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Decoupling livestock from land use through industrial feed production pathways

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Abstract

One of the main challenges for the 21st century is to balance the increasing demand for high-quality proteins while mitigating environmental impacts. In particular, cropland-based production of protein-rich animal feed for livestock rearing results in large-scale agricultural land-expansion, nitrogen pollution, and greenhouse gas emissions. Here we propose and analyse the long-term potential of alternative animal feed supply routes based on industrial production of microbial proteins (MP). Our analysis reveals that by 2050, MP can replace, depending on socio-economic development and MP production pathways, between 10–19% of conventional crop-based animal feed protein demand. As a result, global cropland area, global nitrogen losses from croplands and agricultural greenhouse gas emissions can be decreased by 6% (0–13%), 8% (-3–8%) and 7% (-6 – 9%), respectively. Interestingly, the technology to industrially produce MP at competitive costs is directly accessible for implementation and has the potential to cause a major structural change in the agro-food system.

Introduction

The livestock sector provides essential nutrients, generates economic benefits, results in improved livelihoods, and provides labour to the worlds growing population. On the other hand, the livestock sector and especially the associated animal feed production through contemporary agriculture, also represents one of the most important contributors to global environmental pollution. [1] Two thirds of agricultural lands, furthermore, are used for pastures and about one third of the remaining croplands is devoted to produce animal feed like soybeans and cereals. [2, 3] The increasing demand for livestock products [4] has entailed a range of serious global environmental concerns including large scale deforestation, greenhouse gas emissions from land use change and biodiversity loss [5-10] as well as global nitrogen pollution due to low nitrogen fertilizer uptake efficiency of plant-soil systems and nutrient losses in animal waste management. [11, 12] These environmental impacts are largely driven by the production of protein-rich crops destined to feed livestock. [12]

By 2050 the world's growing population is expected to reach more than 9 billion people [13], a growth that combined with wealth increase will further drive the demand for animal-based proteins as part of the human diet. [14] Due to this, estimates of various Integrated Assessment Models foresee a further increase of 30 – 60% [15] in global crop production until 2050. Meeting this increasing demand by land expansion or intensification will both result in negative environmental impacts. [12, 16] One of the future challenges, therefore, is to decrease the land pressure from current livestock production and therefore simultaneously lower GWP, and nitrogen pollution. Instead of incremental improvements in efficiency, structural changes of the agricultural land use for feed production should therefore be explored.

An alternative to cultivating protein-crops to feed livestock is the use of microbes like bacteria, yeast, fungi and algae for the industrial production of Microbial Proteins (MP), also known as Single Cell Protein. [17-19] MP can be produced in intensive, confined and efficient high-rate aerobic fermentation reactors and can decouple protein production from the cultivation of agricultural land and agricultural pollution by substituting traditional crop-based protein in feed and even food. Protein volumetric productivity by microbes in bioreactors reaches several kg per m^3 per hour [18], which is several order of magnitude above that reached by higher biota. Equally important, contrarily to higher plants, microbes convert reactive nitrogen into cellular proteins with an unmatched efficiency close to 100% with proteins constituting up to 70-75% of the dry biomass weight. [17, 20] Bacteria thereby have the advantage of rapid growth on organic substrates like sugars and starch [17, 21] as well as on gaseous substrates like methane [22], hydrogen (with CO_2 and/or CO as carbon source) and syngas. [23, 24]

The production of MP is not new at all. In fact, the production of MP from methane was already achieved at industrial scale in the 70's. [25] Due to comparatively low market prices of conventional agriculture-based animal feed, the relatively under-developed fermentation technology, limited focus on resource efficiency and low environmental awareness in those days, the commercialization of MP ceased in the 80’s. [26] In recent years, several developments have led to the renaissance of MP. [19, 27, 28] First, the progress in the domains of industrial biotechnology, microbial engineering, and process and reactor technology has reduced the cost of MP production substantially with methane and sugar based MP production already commercially available. [29, 30] Our assessment also shows the economic potential of other MP production routes (table S5-S9). Second, bacterial MP has been officially recognized and approved as commercial feed ingredient for all livestock species [31] and is of high quality and resembles in amino acid composition that of fish meal. [32] Third, the large negative economic, environmental and social externalities of agricultural practices on e.g. climate change, human health, biodiversity loss and ecosystem functioning have become evident. For example, recent estimates of the costs of reactive nitrogen pollution are as high as 0.3 – 3.0% (Table S2) of the global gross domestic product annually. Finally, the global recognition that to feeding the world with high quality proteins from animal-based food in a sustainable way contemporary agriculture practice will not suffice. Altogether, MP, therefore, seem to be a promising feed source for livestock that can be part of the solution to fulfil the growing demand for animal protein, within the carrying capacity of the earth.

In this study, we conducted comprehensive model simulations until the year 2050 using the Model of Agricultural Production and its Impact on the Environment (MAgPIE) [12, 16, 33] aiming to assess the environmental impacts of the implementation of these MP production pathways on agriculture and the environment in terms of cropland expansion, nitrogen pollution and greenhouse gas emissions from land use change.

Materials and Methods

General approach simulation studies

In order to provide a comprehensive assessment of the impact of widespread adoption of MP as protein source in animal feed on the respective features of cropland expansion, nitrogen pollution and greenhouse gas emissions, we considered three potential socio-economic futures based on the Shared Socioeconomic Pathways (SSPs) [34] (i.e. SSP1 (“Sustainability pathway”), SSP2 (“middle-of-the-road pathway”) and SSP5 ("Resource intensive pathway")), five production pathways using different substrates for MP production; Figure 1) and three MP feed replacements rates for all major livestock (i.e. pigs, cattle and chicken). Using natural gas or hydrogen generated through water electrolysis driven by renewable energy would allow for the land-use decoupling of MP production. Hydrogen-based production through water electrolysis would rely on external concentrated CO_2 from industrial point sources (e.g. flue gases from power stations), which we assessed being available in sufficient quantity.

Shared Socio-economic Pathways (SSPs)

The general outcomes and dynamics of the reference scenarios SSP1, SSP2 and SSP5 are broadly documented and discussed within the publications [15, 35], and the results are deposited in a public database (https://tntcat.iiasa.ac.at/SspDb).

Technological pathways for production of Microbial Protein (MP)

MP can be produced at achievable protein production rate of ~2-4 kg protein per m^3 reactor per hour through aerobic fermentation, using bioreactors similar to those widely used in the food industry. As depicted in Figure 1, and described in more detail below, different carbon and energy sources can be used in the MP production process.

Sugarcane-to-MP

Heterotrophic production of MP with raw sugar, derived from agricultural production of sugar cane, providing both the energy and carbon source required for microbial growth. We considered the agricultural production of sugar cane to produce raw sugar as the required energy and carbon source to drive heterotrophic MP production. Besides raw sugar, the processing of the sugar cane yields also other by-products such as bagasse, and molasses which can either be used as livestock feed [36], or further fermented to produce MP. [37, 38] Other possibilities are offered by the anaerobic digestion or the gasification of such substrates, to produce bio-methane and syngas respectively. [39, 40] In our simulations, we have focused exclusively on the use of raw sugar as substrate for MP production, without accounting for the use of other by-products as livestock feed or for further MP production. Considering a raw sugar conversion factor of 14 ton sugarcane/ton raw sugar, and a dry matter (DM) content of 30% [41], the amount of sugarcane necessary to produce 1 ton MP is 4.3 ton of sugarcane (table S3).

Hydrogen-to-MP

Autotrophic production of MP using hydrogen produced by means of water electrolysis using polymer electrolyte membrane (PEM) electrolysis [42], driven by renewable energy. In this case, a crucial factor is the availability of technically exploitable CO_2 from (industrial) point sources (e.g. flue gases from power stations). In a recent study of the International Panel for Climate Change (IPCC), it was found that by 2050 the CO_2 capture potentials are estimated at 4.9 to 37.5 $GtCO_2$ per year (1.3 – 10 GtC). [43] Considering an average C/N of 5 for MP production [20], the latter would be enough to produce 2.6 – 20.2 Gt of MP, while our simulations show that 175 – 307 Mton MP can be replaced in 2050 (Supplementary Materials excel spreadsheet). It is therefore paramount that there is sufficient technically exploitable CO_2 available to produce MP through PEM electrolysis.

Availability of renewable energy: Recent estimates by the International Energy Agency indicate installed capacities for wind and solar energy to increase to 2700GW and 4670GW by 2050 (assuming the hi-Ren scenario of the IEA), respectively. [44, 45] In the scenario where all MP is produced solely by means of hydrogen as energy source delivered through PEM electrolysis, the maximum amount of renewable energy needed would be 537 – 902 GW (in order to produce 175 – 307 Mton MP with a nitrogen content of 11.2%, which equals to a protein content of 70%). Hence, this represents 7 – 12% of the total estimated combined installed wind and solar energy in 2050, respectively.

Syngas-to-MP

Autotrophic production of MP using hydrogen as energy source from syngas produced by means of biomass gasification. The syngas would also provide CO_2 used as carbon source.

Agricultural production of *Miscanthus* spp. as high C/N crop was used as source crop for gasification. We assumed a biomass-to-hydrogen yield of 0.1 kg H_2/kg biomass. [46] Note that yields during gasification found in literature are as high as 0.127 kg H_2/kg biomass. [47] A yield of 0.1 kg H_2/kg biomass corresponds to 5.5 ton of dry biomass being necessary to produce 1 ton MP (Table S3). In our simulations, we considered the use of Miscanthus as biomass substrate for the gasification process. Note that a variety of other biomass substrates is suitable for this purpose. [48] The overall biomass gasification reaction stoichiometry is as follows [49]:

$$\text{biomass} + \mathrm{O_2} + H_2\mathrm{O}\ (\text{steam}) \rightarrow \mathrm{C}H_4 + \mathrm{CO} + \mathrm{C}O_2 + H_2\ + H_2\mathrm{O} + \mathrm{C} + \text{tar} \qquad \text{(Eq. 1)}$$

The formed methane will subsequently follow a steam reforming reaction:

$$2H_2O + CH_4 \rightarrow CO_2 + 4H_2 \qquad \text{(Eq. 2)}$$

The overall ratio of H_2:CO_2 obtained during biomass gasification is thus 2.5. With stoichiometric requirements of H_2:CO_2 for the production of MP of 5.22:1 (Table S10), it is evident that there is sufficient CO_2 must be available for incorporation into MP.

Natural gas-to-MP

Methylotrophic production of MP using methane oxidizing bacteria using natural gas, providing both the carbon and energy required for microbial growth. Natural gas from the grid offers a readily available energy and carbon source for MP production at virtually any place. Assuming a methane utilization efficiency of 80%, the production of 1 ton MP requires 1767 Nm^3 methane. As such, in order to produce 175 – 307 Mton MP, 316 – 542 G Nm^3 is needed. The latter corresponds to ~ 9 – 16% of the current global natural consumption [50].

Biogas-to-MP

Methylotrophic production of MP using methane oxidizing bacteria using biogas produced by anaerobic digestion of biomass, providing both the carbon and energy required for microbial growth. Agricultural production of energy maize was used as source crop for the digestion step. We considered the agricultural production of *energy* m*aize* as substrate for the production of biogas by means of anaerobic digestion. Considering a dry matter content of 30%, we assumed a yield of 315 Nm^3 methane per ton of dry maize. [51] The latter yield translated to 5.6 ton of dry maize needed to produce 1 ton MP (Table S3). Note that also other energy crops such as switch grass, clover grass, alfa alfa, sunflower and miscanthus can be used for this purpose. [52, 53]

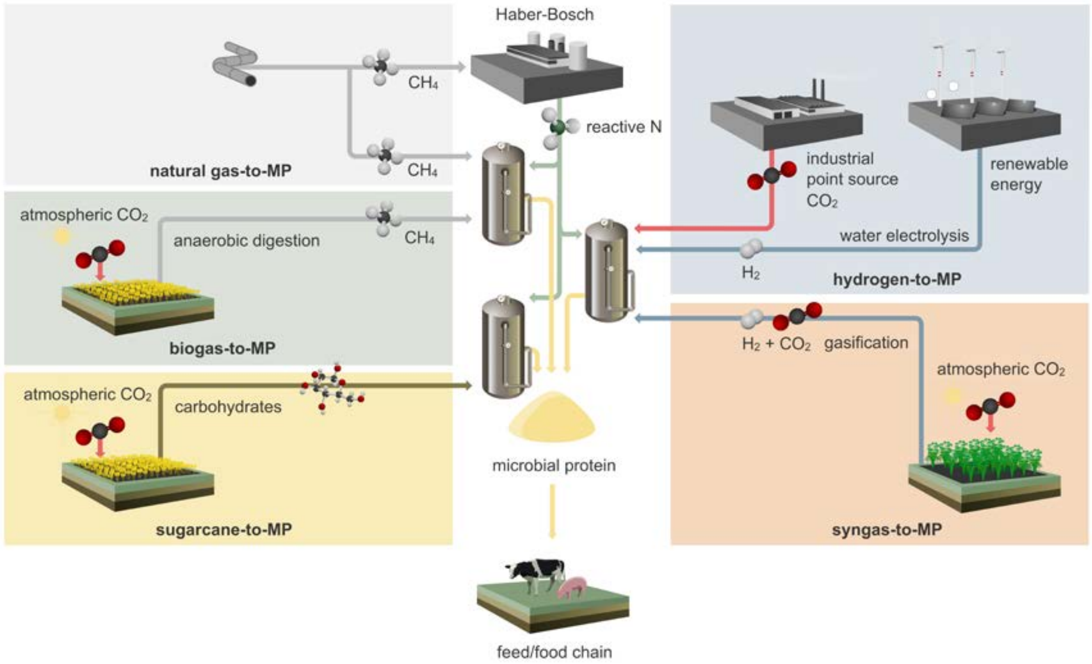

Figure 1. Proposed protein supply routes for livestock production based on microbial protein (MP).

Hydrogen-to-MP:

Syngas-to-MP:

Natural gas-to-MP:

Biogas-to-MP:

Literature survey on MP feed replacement rates

A comprehensive literature survey was conducted comprising feeding trials of all major livestock categories (i.e. beef cattle, dairy cattle, pigs, broiler chickens and laying hen) to determine the amount of MP that can be used as replacement of protein-rich oil crops, oilcakes and pulses in the feed basket without compromising animal growth and welfare. The survey reposted data on both ruminant and monogastric animals at different ages and growth stages fed with different levels of MP, as summarized in Table S1. In addition to our literature survey, we would like to refer to the review studies of Øverland *et al.*,(2010) [32] which evaluated the use of methane based MP in monogastric animals as well as other comprehensive literatures reviews conducted in the 1970's and 1990's, in which the nutritional value and evaluation of food safety of various MP are evaluated in detail. [54, 55]

Model simulations with the Model of Agricultural Production and its Impact on the Environment (MAgPIE)

The projections of the future potential environmental impacts of widespread adoption of the MP production pathways were made using the Model of Agricultural Production and its Impact on the Environment,MAgPIE 2 revision 11544. A detailed description of the MAgPIE model including its equations is available at *https://redmine.pik-potsdam.de/projects/magpie/wiki/*. In the following section, the key features of MAgPIE relevant for the MP production pathways presented in this paper are summarized. Note that the description of the existing model outlined in the section below contains text elements of descriptions of the MAgPIE model described in detail in some of our previous studies. [12, 56-64]

In this study, the MAgPIE model was extended by a new product category, namely microbial protein (MP). The simulated scenarios differ in respect to three dimensions, namely

(i) the dominant MP technology, (ii) the replacement share in animal feed baskets and (iii) Simulations within the context of three different socio-economic storylines for the general development of the agricultural sector which were based on the Shared Socio-economic Pathways (SSPs) SSP1, SSP2, and SSP5.

The dominant MP technology

The hydrogen-to-MP and natural gas-to-MP scenarios simulate land-less microbial protein production on the basis of hydrogen/methane and Haber-Bosch synthesized reactive nitrogen. Here, MP production requires no agricultural feedstock. The syngas-to-MP scenario uses as reference crop the fast-growing cellulosic grass Miscanthus [65] for MP production, requiring 5.5 tons of Miscanthus per ton MP; the sugarcane-to-MP production pathway requires 4.3 tons of sugarcane for each ton MP; the biomethane-to-MP scenario requires for the production of one ton MP 5.6 tons of forage crops (see Table S4). These forage crops include a mixture of whole-plant silage crops like maize, alfalfa, clover, or rye grass, that are currently mainly cultivated for feed production. Forage crops include leguminous crops with the ability to fix nitrogen.

The replacement share in animal feed baskets

MP is a highly valuable feed ingredient that mainly replaces the protein part of the feed baskets. We therefore allowed the unrestricted replacement of oil crops and pulses. For oilcakes, we assumed that these processing by-products can only be substituted economically by MP where oilcake demand exceeds the amount of oilcake production as side-product from oil milling. As the food demand for oil remains price-inelastic, we thereby tend to underestimate the potential to substitute oilcakes by MP in feed baskets. MP is a limited substitute for the feed components that provide starch or fibres for digestibility. We therefore restrict the replacement of cereals in a way that the resulting share is still consistent with the highest regional estimate of the minimum percentage inclusion of feed ingredients in concentrates for dairy and beef cattle used by Herrero et al. (2013) [66]to harmonize their feed model with FAO commodity balance sheets. Following this conservative approach, we assumed that cereals exceeding 60% of the concentrates in the feed basket for poultry or 70% for other animals can be replaced by MP. Crop residues, forage crops, pasture, molasses and other feed items were assumed to be irreplaceable by MP. Finally, we additionally restricted the maximum share of feed basket replacement in each world region based on the literature survey (see supplementary information). We defined a conservative (low), a medium (default) and a more ambitious (high) level of replacement for MP in feed baskets that can be attained without decreasing animal productivity (see Table S1). These maximum replacement shares are 3% (low), 6% (default) and 12% (high) for poultry, and 4%, 8% and 15% for other animals. Actual replacement shares often remain below these maximum shares due to unreplaceable items in the feed baskets and outcompeting availability of oilcakes from oil milling (see Figure S11-S15). Substitution of feed was based on equal protein content. No productivity increases due to improved feed composition were considered.

Simulations within the context of three different socio-economic storylines for the general development of the agricultural sector which were based on the Shared Socio-economic Pathways (SSPs) SSP1, SSP2, and SSP5

SSP1 describes a world with green growth, dematerialized lifestyles, global cooperation and functioning institutions. SSP5 represents a world characterized by fossil-fuel driven growth and rapid technological progress, but material-intensive lifestyles. SSP2 is the “middle-of the road scenario”, which assumes largely a continuation of current trends. Relevant in the context of this study are the different assumptions with respect to the dietary developments in SSP1, SSP2 and SSP5, with much higher consumption of animal-based products and more household waste in SSP5. Both SSP1 and SSP5 project a rapid intensification of the livestock sector. Yet, while SSP1 mainly assumes a rapid improvement in feeding efficiency in developing countries, SSP5 also assumes continuous and fast intensification in developed regions. The employment of MP is consistent with the techno-optimistic storylines. Finally, while the nitrogen uptake efficiency in crop production is assumed to improve in all scenarios, the advances are highest in SSP1, reducing reactive nitrogen (Nr) losses to the environment.

In total this results in 48 scenarios (5x3x3 MP scenarios, plus 3 BASE scenarios (i.e. SSP 1,2 and 5 assuming no MP use), as summarized in the Supplementary Materials excel spreadsheet.

Results

Potential of MP as a protein source in animal diets

The three feed replacements rates for all major livestock categories (i.e. beef cattle, dairy cattle, pigs, broiler chickens and laying hen) were based on a detailed literature survey (Table S1). We determined besides a default, a high and low inclusion rate of MP that can be used as protein source without negative consequences on animal productivity and wellbeing (Table S1). Our assessment revealed that in many world regions the share of conventional protein concentrates in the animal feed baskets that could be replaced by MP is substantially lower than the potential concentrate feeding rates we found in the literature survey. This is because part of the proteins in the feed composition still contain protein-rich by-products like cake from oil production as we considered that those products would remain available on the market. MP shares, therefore, remain below 5% of dry matter for all livestock types in all world regions. Based on these values, our simulations indicated that globally between 175 – 307 Mton of MP could substitute concentrated protein feeds in the livestock sector (supplementary information, excel file), comprising only 2% (2 – 4%) of the total dry matter feed demand in 2050, but 13 (10–19%) on a protein basis because of the high protein-content of MP (supplementary excel spreadsheet).

Impact of inclusion of MP on cropland expansion, greenhouse gas emissions and nitrogen pollution

Remarkably, the small changes in livestock feed (, Figure S11-S15) have a substantial global environmental impact in most scenarios (Figure 2). For SSP2 with default protein replacement rates, the agriculture-free and climate independent production of MP would result in the largest decrease in global cropland expansion of 109 Mha (6%) until 2050 (Figure 2). This scenario would also lower the global reactive nitrogen losses (N_r) from croplands by 10 Mton N_r (8%), 5 Gt CO_2 equivalents in N_2O (4%) and 35 Gt CO_2 (28%) due to the decrease in emissions deriving from cumulated land use and land-use change (LULUC) in the period between 2005 and 2050. This production route would require 413 billion Nm^3 (316 – 542) of natural gas (i.e. ~12% (9 – 16%)) of the current global natural gas consumption), thereby reducing its viability as a long-term sustainable solution. In case hydrogen is generated through water electrolysis it would require 702 GW (537 – 911) of electricity, which equals to ~10% (7 – 12%) of the estimated combined installed solar and wind energy by the year 2050 (hiRen Scenarios of the International Energy Agency (IEA). [67, 68] This emphasizes the importance of investing in sustainable energy sources.

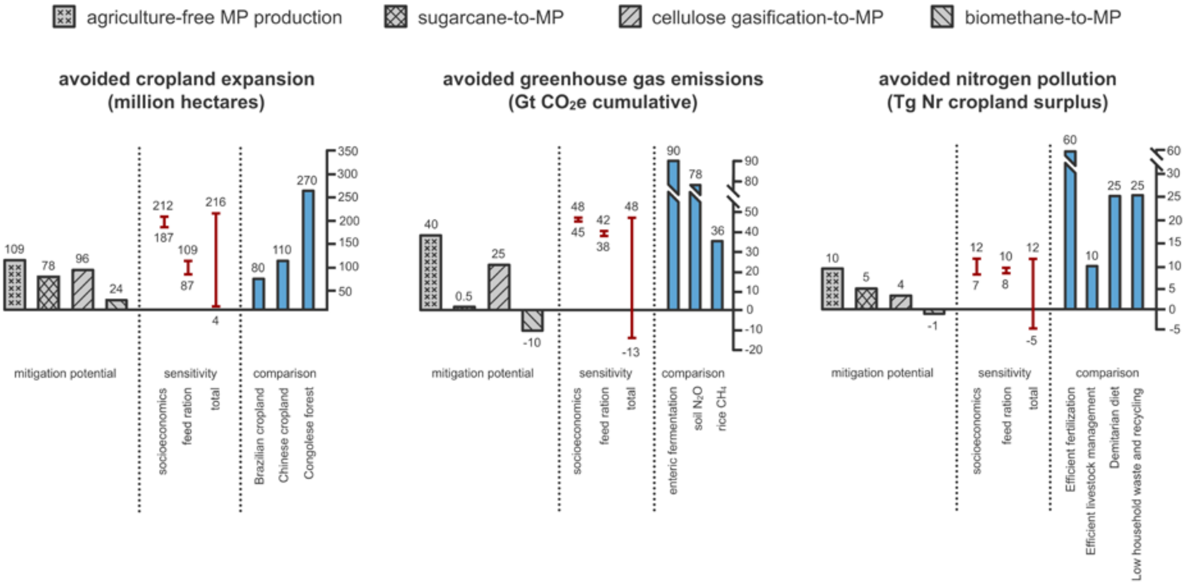

Figure 2: Feeding microbial protein (MP) to animals can substantially decrease global cropland expansion, greenhouse gas emissions and nitrogen pollution. Note that agriculture-free MP production scenario refers to both hydrogen-to-MP as well as natural gas-to-MP. The impact of agriculture-free microbial protein or upgrading agricultural substrates on global

(a) cropland expansion until 2050, (b) cumulative greenhouse gas emissions until 2050 and (c) nitrogen pollution in 2050 relative to the baseline scenario without MP. The sensitivity analysis varies the agriculture-free MP production scenario in respect to the socioeconomic scenario (SSP1, 2, 5) and low or high MP feed ratio (LF, HF). "Total" indicates the full range across the 48 simulated MP scenarios. For illustration of the order of magnitude of mitigation potentials, the figure also shows (i) land-areas (i.e. Brazilian and Chinese cropland and Congolese forest) [69], (ii) cumulative greenhouse gas emissions (expressed in Gt CO_2-equivalents) based on projections for annual emissions of enteric fermentation, soil N_2O and rice methane for the period 2000-2050) [70], and (iii) nitrogen mitigation potentials of improved nitrogen fertilizer efficiency, demitarian (low meat and household waste) diet, and reduced household waste and recycling. [12]

Natural gas or electricity needs are avoided when cellulosic bioenergy crops (2nd generation) are used as energy and carbon source via syngas, sugar or biogas (Figure 1). Our estimates indicate that for providing the same amount of MP based on these substrates for microbiological growth would require 1282 Mt of miscanthus, 1002 Mt of sugarcane or 1306 Mt of forage crops (see excel spreadsheet supplementary information). Using the global agro-food system model MAgPIE, we estimated that the mitigation potential in regard to land-expansion, nitrogen pollution and GHGs would be still less polluting in most scenarios (Figure 2). However, in particular for the production of MP out of biomethane from forage crops, also negative environmental impacts can occur in terms of GHG emissions and nitrogen pollution(Figure 2).

Partly replacing crop-based protein in animal feed by MP, as well as the substrate cultivation for MP production would restructure the agricultural supply chain and global nitrogen flows considerably, as illustrated in Figure 3 for the sugar-to-protein pathway in SSP2.

Here, global Haber-Bosch nitrogen fertilization would drop by 5 Mton Nr (4%). The quantity of harvested nitrogen from crops and crop residues would then drop by 25 Mton N_r (16%) and 3 Mton N_r (3%), respectively. In addition, by replacing large amounts of soybean by MP, the global biological fixation would also substantially decrease by 19 Mton (23%). Furthermore, substantial changes in the global use of phosphorus (another essential nutrient for crops used in large amounts) [71], fresh water for irrigation [72, 73] and the use of pesticides [74] can be expected, albeit not assessed in this study.

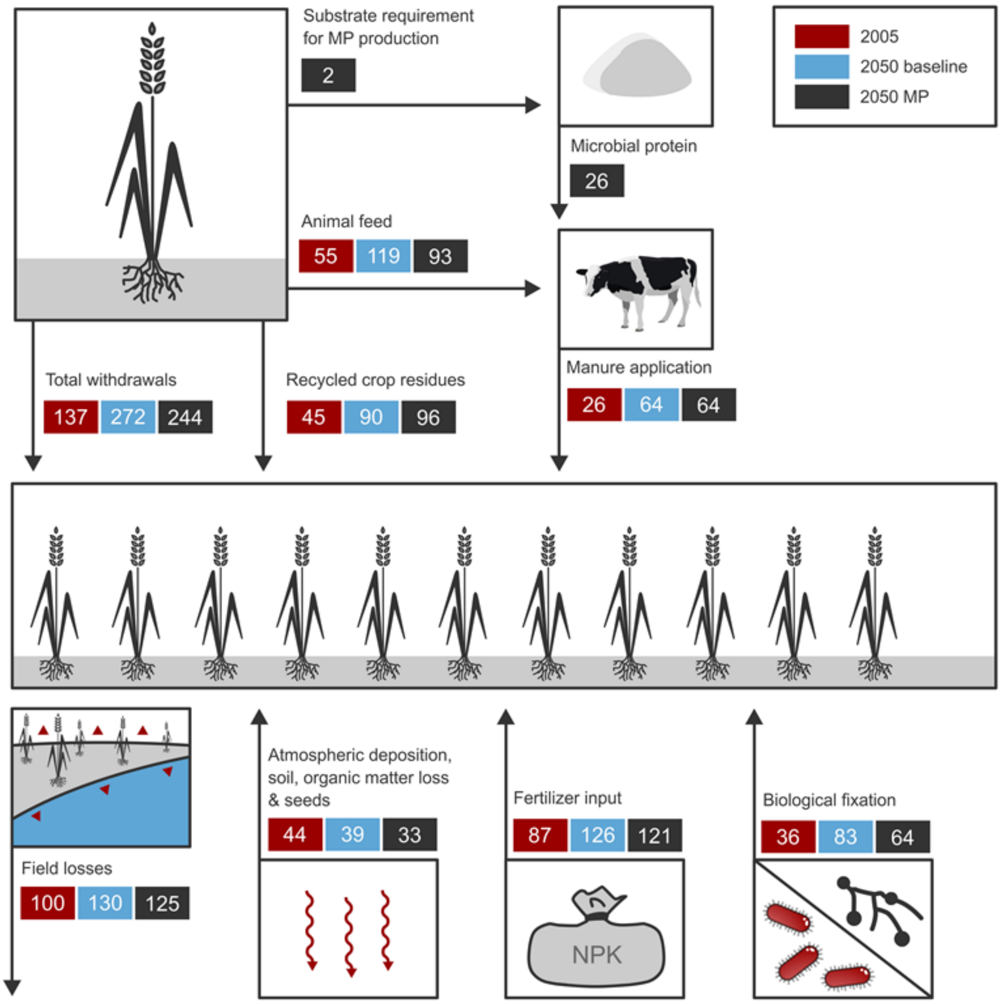

Figure 3: Global agricultural reactive nitrogen flow flows by the year 2050. The flows are based on the inclusion of MP as animal feed based on the sugar-to-protein pathway, default feed replacement rates and SSP2 (“middle-of-the-road”) scenario.

Discussion

Overall, our results show that production of MP can alleviate a set of critical limitations in the agricultural food supply chain by decoupling livestock production from land-based production of protein-rich animal feed. The large decrease in global cropland due to the use of MP results in less feed-food competition, or in other words more people can be fed from the same area of cropland. This can already be achieved with only minor changes to animal diets and based on feeding technologies ready for application already today.

Our model simulations may underestimate the actual transformational potential of MP for the agricultural sector. Most importantly, we assume that the production of oilcakes will not be influenced by the competition from MP, as oilcakes are anyway produced as by-product of oil milling. In reality, falling oilcake prices through MP competition may drive up prices for oils and lead to falling oil and oil cake production. Given the rather low price-elasticity of soybean oil, effects would probably not be large; however, a switch from oils with high quantity of by-products (e.g. soy) to oils with few by-products (e.g. oil palms) may be a possible consequence of MP market entrance. Moreover, we assume that the inclusion of MP does not affect livestock productivity. In reality, a balanced and customizable amino acid composition and digestibility of MP could have positive effects in relation to animal growth performance, digestibility of amino acids, sensory quality of meat, dry matter intake and digestibility, milk production and quality and feed conversion efficiency. Finally, beyond the use of MP for feed, the use of MP for food products would increase the efficiency of the food supply chain even further, in particular if animal products would be substituted [19] . The potential of MP for food so far remains speculative. In contrast to the feed market, where feed composition is today based on efficiency criteria, food markets are governed by complex consumer preferences and tastes. So far, MP as food is only used in niche markets [27] and it remains questionable whether MP will be used in more widespread formulations in the future.

On the other side our study may overestimate actual adoption rates. Even under economic profitability, the adoption of new technologies often faces other constraints such as cultural factors in farm management, risk-aversion towards new technologies, lacking market access or inactive market incentives due to regulation of markets.

Clearly, our findings also highlight the fact that widespread adoption of MP as a "stand-alone" solution will not be sufficient for sustainable land-use futures and, depending on the MP production pathway, could even result in an increase in reactive nitrogen pollution and greenhouse gas emissions. In order to reduce the environmental impact of the food supply chain, it will also require improvements in current livestock and manure management, fertilization practices and changes in human dietary patterns. [12, 75] Also, further structural changes in the food system can be foreseen, like the use of insects, microalgae, seaweed, or technologies to increase feed digestibility (e.g. by the use of fungus). [75, 76] Moreover, recent studies emphasize that the role of livestock in sustainable diets lies in its capacity to convert leftover streams (e.g. co-products from the food industry, food residues, food waste, and biomass from marginal lands) - products that we cannot or do not want to eat - to high quality food products (e.g. beef, milk, or eggs). [75, 77-80] The development of technologies that can effectively recover used reactive nitrogen [28] and organics embedded in these leftover streams [81] as substrates for MP production are essential to further reduce the environmental impact and creating a more sustainable and cyclic use of nutrient resources. Ultimately, all the above are needed to ensure feeding future generations with high-quality proteins in a sustainable way.

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