# Core Model Proposal #389: Ammonia Trade and Miscellaneous GCAM 7.0 Bugfixes

**Product:** Global Change Analysis Model (GCAM)

**Institution:** Joint Global Change Research Institute (JGCRI)

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**Related sector:** energy

**Type of development:** data, code, queries

**Purpose:** This proposal re-structures the N fertilizer sector in the model, replacing the trade structure which was implemented before GCAM had the capability to trade secondary goods between regions, and re-naming the production commodity "ammonia" in order to better set up the model for representing ammonia as an energy carrier in subsequent work. Several bugfixes for GCAM 7.0 are also included in the proposal.

# Description of Changes

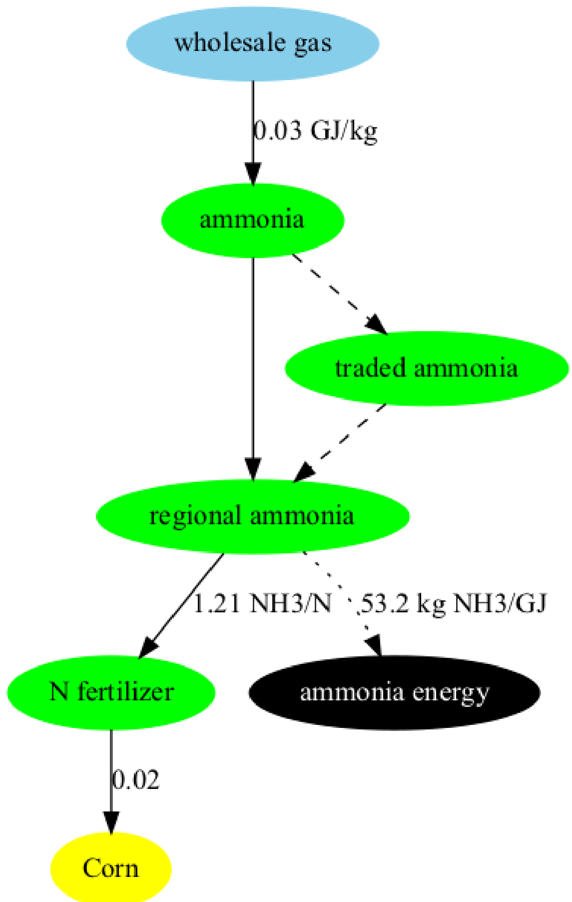
## Ammonia Production and Trade

The trade structure for fertilizer ("N fertilizer") hasn't been updated since its initial core model proposal (#140), in 2012, before GCAM could represent inter-regional trade of secondary commodities (i.e., supplysectors). This proposal implements the standard improved trade structure, for example Core Model Proposal 312 which represents trade of livestock products, **with the exception that due to lack of data availability, this proposal uses a net rather than gross trade implementation for calibration, although the gross trade structure is still used.** N fertilizer is the last remaining commodity whose trade is represented through "fixedOutput" Imports technologies in net importing regions, and "Exports" final demand sectors in net exporting regions, whose quantity flow volumes are fixed over time at base-year levels.

The key difference between this and the other secondary product trade proposals (Core Model Proposal 308: Regional Fossil Fuel Markets, and the aforementioned CMP 312) is that this one does not use the UN Comtrade data on bi-lateral trade flows in order to calibrate the gross trade flows to and from each region, dropping the intra-regional trade. Since the time of those proposals, the UN Comtrade data has been placed behind a paywall for all but small queries, which are impractical for constructing bilateral trade matrices. In this proposal, the inter-regional trade is calibrated on the basis of net rather than gross trade flows to and from each region. If users want to represent scenarios with e.g., green ammonia being produced and exported from regions that weren't exporters in the model base year (2015), then these regions that are expected to be exporters would need to have their share-weights modified from the calibration-derived values in the base year. This would be implemented by revised subsector share-weights and interpolation rules in the USA traded ammonia sector, where the subsectors are the different exporting regions. Note that such a revision would be required even if bi-lateral trade were calibrated, as today's distribution of exports by region largely reflects the distribution of natural gas, which differs from the distribution of renewable energy resources.

As part of the revised trade structure, the "N fertilizer" commodity's name and physical characteristics (flow volumes, energy intensities, costs) are switched to "ammonia" for the production and trade, using the 17/14 mass ratio of $NH_3$ versus N to adjust all parameters. The revised structure is shown in Figure 1. The "N fertilizer" commodity is still represented in terms of mass of N, so it has an input-output coefficient of 17/14 (1.21 in Figure 1), and the N fertilizer quantities and input-output coefficients are not changed in this proposal (neither the commodity name nor the IO-coefficient assigned). This set of conventions, tracking the mass of ammonia in the production and trade sectors, but the nitrogen-only in agricultural uses, is actually consistent with the standard reporting conventions in the literature and associated datasets. That is, industry production and trade data focus on ammonia, but because ammonia is used to produce composite fertilizers for agricultural uses (e.g., urea, ammonium nitrate, etc.), all of which have different nitrogen contents, the agricultural statistics focus instead on the nutrient quantities alone (e.g., N, P, K).

Also shown in Figure 1, with the dotted line, is an "ammonia energy" commodity, which is not added in this proposal, as no ammonia energy technologies are implemented in the energy system here. Still, having the "regional ammonia" commodity for domestic uses defined and represented in terms of Mt of NH3 makes the implementation of an "ammonia energy" commodity simple; its input-output coefficient, 53.2 kg NH3 per GJ of energy delivered, is simply the inverse of the energy content of ammonia, 18.8 GJ per tonne NH3. This proposal thus sets up future model developers to accommodate the use of ammonia for energy purposes without having to work backwards from the agricultural sector's reporting conventions.




## Bugfixes

Three minor bugfixes are included with this proposal:

1. R/zgcamusa_L270.limits.R: The data table L270.NegEmissBudget has its inherited attributes stripped when being loaded. The prior code was causing gcamdata to crash where driver() rather than driver_drake() was being used.
2. A comment is added to the DISABLED_MODULES object in constants.R, warning users that lower-case "none" will inadvertently pick up an R code file "nonewcoal" because it has the string "none"

3. R/zenergy_L210.resources.R: a small bug is fixed that was resulting in NA's being generated, which could cause gcamdata to crash depending on R package versions.

### Query Updates

Most of the query updates are in the enduse/industry/fertilizer section, as the name of the production sector changed from "N fertilizer" to "ammonia", and as there are now trade sectors to be queried. The revised queries are listed below.

| new query | old query |
|---|---|
| ammonia production by region | fertilizer production by region |
| ammonia production by tech | fertilizer production by tech |
| ammonia inputs by tech (energy and feedstocks) | fertilizer inputs by tech (energy and feedstocks) |
| ammonia and N fertilizer prices | fertilizer prices |
| ammonia domestic supply | |
| ammonia exports (query USA region) | |

## Validation

Note that the SSP2_2.6 and SSP5 scenarios did not converge in the testing runs. This is not considered to be directly attributable to the changes in this proposal, and it's likely that these scenarios will converge once again in the future, with ancillary model development. Most high-level results are the same as before, which isn't surprising; Figure 2 shows the CO2 prices in the mitigation scenarios as an example.

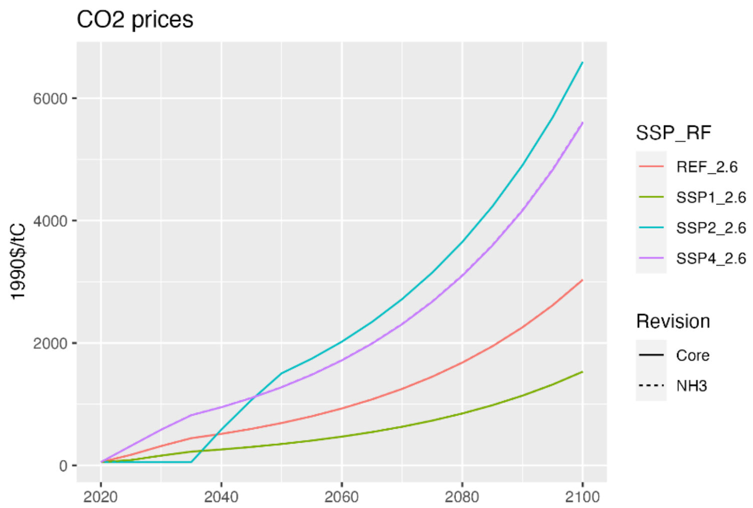
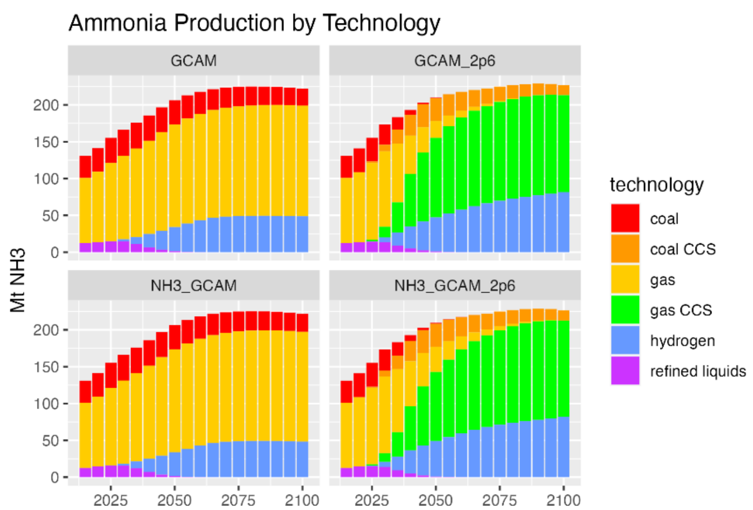



**Figure 2.** CO2 prices by scenario.

The remainder of the figures address the fertilizer sector specifically, which is where one might expect to see some differences. Figure 3 presents three visualizations of fertilizer production by technology and scenario which highlight these similarities. In Figure 3 and in the subsequent production and trade figures in this section, the core model's results for the "N fertilizer" commodity are multiplied by 17/14 in order to convert to ammonia equivalent for the comparison. As shown in the figures, the total global production (and consumption) of ammonia is not affected in this proposal, nor is the technology choice, at least at the global level.



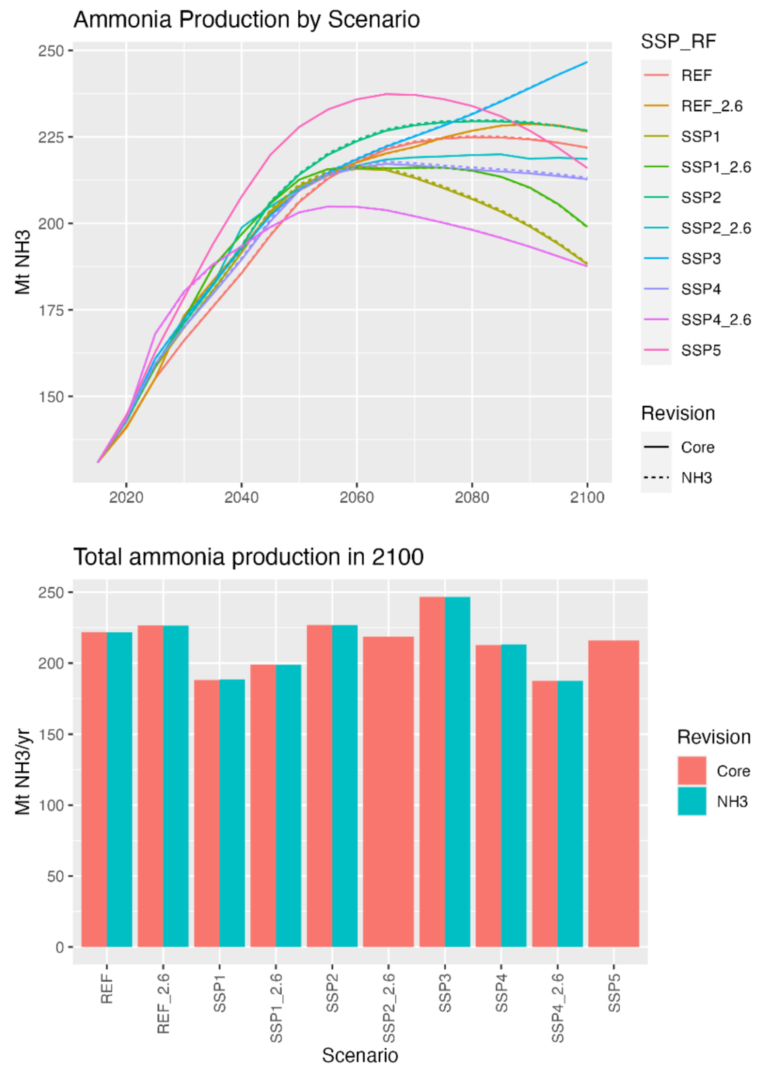



**Figure 3**. Ammonia production by (a) technology and year, (b) scenario and year, and (c) scenario in 2100, comparing the core model to the revision implemented here. The core model's "N fertilizer" production values are multiplied by 17/14 to translate from the modeled commodity to ammonia equivalent. The SSP2_2.6 and SSP5 scenarios did not solve in the testing runs of the NH3 revision model branch.

The major change in this proposal is the trade, and the resulting regional allocation in the growth of production from the model base year (2015). In the core model, future imports and exports are fixed to the 2015 value, and all future growth in the demand for fertilizer in each region is met by expanded domestic production. In the revision scenarios, the choice between imports and domestic self-supply is calibrated, and the calibrated share-weights are passed forward to future years. Figure 4 is presented as a diagnostic check to confirm that the proposal does not change any of the base year import and export volumes. All of the regions' flow volumes are unchanged in the proposal.

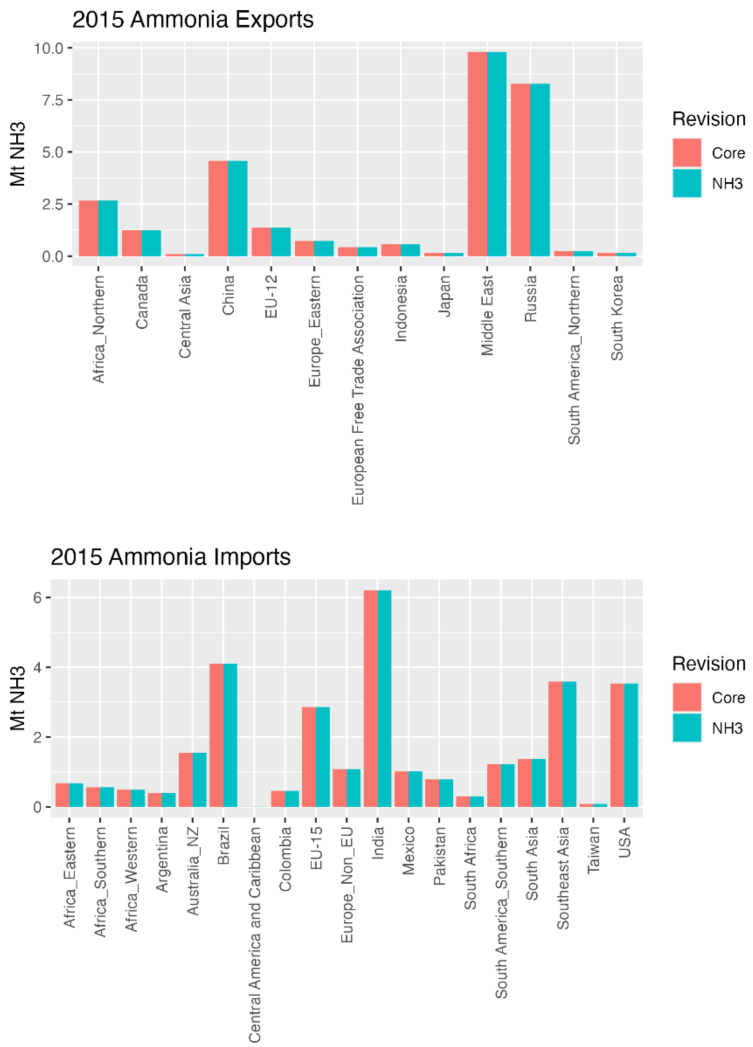



**Figure 4**. Base-year (2015) ammonia exports (left panel) and imports (right panel), with the core model's "N fertilizer" flow volumes converted to ammonia-equivalent.

However, going into the future the differences are significant, and are presented for 4 major exporters of fertilizer and 6 major importers of fertilizer, in the standard reference and policy scenarios in Figure 5 (REF and REF_2.6).


**Figure 5**. Ammonia exports (left panel) and imports (right panel) in the reference and REF_2.6 mitigation scenarios, comparing the core model to the revision.

In general, the total volume of inter-regional trade increases significantly in this revision. This phenomenon is, at least to some extent, a realistic result, absent any large-scale switch in how ammonia is produced, such as a switch to renewable electrolysis as the dominant ammonia production technology, which would dramatically change the inter-regional allocation of production, and likely switch the direction of many present-day trade flows. These base-year trade flows are structurally carried into the future, both in the core and revision scenarios. Regions with large reserves of natural gas account for the bulk of the exports at present and are well positioned to expand production in order to meet the demands of an expanding and increasingly fertilizer-intensive global agricultural sector. This remains true in mitigation scenarios as these regions also tend to have abundant CO2 storage reservoirs. Unless there are gas pipelines, ammonia is easier to transport between regions than natural gas, incurring fewer fugitive losses and less energy and capital costs for liquefaction. In the interpretation of Figure 5, note that the consumption of ammonia in each region is pretty similar in the core and revision scenarios (Figure 6); what is at stake is the question of whether the increase in ammonia demand (by a net importing region's agricultural sector) is met by imported ammonia, or by domestically produced ammonia, likely from imported natural gas. In the Core scenarios, the future growth in ammonia demand in any region is structurally forced to come from domestically produced ammonia, itself produced from either imported natural gas or expanded domestic natural gas production. In the NH3 Revision scenarios, there is also a modeled competition between domestically produced ammonia and imported ammonia. There are two caveats on the prior statement that are worth noting. First, in China, there is competition represented in the ammonia production sector, between coal and natural gas. Second, in all regions there is competition represented in the ammonia production sector between on-site steam methane reforming and purchased hydrogen (Figure 3a). However, most of this hydrogen is itself produced from natural gas in these scenarios.

On the consumption side, the remainder of this analysis focuses on nitrogen rather than ammonia. Input-output coefficients of "N fertilizer" to crop production are not affected in this proposal; in fact, the XML file that prescribes the fertilizer input-output coefficients is identical between the revision and the core model, shown in Figure 6.

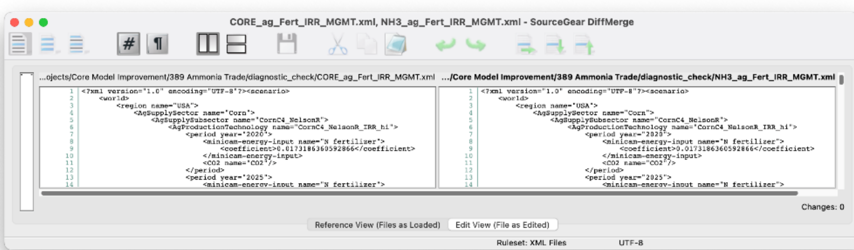



**Figure 6**. Screenshot of the comparison between the ag_Fert_IRR_MGMT.xml file, comparing the core model to the present proposal.

Figure 7 addresses how these changes influence the prices paid for nitrogen fertilizers ("N fertilizer") in each of 9 key regions and over time for the REF and REF_2.6 scenarios. In general, regions that are significant exporters (China and Middle East shown; see Figure 5) do not see any noticeable change in future prices, which is an expected result. The main mechanism by which the changes in this proposal could influence prices in ammonia exporting regions would be the increased exports causing an increase in the marginal cost of production. Again, this is not observed. Among the seven importing regions shown in Figure 7 (all but China and the Middle East), many see little influence on prices from these revisions, but in several cases the access to the endogenous globally traded ammonia markets causes a modest reduction in prices. While this result is expected, it should be noted that there aren't any additional shipping costs applied to imported ammonia. All importing regions see the same price for globally traded ammonia, and this price is calculated as the weighted average producer price amongst exporting regions. So, while the prices of imported ammonia may be underestimated, as with the energy requirements, this structural approach is similar to all of the other traded secondary commodities in the model. Another noteworthy change shown in Figure 7 is the reduction in prices in several regions (Southeast Asia, Africa_Western) whose end-of-century nitrogen prices were especially high in the core model.


**Figure 7**. Prices for Nitrogen ("N fertilizer") paid by the agricultural sector in each of 9 regions, for the REF and REF_2.6 scenarios.

The final set of plots, in Figure 8, examines the net impact of the N fertilizer price differences shown in Figure 7, focusing on three regions in the year 2050: Brazil, Southeast Asia, and the USA. In Brazil and Southeast Asia, the prices in the revised scenarios are lower than in the core model; the USA sees a slight increase in prices in 2050 in the REF_2.6 scenario, and a slight decrease in the REF scenario.

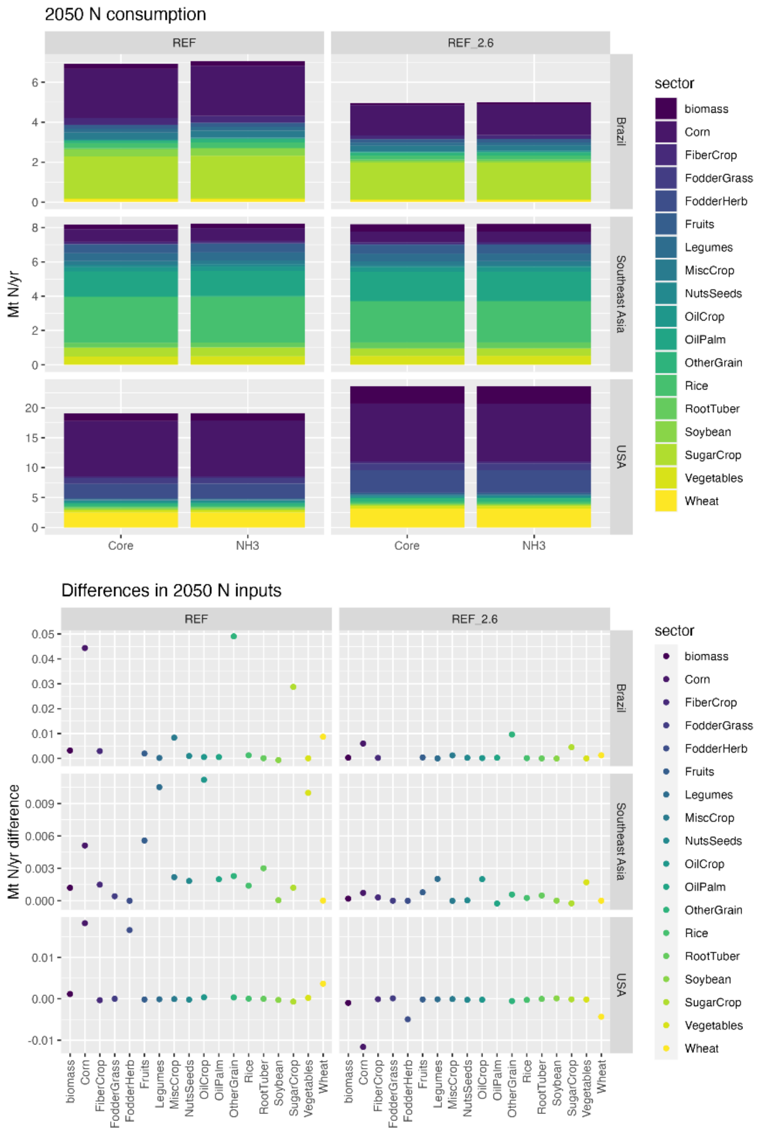



**Figure 8.** Left panel: Year 2050 N fertilizer consumption by crop type in selected scenarios and regions, comparing Core to NH3 Revision scenarios. Right panel: Difference in fertilizer consumption in going from Core to NH3 Revision, by crop type, in the same three regions (Brazil, Southeast Asia, USA).

The price differences for the REF scenario cause an overall 2% increase in the consumption of fertilizer in 2050 in Brazil, and 0.7% in Southeast Asia; the impacts on consumption in the other four regions and scenarios shown are well below 1%. Within crop types, the only region and crop that sees more than 10% difference in N fertilizer demand is OtherGrain in Brazil (a 40% increase), which is a crop that is characterized by relatively low profit rates. As such, its future production levels are sensitive to the fertilizer price increases, and in the Core REF scenario its output declines by about 50% from 2015 to 2050. The flatter price trajectory for N fertilizer results in a similarly flatter production trajectory for OtherGrain in Brazil.

In summary, the re-structuring of the ammonia production and trade segments of the model in the NH3 Revision do not impact the production technology choice in any region, but they do impact the regional distribution of production and consumption, with present-day exporters capturing a larger share of the future global market demand than is seen in the Core scenarios. These changes, in turn, influence the modeled N fertilizer prices in net importing regions, generally mitigating the price increases observed when these regions are required to supply all of their future fertilizer demands with domestic production. These price differences flow through to N demand quantities, but the vast majority of such changes are modest and/or explainable from the heterogeneity in the model data.