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Implication of imposing fertilizer limitations on energy, agriculture, and land systems

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ABSTRACT

Since the 1950's, global fertilizer usage has increased by more than 800% resulting in detrimental impacts to the environment. The projected increase in crop production due to increasing demands for food, feed, biofuel, and other uses, may further increase fertilizer usage. Studies have examined achieving agricultural intensification in environmentally sustainable ways, however, they have not focused on the whole-system economic aspects of changes in fertilizer usage over the long term. We utilize the Global Change Analysis Model (GCAM) to explore the impact of reducing global fertilizer usage on land use change, agricultural commodity price and production, energy production, and greenhouse gas emissions. We find that constrained fertilizer availability results in reduced global cropland area, particularly land used for bioenergy production, and expanded forested area. These results are driven by price impacts which lead to shifts in agricultural production between commodity types, regions, and technologies, and which lead to decreased agricultural commodity demands.

1. Introduction

From the 1960's to 2015 the global population increased from 3 to 7.3 billion persons (WorldBank, 2019). This increase in population in conjunction with increase in per capita food demand (32% increase from 1960 to 2015 (FAO, 2020)) has resulted in the need for increased crop production (Foley et al., 2005). The increased crop production was achieved by expansion in cropland area and yield increase, often called the "*Green Revolution*," which includes various technological advances such as increased fertilizer application, pesticide use, irrigation, and utilization of high-yielding crops (Foley et al., 2005). The global cropland area has increased by 15% from 1961 to 2015 (FAO, 2019) while synthetic nitrogen fertilizer use has increased by more than 800% during this period (Roser and Ritchie, 2019).

The expansion of cropland in conjunction with the "*Green Revolution*" has contributed to a tripling of world grain production between 1961 and 2015 (USDA, 2019), but has also led to detrimental environmental impacts. Specifically, there have been increases in land-use-related greenhouse gas emissions (Wise et al., 2009), modifications of the hydrologic cycle (Foley et al., 2005), declines in biodiversity and species extinction (Cardinale et al., 2012), soil erosion (Borrelli et al., 2017), and water quality impairment (Diaz and Rosenberg, 2008; Foley et al., 2005; Power, 2010).

The more than eight-fold increase in fertilizer usage that has occurred since 1961 has tremendously benefitted humanity by increasing agricultural production and feeding the world's growing population (Erisman et al., 2008). However, approximately half of the reactive nitrogen in applied fertilizers is lost to the atmosphere as nitrogen oxide [NO_x], ammonia [NH_3], nitrous oxide [N_2O], and nitrogen [N_2] gas or lost to the ground or surface water as nitrate [NO_3^-] (Galloway et al., 2003, 2004). Out of the reactive nitrogen fraction that is lost, approximately 45% of is lost to the atmosphere and 55% is lost to the ground or surface water (Ciais et al., 2013). All of the lost nitrogen forms except for the N_2 gas are reactive forms of nitrogen, which have detrimental impacts on the environment along with contributing to human-induced climate change. The NO_x and NH_3 emissions contribute

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to the formation of ozone and aerosols in the troposphere. When these two forms are deposited on Earth via rainfall, they along with NO_3^- contribute to acidification of soil and water bodies and formation of eutrophic conditions in streams, lakes, and rivers. N_2O gas is a potent greenhouse gas with a residence time of approximately 100 years in the troposphere (Galloway et al., 2003, 2008).

The demand for crop commodities could further increase in the future due to projected changes in population, income, diet, and bioenergy production. However, there is large uncertainty in projections of these demographic and lifestyle elements. For instance, the Shared Socioeconomic Pathways (SSPs) quantify a range of scenarios wherein, by the end of the century, future population spans a range from 7 billion to 12.6 billion (KC & Lutz, 2017); global average per-capita income varies by a factor of more than six (Dellink et al., 2017); and future diet ranges from mostly plant-based with low waste in the food system, to meat-intensive diets with high system-wide food waste (Popp et al., 2017). These scenarios project 49%–117% increase in crop commodity demands in 2100 compared to 2005 (Popp et al., 2017). Bioenergy demand is also projected to increase in the future with an even larger range of possible outcomes depending on the specific scenario and end-of-the-century radiative forcing target (Popp et al., 2017).

These increased demands for crop production are likely to require expansion of agricultural land as well as increased fertilizer usage. Analogous to future crop supply and demand, there is huge uncertainty in future fertilizer usage depending on population, dietary habits, technological advances, food trade, and bioenergy demand. For instance, across the five different SSPs, the IMAGE model estimates that fertilizer usage will range from 85 to 260 TgN yr^{-1} by 2050 (Mogollón et al., 2018). As well, the Land Use Harmonization (LUH2) database projects future fertilizer usage to range from 121 to 167 TgN yr^{-1} by 2050 and 101 to 240 TgN yr^{-1} by 2100 (Chini et al., 2020).

Fertilizers are required for future crop production; however, the negative externalities of fertilizer usage implies that there is significant value in meeting the crop production requirements of the future while limiting increase in fertilizer usage. For example (Tilman et al., 2011), have shown that if the projected increase in crop production by 2050 is achieved via agricultural intensification it can result in substantial reduction in land clearing, greenhouse gas emissions, and nitrogen use. Similarly (Zhang et al., 2015), found that increasing global nitrogen use efficiency (NUE) from 0.4 to 0.7, with the largest regional gains in NUE in China and India, would make it possible to meet the future food demand in an environmentally sustainable way. Field based experiments in China by (Chen et al., 2011, 2014) have shown that substantial increase in yield can be achieved without increasing fertilizer usage by utilizing advanced cropping system and efficiently managing fertilizer application. These prior studies have examined the effect of farming practices on reducing fertilizer usage, however studies have not examined how reduced fertilizer usage will impact the increased demand for agricultural production until the end of the century. Additionally, the impact of limiting fertilizer usage on energy production and greenhouse gas emissions has also not been studied.

Here, we examine the impact of reducing fertilizer usage on land use change, food security, energy production, and greenhouse gas emissions. The reduction in fertilizer usage will limit its loss to the ecosystem and thereby reduce the harmful impacts on the environment. We developed two scenarios to study the impact of constraining fertilizer usage on energy, agriculture, and land systems. In addition, we also tested two scenarios with increased bioenergy production to show their impact on fertilizer usage.

2. Material and methods

2.1. Global Change Analysis Model (GCAM)

To study the impact of reduction in fertilizer usage on land use change, agricultural productivity, energy production, and greenhouse gas emissions we utilized the Global Change Analysis Model (GCAM). GCAM (Calvin et al., 2019) is an integrated human and Earth system model that links representations of energy, water, land, climate, and economy at global and regional scales. Other integrated assessment models exist that are utilized for studying the impact of land use and land cover change. For e.g., ReMIND/MAgPIE (Kriegler et al., 2017), IMAGE (Stehfest et al., 2014), AIM/CGE (Fujimori et al., 2017), and MESSAGE-GLOBIOM (Fricko et al., 2017). These models differ in their structural representation and parameterization of various biogeophysical and biophysical process. Comparison of GCAM and other similar models is provided in several recent publications (Bauer et al., 2020; Popp et al., 2017; Rao et al., 2017).

GCAM divides the world into 32 geopolitical regions for the energy and economic systems and uses a finer resolution for the land and water systems, described below. GCAM operates at 5-year time steps from 2010 to 2100. Various assumptions about future demographics, economy, lifestyle choices, technological advances, and resources are utilized for running GCAM from 2010 to 2100. These assumptions are described in the scenarios section.

GCAM is a dynamic recursive model in which decisions are made based on the currently available information and the future is unknown. After solving for each time step the resulting state of the world is utilized for solving the next time step.

GCAM utilizes the market equilibrium approach for allocating resources. This approach solves for prices such that supplies match demands for all markets. Supply and demand for all markets are price responsive (i.e., an increase in price will increase supply but decrease demand), with different price elasticities depending on the sector and time period. The different sectors and fuels are linked, such that an increase in cost in one may alter the demand for another. For example, fertilizer cost and production is affected by the cost of natural gas. We refer to previous publications for details of GCAM's approach for modeling land use (Calvin et al., 2019; Wise et al., 2014) and the energy system (Calvin et al., 2019; Clarke et al., 2007; Kim et al., 2006). Hindcast experiments have been utilized to evaluate GCAM model's agriculture and land use modules (Calvin et al., 2017; Snyder et al., 2017).

For representing land allocation and agricultural production, GCAM divides the world into 384 land use regions, based on the intersection of 32 geopolitical regions and 235 water basins. Each land use region is sub-divided into various land use and land cover types, including natural vegetation types and commercial uses such as agriculture and forestry. Historical land allocations are calibrated, and future changes to these allocations are driven by changes in relative profitability of the different land uses over time (Calvin et al., 2019; Wise et al., 2009, 2014). Agricultural crop production is modeled for 15 different commodity classes that are constructed by aggregating the 175 crop commodities reported by FAO. For each GCAM commodity within each land use region, four different crop production technologies are available: irrigated/high-yield, irrigated/low-yield, rain-fed/high-yield, and rain-fed/low-yield (Calvin et al., 2019). Each crop technology is assigned future yield improvement rates based on FAO's projections by country, crop, and irrigation level (Bruinsma, 2009).

In this representation of crop production, within each nest (i.e., land use region, crop, and irrigation level), the low- and high-yield technologies are assigned yields 10% below and 10% above the baseline crop yield for the given nest, respectively (Fig. 1). The baseline crop yield is estimated based on FAO projections. This allows the yields within the nest to be endogenous in future time periods, responsive to changes in relative profitability. In order to have consistency between these endogenous changes in yields and the fertilizer requirements thereof, for this study we incorporate newly developed country- and crop-specific nitrogen-yield response functions from Vishwakarma et al. (2021). These asymptotic nitrogen-yield response functions describe the yield change per increase or decrease in N fertilizer application rates, from a provided starting point. Thus, for a crop and land use region that is in the

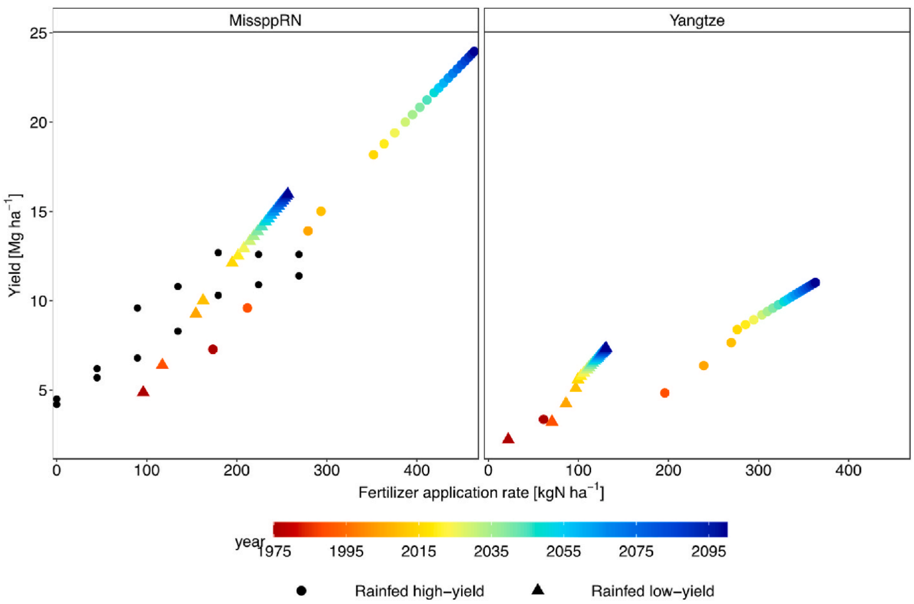

Fig. 1. Yield vs. nitrogen fertilizer usage for the high-yield (circles) and low-yield (triangles) technologies for corn production in the Mississippi River basin in USA and the Yangtze River basin in China for the reference scenario. The yield-response curves for the two regions are different because the fertilizer input-output coefficients vary by crop and land use region. The black dots are yield vs. fertilizer application rate based on field study conducted by Sawyer and Barker (2014) on the Northeast Research Farm in Nashua, Iowa.

flat part of the yield-response function—i.e., where little yield change occurs per change in N application rates—comparatively large changes in the fertilizer application rates are required per change in yield than a similar observation in the steeper part of the curve.

GCAM also estimates emissions of CO_2 and other species from land use change, fossil fuel consumption, and industrial processes.

2.2. Scenarios

The GCAM scenarios developed to study the impact of lowering fertilizer usage on land use and land cover, agricultural production, food prices, energy production, and greenhouse gas emissions are based on a reference scenario that implements the SSP2 storyline (O'Neill et al., 2017). In this study, the SSP2 pathway reaches a total radiative forcing of 6.2 W m^{-2} by 2100. In SSP2 the technological growth continues the trends from the historical period. In this reference scenario both projected population and gross domestic product (GDP) fall in the middle of the range of projections for the five SSPs. The population grows to 9.4 billion by 2070 followed by a decline to 9 billion by 2100 (KC & Lutz, 2017). The gross domestic product (GDP) grows by a factor of 5 from 2015 to 2100 (Dellink et al., 2017). The energy consumption more than doubles between 2015 and 2100 and by the end of the century 8% of it is produced from biomass. The cropland area increases by 11% by 2065 followed by a decline till the end-of-the-century. Conversely the forested area decreases by approximately 3% from 2015 to 2100. Globally, fertilizer consumption increases by approximately 40% between 2015 and 2065 followed by a decline, resulting in 30% increase from 2015 to 2100.

Table 1
Fertilizer constraint scenarios.

Scenario	Fertilizer constraint	Carbon price
Reference	None	None
Global constraint (15%) on fertilizer	15% globally	None
Low carbon	None	Carbon price starting at \$10/tC O_2 (in \$2010) in 2025 and increasing by 5% per year
Low carbon with global constraint (15%)	15% globally	Carbon price starting at \$10/tC O_2 (in \$2010) in 2025 and increasing by 5% per year

Four different scenarios were implemented for studying the impact of reducing fertilizer usage (see Table 1). The first scenario is the SSP2 baseline scenario described above. The second scenario implements a global fertilizer constraint, achieved by an endogenous fertilizer tax, at a level that is 15% less than the maximum observed global fertilizer consumption in any year in the baseline scenario. The exact reduction amount targeted here is somewhat arbitrary, but the qualitative results would hold for other levels of reduction. Additionally, prior studies have shown that improving the nitrogen use efficiency results in 8% reduction in global nitrogen inputs (Galloway et al., 2008; Zhang et al., 2015), while utilization of advanced cropping and nutrient management approach for select crops in China results in 33% less fertilizer requirement (Chen et al., 2014). Here, we take a middle of the road approach and test the impact of 15% reduction in global fertilizer usage, implemented as a global constraint achieved by an endogenous fertilizer tax. In years where the constraint is not binding, no such tax is applied, and the model behavior is generally similar to that of baseline scenario.

The third scenario referred to as the low carbon scenario includes increased bioenergy production, achieved by placing a value on carbon emissions from fossil fuel and industrial emissions. The low carbon scenario applies a carbon price of \$10/tCO_2 (in \$2010) on fossil fuel and industrial carbon emissions, starting in the year 2025 and increasing by 5% per year for all future years. The price on carbon results in a price on fossil fuel emissions that in turn results in reduced fossil fuel consumption and increased energy generation from alternative sources with lower emissions, such as bioenergy.

The fourth scenario combines the 15% global fertilizer constraint with increased bioenergy production, effectively combining the second and third scenarios.

We also developed regional fertilizer constraint scenarios to understand the impacts in select regions as well as the mechanism driving the impacts. These regional scenarios applied constraints on fertilizer consumption in three countries that are the largest consumers of fertilizer, namely China, India, and the USA.

3. Results

3.1. Land-use change

We find that constraining fertilizer usage results in reduction in land used for agricultural production. This occurs because constraining fertilizer usage (Fig. S1A) in GCAM through the imposition of a tax on fertilizer increases fertilizer prices (Fig. S1 B), which leads to two primary responses with different implications for land use. First, the increased fertilizer price leads to higher prices of all agricultural commodities. The price increase results in decreased bioenergy crop production that is replaced by other competing fuels. The use of crops for animal feed and biofuel production also declines, and is substituted by non-crop sources (e.g., grasses, wild forage) in the case of animal feed, and fossil fuels for energy production in the case of bioenergy. Thus, the result of these price increases is a reduction in total crop commodity demands, which reduces total cropland area. Second, in response to the fertilizer price increases, crop production shifts towards technologies and regions with lower yields and lower fertilizer requirements per unit crop production, effectively substituting land for fertilizer. In isolation, this response tends to increase the total land under cultivation. However, agricultural commodity price increases leads to agricultural intensification, an effect known as yield-price elasticity (Taheripour et al., 2017), counter-acting the second mechanism. The scenarios in this study find that the net effect is that the fertilizer constraint scenario observes a significant reduction in land used for agricultural production, primarily driven by a reduction in land used for bioenergy production and for producing animal feed, and conversely there is a corresponding increase in forested land. For the fertilizer constraint scenario, the land used for bioenergy production reduces by 5.6% by 2100 compared to the reference scenario, and total cropland area reduces by 0.1% by 2100 (Fig. 2A). The observed reduction in land is larger for bioenergy production than for other crops due to its price elasticities of demand throughout the energy system, where substitute fuels are available.

We find that the direction and mechanisms of change in the regional fertilizer constraint scenarios are similar to the global constraint scenario with the majority of the land impact being observed in the three regions (i.e., China, India, and the USA) with the fertilizer constraint (figures not shown).

The combined impact of constraining fertilizer usage (Fig. S1A) and resulting reduction in agricultural land area (Fig. S1C) results in reduction of fertilizer usage per unit area (i.e., fertilizer use intensity) (Fig. S1D). In this work, we focus on the impacts of constraining fertilizer usage on changes in land use, food security, energy, and emissions.

At the commodity level, production of corn and sugar crops is reduced while production of oil crops increases (Fig. 3). The largest reduction in corn occurs in the USA, Brazil, and China (Fig. S2) while the largest reduction in sugar crops occurs in Brazil (Fig. S2). The shift from corn and sugar crops to oil crops is driven by price elasticities of demand, and by nitrogen requirements of various crops. Corn and sugar crops have high price elasticities (Calvin et al., 2019), as a large portion of each is used for animal feed, biofuel feedstocks, or both; these uses have readily available non-crop substitutes (e.g., grass in pastures, or crude oil derived fuels, respectively). This allows for reduction in corn and sugar crops demands in response to increased production costs. This reduction in production significantly impacts animal feed consumption and bioenergy production, whereas the food and other demands remain generally unaffected. In contrast, oil crops are comprised largely of nitrogen-fixing plants (primarily soybean; also peanut); their relatively low fertilizer use intensity makes them more suitable for production under the fertilizer constraint scenario. As an example, for the USA, the global fertilizer constraint scenario results in a reduction in corn being used for animal feed consumption (Fig. S3 A) and ethanol production (Fig. S3 B). The quantity of corn used for food and non-food (includes industrial processing, seed etc.) is not impacted (Fig. S3 C and D). This results in reduction in cropland area for corn (Fig. S4 D). Furthermore, overall animal feed consumption of feed crops declines (Fig. S3 E), and is substituted by dedicated fodder crops (e.g., alfalfa) and grasses which have minimal synthetic nitrogen requirements (Fig. S3 F and G). Overall, these changes result in a net reduction in total cropland area (Fig. S3 H). Additional sensitivity analysis to explore the impact of animal feed source substitution on cropland reduction found our findings to be robust across parameters controlling livestock and animal feed source replacement. The sensitivity analysis is described in more detail in the Supplementary Material.

Agricultural production also shifts at large-scale between regions in response to constrained fertilizer; crop production shifts from regions with higher fertilizer usage per unit cropland area (i.e., fertilizer use intensity) to regions with lower fertilizer use intensity. For example, rice production shifts from China, India, and South Asia to regions in Africa and Southeast Asia which results in reduced global average fertilizer use intensity for rice production (Fig. 4). The amount of rice production that shifts to low fertilizer use intensity, however, is marginal compared to the global rice production (Fig. 4). Such a regional shift in production and fertilizer usage will also increase global nitrogen use efficiency and reduce nitrogen lost to the environment (Mueller et al., 2017; Zhang, 2017). In this study, technological advancements to cropping and nutrient management that could improve fertilizer use intensity within land use regions and crop types are not explicitly considered; such

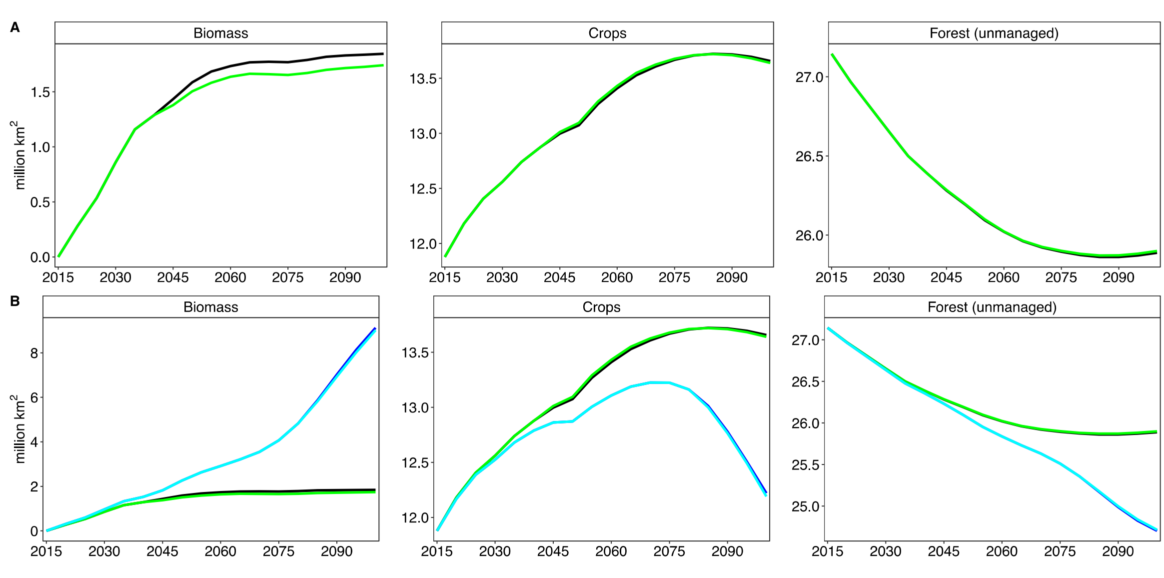

Fig. 2. Global land cover for (A) biomass grass, crops, and forest across the reference, global constraint (15%) on fertilizer scenarios and (B) for all four scenarios.

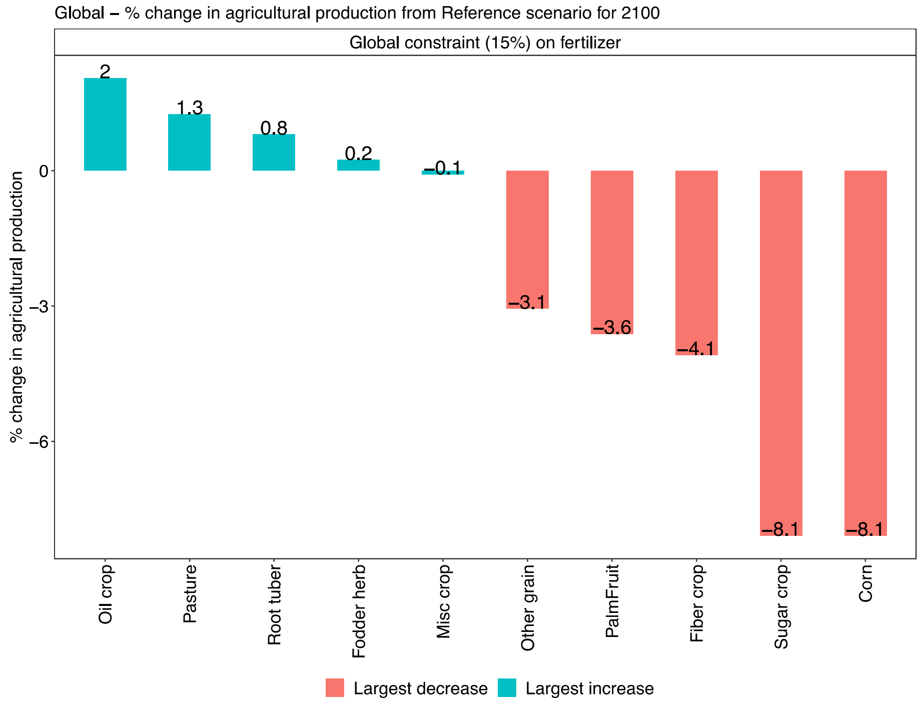

Fig. 3. Percentage change in agricultural production for various agricultural commodities by 2100 for the global constraint (15%) on fertilizer scenario compared to the reference scenario.

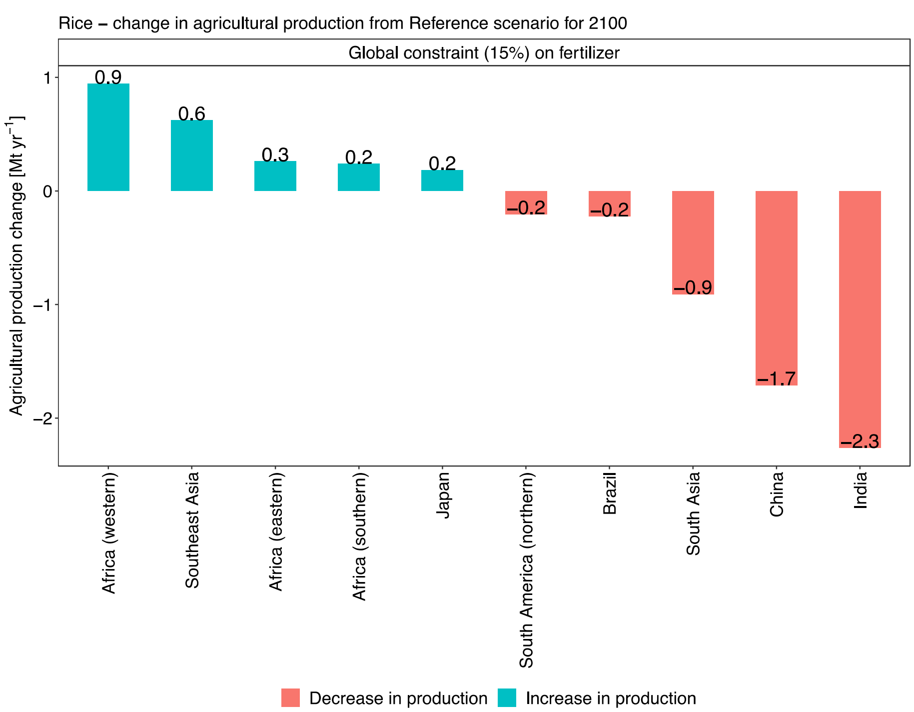

Fig. 4. Change in rice production by various regions by 2100 for the global constraint (15%) on fertilizer scenario compared to the reference scenario.

advancements may make it feasible to sustain or enhance current yield while lowering fertilizer use intensity, and thus limit the scale of inter-regional shifting in agricultural production seen in these scenarios. For example, field-based studies in China, utilizing integrated soil-crop system management (ISSM) approach (Chen et al., 2011), have shown that yield can be increased without increasing fertilizer application by utilizing advanced cropping system and fertilizer management that balance nitrogen inputs and outputs and apply fertilizer in various doses to match different stages of plant growth (Chen et al., 2011, 2014). Chen et al. (2014) estimate that by utilizing ISSM approach, China's projected demand for rice, wheat, and corn by 2030 can be achieved with 33% less fertilizer usage and 22% less cropland area compared to 2012. The reduction in fertilizer usage and cropland area will, however, vary by region and crop type. Regions with large nutrient imbalances (Vitousek et al., 2009) have higher potential for achieving fertilizer reduction without impacting yield.

The fertilizer constraint scenarios also see a technological response within land use regions, crop types, and irrigation levels, which influences the average fertilizer intensity and yields; such responses are driven by two countervailing effects. First, due to its relatively high fertilizer intensity, the production cost of the representative high-yield technology increases more than that of the low-yield technology, which results in a reduction in production from the high-yield technology and an increase in production from the low-yield technology (Fig. S4 A and B). Second, the increase in fertilizer price increases crop production costs and therefore increases crop commodity prices, which makes the high-yield production technology relatively more profitable. These two mechanisms counteract each other in terms of their net effects on average fertilizer intensities and yields. Nevertheless, the net result is an increase in crop prices (Fig. S4 C), which drive a reduction in crop demand, and reduction in cropland area (Fig. S4 D).

The global fertilizer constraint scenario results in a potential nitrogen fertilizer reduction of 22 TgN yr^{-1} (teragrams nitrogen) in 2100, and a cumulative decrease of 268 TgN yr^{-1} between 2020 and 2100 compared to the reference scenario (Fig. S6). This reduction will offset some of the fertilizer nitrogen that is lost to the ecosystem and thereby limit the detrimental impact on the environment, such as the increased production of aerosols and ozone in the troposphere, the acidification of water bodies, and formation of eutrophic conditions in terrestrial and aquatic ecosystems. The reduction in nitrogen loss amount will vary by region and will depend on factors such as nutrient management strategy, crop type, and climatic conditions.

The low carbon scenario is implemented with prices on carbon emissions from the energy system. The increase in bioenergy production from biomass grass (Fig. 2B) results in 36% more global fertilizer usage by the end-of-the-century compared to the reference scenario (Fig. S6). This result highlights trade-offs between mitigating climate change using bioenergy and environmental degradation. Climate change mitigation achieved by increased bioenergy production can have unintended consequences in terms of increased fertilizer usage and its harmful impact on ecosystems. However, field scale studies have shown that second generation bioenergy crops can be grown with minimal fertilizer application (Zeri et al., 2011), which will likely reduce the negative impacts of increased fertilizer usage. The bioenergy fertilizer input-output coefficients used in this study are based on Adler et al. (2007).

Constraining global fertilizer usage in conjunction with low carbon production results in reduced fertilizer usage compared to the scenario with low carbon only (Fig. S6) with marginal reduction in biomass consumption and energy production from it. However, the costs of food crops (Fig. S7) and fertilizer increase sharply in this scenario. Thus, achieving climate mitigation using bioenergy in conjunction with reduced fertilizer usage will amplify the food price impacts of climate change mitigation policy documented elsewhere (Fujimori et al., 2019; Hasegawa et al., 2018).

3.2. Food security

Constraining fertilizer usage results in higher price for food (Fig. S4 C and 7), minimal impact on food consumption, and a shift in food trade patterns. The lack of impact on food consumption (Fig. S3 C) is due to the assumed low price elasticity of food demand in GCAM. An example of shift in trade patterns is the increased cost of rice production in China noted above (Fig. 5) driving a reduction in the export of rice (Fig. S5) and an increase in its import (Fig. S5). While trade responses to relative price changes are seen in all regions, the traded volumes of rice in both China and India, however, are especially small, less than 1% of total production. This is because these regions are mostly self-sufficient for rice in the base-year, and this preference is carried into the future in GCAM through calibrated logit choice functions. This limited ability to change trade patterns for this commodity and in these regions means that the consumer food prices are generally tied to the local production costs. For this reason, in the regional fertilizer constraint scenarios, these regions will experience comparatively greater price shocks than a similar constraint in a region such as the United States, which tends to substitute imported rice in response to local producer price increases (Fig. 5).

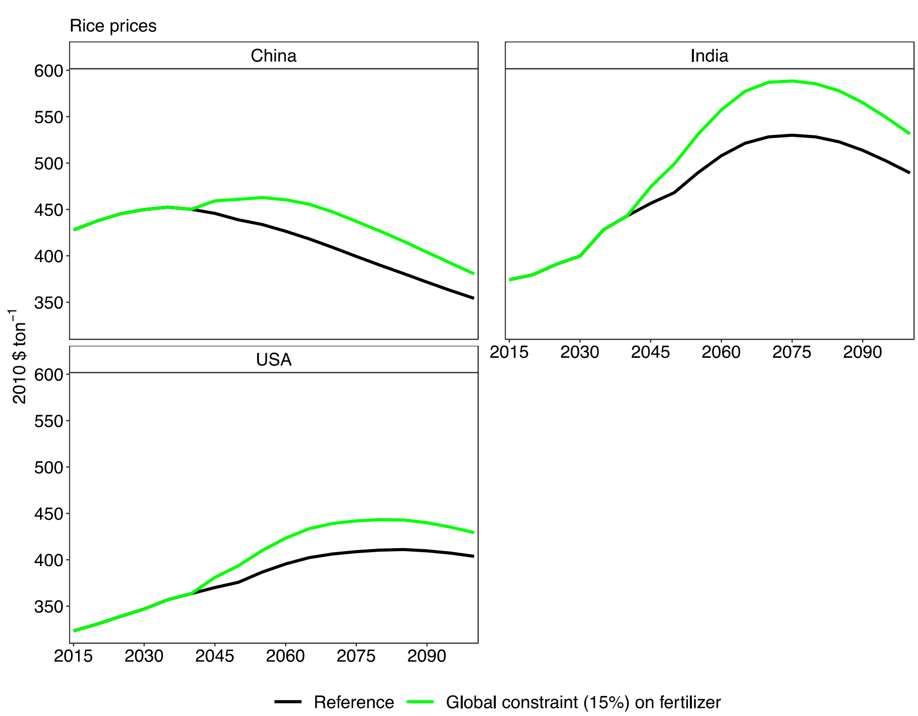

Fig. 5. Projected price of rice for China, India, and USA for the reference and global constraint (15%) on fertilizer scenarios.

3.3. Energy change

Constraining fertilizer usage impacts the energy sector as well and marginally lowers primary energy consumption. The reduction in energy consumption is driven by increased price of biomass energy, reduced natural gas requirements for fertilizer production, and substitution of biomass energy with competing fuels with higher energy efficiencies. For the global fertilizer constraint scenario, the price of biomass energy increases by 2% by 2100 compared to the reference scenario (Fig. S8 A, B, and C) while global natural gas consumption for fertilizer production reduces by 14% by 2100 (Fig. S8 D). The increase in biomass price and agricultural production costs results in energy consumption shifting from bioenergy (Fig. S8 E and F) to oil, natural gas, and coal (Fig. S8 G, H, and I). This shift in energy consumption, however, is small in magnitude compared to the total consumption resulting in marginal shifts in energy consumption including biomass decreasing by 4%, oil increasing by 0.7%, and coal increasing by 0.4% by 2100. The net result is a marginal decrease in global primary energy consumption (0.1% by 2100) for the global fertilizer constraint scenario. Conversely, the low carbon scenario results in large increase in energy produced from biomass and reduction in energy produced from coal, gas, and refined liquids (figure not shown).

3.4. Emission change

Restricting fertilizer consumption results in minimal changes in CO_2 emissions from fossil fuel, industrial, and land use change. For the global fertilizer constraint scenario, the nominal shift in energy production sources as described above result in marginal increase in CO_2 emissions. Overall, the fossil fuel and industrial CO_2 emission increase by 0.4% by 2100 compared to the reference scenario (Fig. S9) while the change in land use change CO_2 emissions is negligible (Fig. S10). On the contrary, and consistent with previous findings, the scenario with carbon emissions pricing results in vast reduction in CO_2 emissions from fossil fuel and industry (Fig. S9), and large increases in land use change emissions due to bioenergy production (Fig. S10).

3.5. Study limitations

This study demonstrates the impact of constraining fertilizer usage on land use change, food security, energy production, and CO_2 emissions. However, there are several limitations of our study. First, the results in this study depend in part on the underlying assumptions about future societal development, and technological progress. These underlying assumptions will strongly influence future land use change, agricultural production, energy production, fertilizer consumption, and greenhouse gas emissions. As such, changing to a different socioeconomic or policy backdrop will change the quantitative results from what is shown in this study, but the basic mechanisms described that are responsible for the results will not.

Second, the results of this study are based on the GCAM model and its underlying assumptions and parameterization. For example, in response to crop supply shocks, GCAM tends to have muted food demand responses compared with other agro-economic models (von Lampe et al., 2014). Future studies should consider using multiple models to account for structural uncertainty and capture the range of possible outcomes arising from this uncertainty.

Third, nitrogen inputs to agricultural fields via manure application (Potter et al., 2010), agricultural crop residue (Turmel et al., 2015), or legume cycling (Miller et al., 2002) are not considered. Fourth, technological options to implement efficient nutrient management and improve NUE are not considered.

Thus, future research is needed that includes nitrogen inputs to cropland from all sources for quantifying the impacts of fertilizer constraints on land use change and agricultural production. In spite of its limitations, the study sheds light on the potential trade-offs resulting from constraining fertilizer usage that haven't been otherwise documented, and that wouldn't be available from more bottom-up approaches.

4. Conclusions

In this study we examine the impact of limiting fertilizer usage on land use change, among other things, and find that constraining fertilizer usage results in increased forested area and reduced land used for crop production, due to price-induced reductions in demands for agricultural commodities. In response to reduced fertilizer usage, corn and sugar crops produced for animal feed and ethanol feedstocks decrease, while oil crops, mostly soybeans, increase. However, demand for food is not impacted in these scenarios due to its comparatively low price elasticities although the cost of food production increases. Agricultural production shifts from regions with high fertilizer use intensity to those with low fertilizer use intensity, which in turn alters international trade patterns accordingly. Restricting fertilizer usage results in minimal decrease in primary energy consumption that results from decline in biomass energy consumption and causes slight increase in emissions.

In summary, constraining fertilizer usage results in trade-offs between improvements to ecosystems in the form of increased forested area and reduction in cropland area and nitrogen application, but with increased cost of food production and slight increase in emissions. Yet another trade-off is shifting of agricultural production away from fertilizer-intensive regions and technologies, which lowers the average fertilizer use intensity, by effectively substituting cropland for fertilizer as an input to production. This work also highlights trade-offs of climate mitigation using bioenergy that results in reduction in carbon emissions but with large increases in fertilizer usage and its consequent impacts on natural ecosystems.

Author statement

Eva Sinha: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft preparation, Writing – review & editing. **Katherine V. Calvin**: Conceptualization, Supervision, Writing – review & editing. **Page G. Kyle**: Methodology, Supervision, Writing – review & editing. **Mohamad I. Hejazi**: Supervision, Writing – review & editing. **Stephanie T. Waldhoff**: Supervision, Writing – review & editing. **Maoyi Huang**: Conceptualization, Supervision, Writing – review & editing. **Srishti Vishwakarma**: Resources, Writing – review & editing. **Xin Zhang**: Resources, Writing – review & editing

Code availability

GCAM is an open source model. The version of GCAM described in this paper is archived on GitHub (https://github.com/JGCRI/gcam-core). A user guide for GCAM is available at http://jgcri.github.io/gcam-doc/user-guide.html.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.114391.

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