dairy, pig-like meat, poultry-like meat, maize, wheat, rice, other cereals, oils (from crops), sugar, vegetables, fruits, and nuts**	System dynamics simulation model (BioLUC) *Examine the effects of demand for crop-based biofuels and food on land use change.*	1990–2050	BAU	80 million ha harvested for biofuels. 7 EJ biofuels. 140–310 kg meat and dairy/capita-yr. 280–290 kg other food/capita-yr.	+750 million ha cropland +2200 million ha pastureland −2950 million ha forest & grassland	–
			Higher biofuel demand	700 million ha harvested for biofuels. 46 EJ biofuels. 140–310 kg meat and dairy/capita-yr. 280–290 kg other food/capita-yr.	+1350 million ha cropland +1700 million ha pastureland −3050 million ha forest & grassland	–
			Higher food demand	80 million ha harvested for biofuels. 7 EJ biofuels. 200–360 kg meat and dairy/capita-yr. 330–340 kg other food/capita-yr.	+1150 million ha cropland +2300 million ha pastureland −3450 million ha forest & grassland	–
			Higher food and biofuel demands	700 million ha harvested for biofuels. 46 EJ biofuels. 200–360 kg meat and dairy/capita-yr. 330–340 kg other food/capita-yr.	+1700 million ha cropland +1750 million ha pastureland −3450 million ha forest & grassland	–
26) Arora & Montenegro (2011) Small temperature benefits provided by realistic afforestation efforts. Nature Geoscience 4, 514–518. **PFTs: needleleaf evergreen and deciduous trees, broadleaf evergreen and cold and drought deciduous trees, and C3 and C4 crops and grasses**	Canadian Earth System Model (CanESM1) *Assess climate-change mitigation potential of afforestation scenarios.*	2010-2100	100% global afforestation	100% croplands or marginal lands converted into forests	20.2 million km^2 forest areas	0.45 °C reduced warming
			50% global afforestation	50% croplands or marginal lands converted into forests	10.1 million km^2 forest areas	0.25 °C reduced warming
27) Tokimatsu et al. (2017) Global zero emissions scenarios: The role of biomass energy with	Three resource balance models *Investigate the*	2010-2100	BAU	No climate policy intervention	2.7 Gha forestry areas	3.5 °C global mean temperature rise
			2100 zero		3.5 Gha forestry areas	

(continued on next page)

Table 2 (*continued*)

Studies **Food representation in model**	Model(s) *Objective(s)*	Temporal horizon *Baseline areas*	Scenario(s)	Assumptions	Primary outputs at the end of temporal horizon	Secondary outputs at the end of temporal horizon
carbon capture and storage by forested land use. Applied Energy 185, 1899–1906. **pork and chicken, lamb and beef, rice, wheat, and corn**	*prospects of three zero-emission scenarios for achieving the target of limiting global mean temperature rise to 2°C or below.*			No climate policy intervention until 2100, when zero emissions are achieved		3.5 °C global mean temperature rise
			350 ppm zero	Near zero emissions through a cumulative emission cap from 2010 to 2150	3.7 Gha forestry areas	2.5 °C global mean temperature rise
			Net zero	Net emissions of zero over the entire time horizon	4.7 Gha forestry areas	2.3 °C global mean temperature rise
28) Melillo et al. (2016) Protected areas' role in climate-change mitigation. Ambio 45, 133–145. **cropland, pastureland, managed forest land, natural grasslands, and natural forest**	Dynamically linked modelling system *Estimate the role of protected areas as carbon sinks*	2005–2100	Full protection	No climate policy, continued economic growth and agricultural productivity growth of 1% per year, integrity of protected areas maintained	15.5 million km^2 protected areas (dominated by forest)	0.3 Pg C/y sequestered in protected areas
			No protection	Same assumptions as above, but allows development in protected areas	9.9 million km^2 protected areas	0 Pg C/y sequestered in protected areas

4. Discussion

Focusing on food and forest scenarios for the middle to the end of the current century, we review 63 main scenarios and 28 modelling studies that rely on varying economic, social and environmental settings with several underlying assumptions. Hence, we expected a wide range of variation in the predicted changes in agricultural and forest areas in 2050 and 2100. The variation in predicted changes in area (Fig. 2a) are mostly consistent with past model intercomparison studies that draw together the findings of many different modelling approaches (Figs. 2b, c and d). Here, we focus primarily on evaluation of scenario outcomes instead of identifying the differences and uncertainties in models (Alexander et al., 2017; Prestele et al., 2016). The scenarios summarized in our review are provided by various models developed by multiple institutions and researchers demonstrating a wide diversity of future scenarios (Table 2). These provide a useful snapshot of future food and forest scenarios and the range of options available to feed the world's population under a changing climate. Our analysis highlights the importance of carbon taxes (prices), reforestation/afforestation and bioenergy in increasing/ maintaining forest or reducing the extent of forest loss. These actions are also crucial to reducing GHG emissions and global temperature in the next decade. In addition, yield improvement and changing diet are key actions to meet future food demand while limiting further agricultural expansion and forest clearance.

Our review shows that the majority of scenarios envisage cropland expansion to feed the world's population in 2050 and a reduction in global forest and pastureland (Figs. 1 and 2). The median and mean of projected cropland change in 2050 are 84 million and 105 million ha, respectively, which are slightly higher than the FAO's forecast of 69 million ha cropland expansion (Alexandratos and Bruinsma, 2012). Forest is not the only source of land for the expansion of cropland with conversion of pastureland also being required in 12 scenarios to meet future cropland demand. Assuming reference or no mitigation action, ten models predict cropland gain associated with forest and pastureland loss. Furthermore, seven models are inclined to yield significant forest loss in the majority of their scenario outputs, despite the diversity in model's types, structures and assumptions within these models. The environmental costs of cropland expansion include, but not limited to, significantly higher GHG emissions and global temperature, loss of carbon sequestration potential and increase in soil erosion (Table 2). These results support the prevailing and compelling narrative of production-at-all-cost at the expense of other land types/ecosystems, which is consistent with other model projections (Reilly and Willenbockel, 2010; Le Mouël and Forslund, 2017; Smith et al., 2010; Hertel et al., 2016; Tilman et al., 2011).

In contrast, we found 20 scenarios that estimate a 20–2800 million ha increase in forest and 11 scenarios showing no change in forest area by 2050. The outcomes of forest gain or no forest loss are only achieved when mitigation actions are actively implemented in each scenario. In other words, cropland expansion is expected in absence of responses such as higher agricultural productivity, shift to low meat diet, penalty on released GHG emission, no deforestation or forest conservation policies. Further, the models constructed within ambitious climate mitigation target framework do tend to yield significant forest gain in all scenarios including reference scenarios (van Vuuren et al., 2017; Walsh et al., 2015; Sands et al., 2014). The scenarios in these models are built based on the assumptions that society has made necessary transition to achieve green growth while respecting environmental boundary (van Vuuren et al., 2017) and to stabilize global carbon dioxide concentration (Sands et al., 2014; Walsh et al., 2015). Forest gain in these models does not jeopardize future food production; rather, future food demand is met via increases in agricultural productivity, dietary changes (e.g. low consumption of animal products) and reduction in food wastes/competition by feedstock. Our findings, consistent with previous global assessments (Foley et al., 2011; Godfray et al., 2010), suggest that it is possible to meet key sustainability challenges of halting further agricultural expansion (Cunningham et al., 2013) and climate change mitigation (Hunter et al., 2017).

4.1. *Assessment of options to achieve food security and forest conservation under changing climate*

Expanding croplands ultimately comes at a high environmental cost to biodiversity, ecosystem functioning and carbon emissions; this tradeoff is often acknowledged when discussing the requirement for more agricultural lands to meet projected food demand (Le Mouël and Forslund, 2017; Tilman et al., 2001). The debates on intensification vs. extensification or land sharing vs. land sparing provide mounting evidence on the validity of each strategy, as well as the diverse options to tackle food security and environmental sustainability (Meyfroidt et al., 2018; Grau et al., 2013; Perfecto and Vandermeer, 2010; Mertz and Mertens, 2017; Ellis and Mehrabi, 2019). Most authors agree that cropland expansion must be halted (Hunter et al., 2017; Godfray et al., 2010; Foley et al., 2011); this view has gained traction amongst the private and public sectors e.g. zero-deforestation commitments and zones (Garrett et al., 2019; Lambin et al., 2018; Nepstad et al., 2014; Meyer and Miller, 2015). In our review, three models deliberately set constant forest area over the temporal horizon as its input parameter and consequently, yield no change in forest area. Given the constraints on agricultural land expansion, future food production must take place on existing cropland via intensification. Varying degrees of yield improvement are used as proxy for intensification (from 1.0% to 2% increase annually, depending on crop types). In general, yield improvement leads to reduction in cropland expansion and GHG emissions when compared to a reference scenario (Humpenoder et al., 2015; Strapasson et al., 2017; Table 2, Bajželj et al., 2014; Wise et al., 2014).

However, intensification targeted solely on yield improvement might have other negative environmental impacts such as run off and nitrogen emissions from fertilizers, depletion of water from irrigation, and ecological and health consequences from pesticide application (Hunter et al., 2017; Tilman, 1999). 'Sustainable intensification' has been proposed as an alternative to address environmental shortcomings of industrial intensification receiving both strong support and criticisms (Rockström et al., 2017; Pretty and Bharucha, 2014; Garnett et al., 2013; Smith, 2013; Benton and Bailey, 2019). Moreover, while industrial intensification (sustainable or otherwise) has a significant role in delivering global food, the contributions of less-intensive smallholders, family-farms and agroecological systems must be acknowledged and better quantified (Ricciardi et al., 2018; Holt-Giménez et al., 2012; Vandermeer et al., 2018; Mijatović et al., 2018). Globally, farms under two ha produce 28–31% of total crop production and 30–34% of food supply on 24% of gross agricultural area, while harbouring greater crop diversity and lower post-harvest loss than larger farms (Ricciardi et al., 2018). Large-scale intensive farms rely heavily on a few high-yielding crop varieties, which are selected for productivity and calorific values rather than for micronutrients (vitamins and minerals) (Ickowitz et al., 2019). Hence, intensification might further homogenize diets and reduce micronutrients in diets, which can have major consequences for health (Larsen, 2006; Bloem et al., 2010; Benton and Bailey, 2019).

Two billion people are affected by micronutrient deficiencies, collectively known as "hidden hunger" (Bailey et al., 2015); this issue is yet to be better represented in modelling global diets. Only eight modelling studies (Stevanovic et al., 2017; Schader et al., 2015; Strapasson et al., 2017; Erb et al., 2016; Pardey et al., 2014; Bajželj et al., 2014; Sands et al., 2014; Warner et al., 2013) directly account for fruit and vegetable intake out of the 28 models in our review. The under-representation of fruits and vegetables, despite their importance in achieving healthy diets, calls for more effort in quantifying and integrating these food groups in current and future food systems (Tomlinson, 2013). This is particularly crucial in the context of climate change as recent studies suggest that many crops are becoming nutritionally impoverished due to higher CO_2, which might result in a greater burden of nutritional deficiencies, infectious diseases, anaemia, and excess mortality for future populations (Smith and Myers, 2018; Myers et al., 2014; DeFries et al., 2015; Springmann et al., 2016; Ebi and Ziska, 2018). Our current global food system leaves millions of people food insecure (Holt-Giménez et al., 2012) and others overweight and obese while generating significant environmental degradation and thus clearly requires a serious make-over (Development Initiatives, 2018). Therefore, systemic changes in our current food system targeted at improvements in food quality, access and distribution with better environmental performance are required (Smith, 2013; Rockström et al., 2017; Vandermeer et al., 2018; Garnett et al., 2013). Mitigation and adaptation measures to minimize climate change impacts such as shifting diets, reductions in food loss and waste and advances in technology and management cannot be carried out in isolation but demand participation across scales and sectors (Smith et al., 2013; Agrawal et al., 2014; Alexander et al., 2018; Springmann et al., 2018; Bajželj et al., 2014; Searchinger et al., 2018; Benton and Bailey, 2019).

Increasing demand for forest products, climate change mitigation and other ecosystem services are likely to be met from expanding areas of planted forests (Alkama and Cescatti, 2016; Sloan and Sayer, 2015). Our review shows that forest gain and lower rates of deforestation are prerequisites to reducing GHG emissions, increasing carbon sequestration and reductions in global temperature over the next decade (Table 2; Sonntag et al., 2016, Walsh et al., 2015, Strapasson et al., 2017, van Vuuren et al., 2017). Moreover, forest gain is projected to meet the growing demand for timber and pulp products as well as other services such as recreation/amenities, while simultaneously achieving global forest restoration targets such as the Aichi Targets, the Bonn Challenge, and New York Declaration on Forests and other local targets such as zero deforestation commitments (Chazdon et al., 2015). In fact, global tree cover has increased by 2.24 million km^2 (for the period 1982 - 2016) with the increase of tree cover predominantly occurring outside the tropics region (Song et al., 2018). However, there are key issues associated with forest expansion. Firstly, an increase in forest area does not necessarily translate to greater provision of a broader range of ecosystem services such as biodiversity and water regulation. This is particularly true for reforestation with tree plantation monocultures that are mostly comprised of fast growing exotic tree species with considerably low ecological and biodiversity value (Hall et al., 2012; Brockerhoff et al., 2013). Moreover, the conversion of different types of forest (e.g. managed conifers at the expense of natural deciduous forest in Europe) has been shown to contribute to climate warming, suggesting that not all forestry contributes to climate change mitigation (Naudts et al., 2016). Retention forestry (Mori and Kitagawa, 2014) and manipulating the configuration of plantings in terms of location, size, species mix and tree density (Cunningham et al., 2013; Liu et al., 2018), amongst others, are practical approaches to improving a range of environmental benefits in forest plantations.

Secondly, forest expansion might intensify pressures on other natural ecosystems perceived to contain lower carbon level and affect the surrounding socio-economic systems. In our review, forest gain is accompanied by a loss in cropland, pastureland and other types of land. The so called 'low carbon' or 'marginal/less productive' ecosystems such as the Latin America's cerrados and African savannas, often harbour high biodiversity and might increasingly become sources of conversion because of pressures to expand forests (Popp et al., 2014a; Reilly and Willenbockel, 2010). In addition, the large-scale monoculture plantations of exotic species in Latin America raise issues about rural autonomy, livelihoods and regional sovereignty (Hecht, 2014; Malkamäki et al., 2018). Finally, forest expansion in one area may give rise to leakage and displacement effects at multiple scales (Lambin and Meyfroidt, 2011; Meyfroidt et al., 2018). Local land use decisions are increasingly driven by distant factors such as international markets (Lambin et al., 2014). At a local scale, the establishment of protected areas might slow tree cover loss and increase deforestation outside (Dewi et al., 2013) and occasionally displace forest dependant communities whom have significant role in conserving the forest (Davies et al., 2014; Garnett et al., 2018). Although global forests are projected to expand, these global estimates hide underlying regional trends. In our globalized world, the implementation of forest conservation policies such as REDD+ at national or regional scales risks shifting deforestation elsewhere (Meyfroidt et al., 2013; Popp et al., 2014a).

An informed projection of food and forest demands and land use may help prioritize policy decisions. We found that the scenarios that projected the application of policy instruments to mitigate climate change generally led to reduction in GHG emission and global temperature in comparison to reference scenario (Table 2, Fig. 3). The

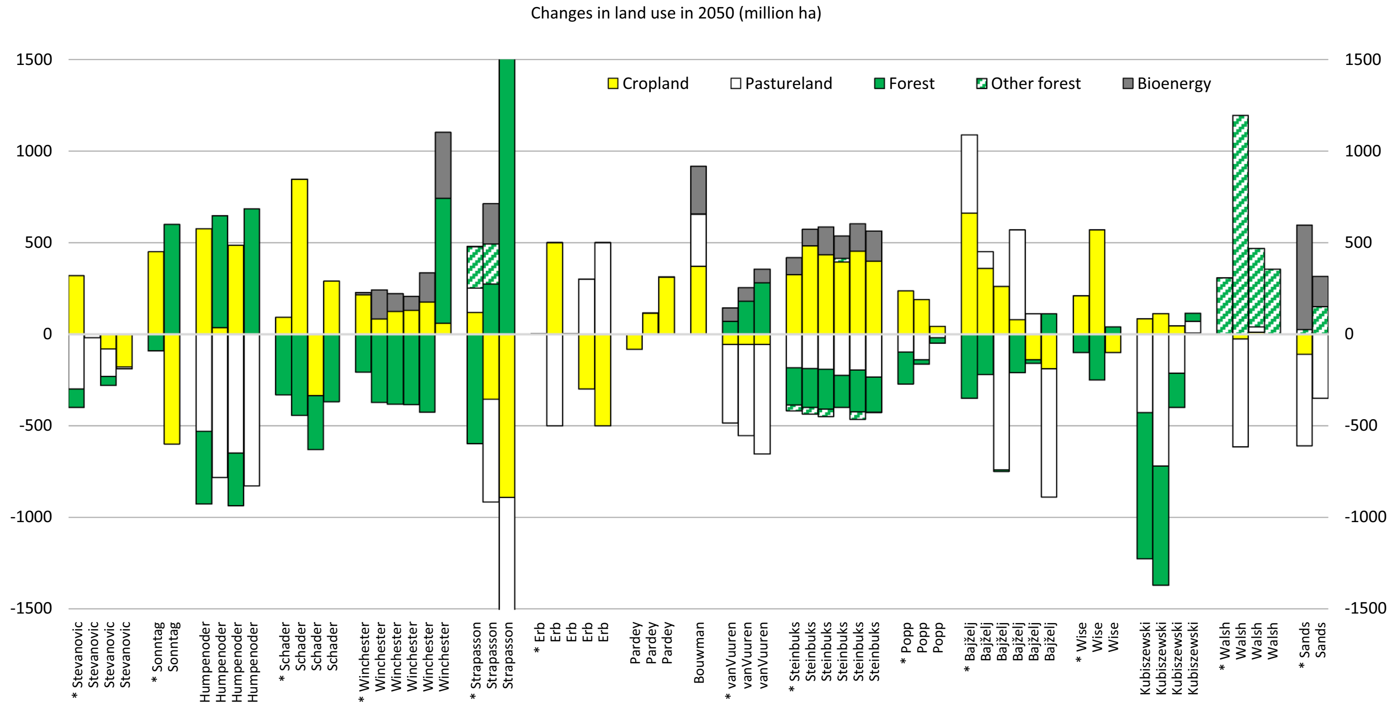

Fig. 1. Bar chart showing changes in land use from base year to 2050 for different types of land use. Each bar corresponds to individual scenario modelled by individual study (provided on vertical axis); the order of appearance for each scenario follows that of Table 2. The reference scenario for each model is indicated with *. Each study employed one model to predict future scenarios, see details of scenarios in Table 2. The temporal horizon provided in Table 2 might differ from that of Fig. 1.

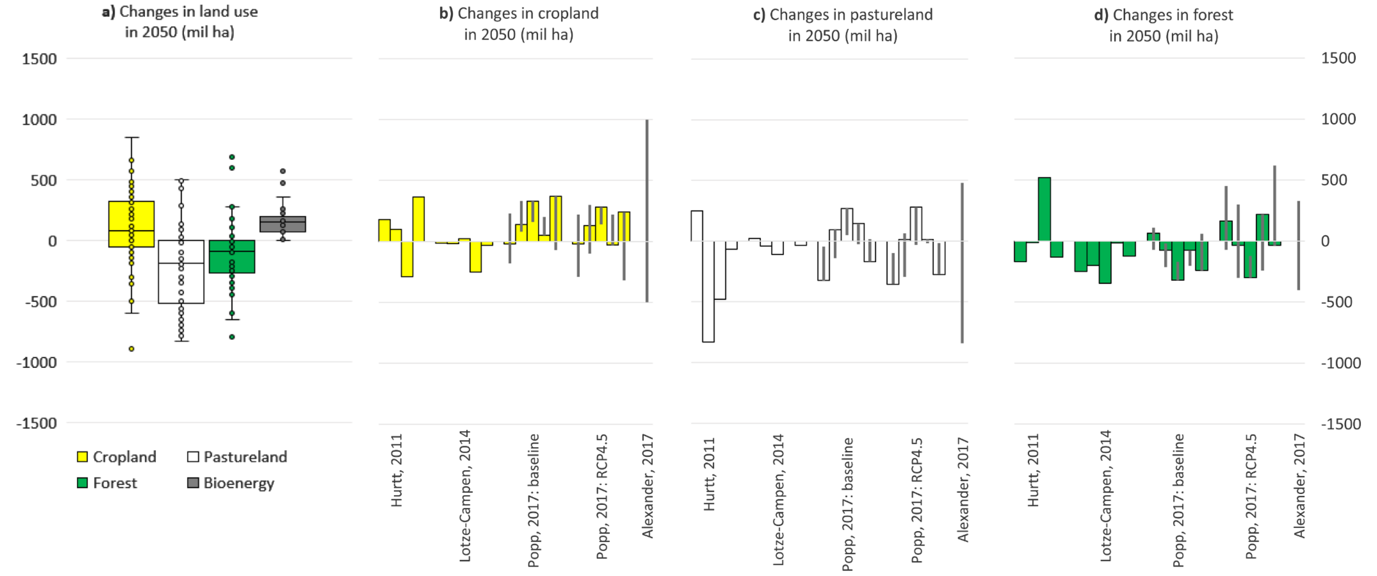

Fig. 2. a) Box and whisker plots showing changes in land use from base year to 2050 for different types of land use for scenarios depicted in Fig. 1. The horizontal line within each box is the median. The upper and lower edges of each box indicate the 75th and 25th percentiles, respectively and the vertical bars indicate the 10th to the 90th percentile ranges. Note that the most extreme values from Strapasson et al. (2017) are not depicted in these plots.
Bar charts illustrate changes in land use from base year to 2050 for b) cropland, c) pastureland and d) forest. Bars correspond to estimates taken from studies by Hurtt et al. (2011), Lotze-Campen et al. (2014), Popp et al. (2017) which modelled baseline and RCP4.5 (representative concentration pathway 4.5) scenarios and Alexander et al. (2017). Each study employed multiple models that are harmonized to explore model uncertainties due to different representation and parameterization of biogeochemical, biophysical and socio-economic processes. The horizontal lines depicted in Popp et al. (2017) and Alexander et al. (2017) indicate the range of changes in land use for each scenarios, as determined by multiple models. There are overlapping scenarios depicted in Popp et al. (2017) and Alexander et al. (2017). See details of scenarios in Table 2.

mitigation actions, often being applied in combination have been shown to potentially ease the pressure on forest and resulted in lower forest loss in comparison to no mitigation actions. Our review indicates policy that provides economic incentives for carbon stock (i.e. forest) conservation and enhancement as the only effective option to reverse the trend of forest loss (Fig. 3), leading to significant emission reduction (Humpenoder et al., 2015; Winchester and Reilly, 2015). The reduction potential of GHG emissions from imposing carbon pricing/ tax is well established in the literature and supported by our review (Stevanovic et al., 2017; Humpenoder et al., 2015; Winchester and Reilly, 2015; Popp et al., 2014a; Bouwman et al., 2010). In these models, the price of carbon varies between 24 and 30 US/tCO_2eq in the first year and occasionally increases over time. In practice, the 2017 price of carbon ranged between <1 to 140 US/tCO_2eq (carbon tax) and between <1 to 24 US/tCO_2eq (GHG emissions trading systems) across 73 jurisdictions (Haites, 2018). Most carbon tax rates and prices are low relative to levels thought to be needed to achieve climate change mitigation objectives e.g. restrict global warming to 2°C above pre-industrial levels under Paris agreement. A more aggressive approach may effectively reduce GHG emissions, but at the expense of achieving food security (Stevanovic et al., 2017; Hasegawa et al., 2018; Kreidenweis et al., 2016). Higher food prices due to taxation of the livestock sector and increasing competition for land amongst forest, food and biofuel production will have negative impacts on low income regions such as sub-Saharan Africa and South Asia, which already have the most acute prevalence of hunger (Hasegawa et al., 2018). However, food price increases could be buffered by more trade liberalisation in agricultural commodities (Kreidenweis et al., 2016) and shifts in preferences e.g. dietary change and better waste management (Stevanovic et al., 2017). This reinforces the need for complementary mitigation policies to ensure that progress towards climate stabilization, environmental/biodiversity protection and food security can be simultaneously achieved (Katila et al., 2019). Assessment of risks, synergies and trade-offs between Sustainable Development Goals (SDGs) and forest (Timko et al., 2018; Dooley and Kartha, 2018; Sayer et al., 2019; Schröder et al., 2019; Louman et al., 2019) and food (Obersteiner et al., 2016; Sunderland et al., 2019) should be conducted by policy makers to maximize synergies between sectors and enhance policy coherence (Nilsson et al., 2016; TEEB, 2018; de Jong et al., 2019).

Recent studies have identified areas of high uncertainty and different sources of uncertainty related to global models (Alexander et al., 2017; Prestele et al., 2016; Hertel et al., 2016). Model type and input data have been identified as key areas where uncertainty arises and thus requires further attention. While we acknowledge the inherent uncertainty associated with specific models and their sources, the evaluation of individual model performance and uncertainties is beyond the scope of our study. In addition to ongoing work to reduce such uncertainties, we recommend future studies to further expand the coverage of models. In our review, we identified a high number of modelling studies that are deemed relevant during abstract screening (169 from using search terms, 44 using snowball search). However, this

Paper	Mitigation interventions / actions						
	Carbon pricing	Reforestation/ conservation	Yield improvement	Waste reduction	Dietary change	Bioenergy	Others
Stevanovic	30 US$/t CO_2eq	-	-	-	-	-	-
Stevanovic	-	-	-	50%	15% livestock diet	-	-
Stevanovic	30 US$/t CO_2eq	-	-	50%	15% livestock diet	-	-
Sonntag	-	Reforestation	-	-	-	-	-
Humpenoder	24 US$/t CO_2	-	-	-	-	-	-
Humpenoder	-	-	-	-	-	-	Climate change: RCP2.6
Humpenoder	24 US$/t CO_2	-	-	-	-	-	Climate change: RCP2.6
Schader	-	-	-	100% food competing feedstuff		-	Climate change
Schader	-	-	-	0% food competing feedstuff		-	-
Schader	-	-	-	0% food competing feedstuff		-	Climate change
Winchester	25 US$/t CO_2	-	1% increase/yr	-	-	-	-
Winchester	25 US$/t CO_2	-	1% increase/yr	-	-	Low ethanol blending	-
Winchester	25 US$/t CO_2	-	1% increase/yr	-	-	50% more expensive ethanol	-
Winchester	25 US$/t CO_2	-	0.75% increase/yr	-	-	-	-
Winchester	25 US$/t CO_2	-	1% increase/yr	-	-	-	Carbon price extends to land use change
Strapasson	-	-	40-60% yield rise	-	22% ruminant meat diet	High mitigation in land, food, bioenergy	
Strapasson	-	-	100% yield rise	-	10% ruminant meat diet	Extreme mitigation in land, food, bioenergy	
van Vuuren	Low REDD, half reforestation		-	-	-	-	Climate target: 4.5 W m^{-2}
van Vuuren	High REDD, full reforestation		-	-	-	-	Climate target: 2.6 W m^{-2}
Steinbuks	-	-	Permanent decline	-	-	-	-
Steinbuks	Increasing fossil fuel cost	-	-	-	-	-	-
Steinbuks	-	-	-	-	-	-	60% reduction in GHG emission
Steinbuks	Increasing fossil fuel cost	-	Permanent decline	-	-	-	-
Steinbuks	Increasing fossil fuel cost	-	Permanent decline	-	-	-	60% reduction in GHG emission
Popp	-	REDD	-	-	-	-	-
Popp	Universal carbon tax	REDD	-	-	-	-	-
Bajželj	-	-	-	50%	-	-	-
Bajželj	-	-	-	50%	Healthy diet	-	-
Bajželj	-	-	No yield gap	-	-	-	-
Bajželj	-	-	No yield gap	50%	-	-	-
Bajželj	-	-	No yield gap	50%	Healthy diet	-	-
Wise	-	-	No improvement	-	-	-	-
Wise	-	-	Twofold crop productivity	-	-	-	-
Walsh	-	-	-	-	-	Microalgae as bioenergy	-
Walsh	-	-	-	-	-	-	Microalgae as feedstock
Walsh	-	-	-	-	-	Expansion of bioenergy	-
Sands	-	-	1% increase/yr	-	-	-	Low energy intensity

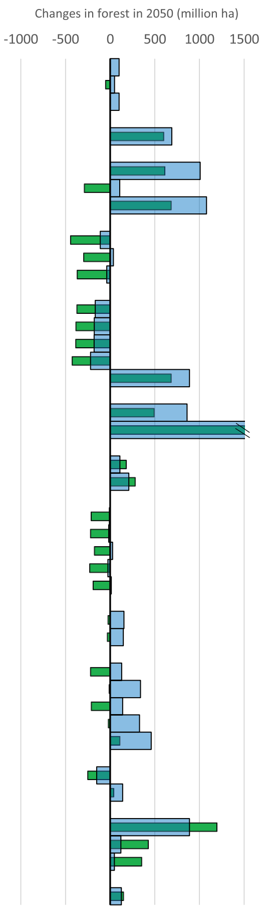

Fig. 3. Vertical bar chart showing changes in forest from base year to 2050 in absolute (green bars) and relative (blue bars) values. Each bar corresponds to individual scenario modelled by individual study; the particular mitigation interventions or actions simulated in the scenarios are tabulated next to the bar. Green bars denote the absolute changes in forest from base year to 2050 i.e. similar values to those illustrated in Fig. 1. Note that the reference scenarios are not included in this figure. Rather, relative changes in forest from base year to 2050 for alternative scenarios are shown (blue bars), relative to the reference scenario for individual model. Hence, the differences between green and blue bars denote the impact of simulated mitigation interventions on projected forest area in 2050 for a given model.

coverage was severely reduced to 28 studies after screening using our inclusion criterias. In most cases, we discovered that the outcomes of the modelling fitting our criteria are not reported in a manner that permits data extraction. For instance, the changes in land use are illustrated by pixelated maps and the values underpinning the pixels were not provided. Future work might involve collaborating and sharing data from these specific studies. The inclusion of more diverse models ensures that the outcomes from particular types of models do not dominate (Alexander et al., 2017), while also capturing a wider coverage of models that provide more data to allow a thorough assessment of mitigation actions, analysis of trade-offs and synergies, and prioritization of actions.

5. Conclusion

Our review shows that 59% of the forecasts for feeding the future global population predict an increase in area of croplands at the expense of forests and pastures, thus reinforces the production-at-all-cost narrative. Even when the necessary mitigation and compensatory measures would have been taken, this pathway perpetuates our currently dysfunctional global food system (Smith, 2014; Holt-Giménez et al., 2012). Alternatively, a significant number (32% of the forecasts) show that it is possible to feed the global population without destroying forests. A combination of carbon pricing/tax, reforestation/ plantation, no deforestation policy, crop yield improvement, waste reduction and changes towards a less energy-intensive diet are feasible approaches to halt further agricultural expansion and mitigate climate change. In particular, our study identifies policy that provides economic incentives for carbon stock (i.e. forest) conservation and enhancement as the only effective option to reverse the trend of forest loss. Such scenarios paint realistic visions of what might be achieved in mid and end of century and highlight potential synergies between food and forestry sectors, with an important caveat that the proposed alternative scenarios need to be further substantiated with action on the ground. None of these policies is easy to adopt and their simultaneous adoption would require the support of policy makers across sectors.

Our study sets to assess the extent of prevailing narratives in the agricultural and forestry sectors. By doing so, we have also identified several underrepresented areas that require better quantification and integration into current models and narratives, including; 1) alternatives to mainstream food/forest production systems (e.g. less-intensive smallholders, family farms and agroforestry/ mix-species/ agroecological systems), 2) quantification of fruit and vegetable intake, 3) role of forests in food production and provisioning, 4) key ecosystem services provided by forests and pastures beyond carbon (biodiversity habitat, water regulation, pollination), and finally 5) prioritization and feasibility assessment of multiple mitigation actions. More work and research would need to be directed to these areas, which currently are understudied due to inherent complexity to measure and contested definitions.

CRediT authorship contribution statement

Nur H.A. Bahar: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Michaela Lo:** Methodology, Validation, Writing - review & editing. **Made Sanjaya:** Validation. **Josh Van Vianen:** Methodology. **Peter Alexander:** Validation, Writing - review & editing. **Amy Ickowitz:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **Terry Sunderland:** Conceptualization, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

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

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Supplementary materials

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