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Mapping Nitrogen Pathways in Organic Manure through GCAM

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U.S. DEPARTMENT OF ENERGY

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Abstract

The current world is the most interconnected and globalized it has ever been. A small change in one region or process can have several downstream effects around the world. With that, there is an ever-growing need for an expansive and comprehensive modeling to track and predict the rates and totals of most pertinent processes, resources, commodities, etc., and knowing how they relate to other aspects in our global environment, which is where the Global Change Analysis Model (GCAM) is useful. One such area is to tracking Nitrogen flows across the natural and industrial processes by tracking synthetic and organic fertilizers. Previously, GCAM only included one category of synthetic fertilizers for nitrogen pathways. This project focuses on quantifying the amount of nitrogen in manure and how much of it is used as fertilizer for crops. To do this, this project takes data from the UN's Food Administration Organization on manure nitrogen applied to soil in every country to be utilized in an input/output coefficient-based approach to determine the amount of nitrogen absorbed by the major crops. Mapping nitrogen pathways is critical to furthering understanding of industrial agriculture, nitrogen runoff, and the roles of nitrifying bacteria and archaea.

Introduction

Nitrogen fertilizer is one of the most important fertilizer our crops need to grow with high yields (Zhang et al., 2024). Humans have understood this for a long time, with the use of manure as fertilizer being older than centuries. That manure fertilizer is critical to keep track of, as tracking the nitrogen flow through that organic fertilizer is pertinent to the practice of industrial agriculture, to our understanding of nutrient runoff (which affects watersheds, and can create algal blooms and ecological dead zones), and that of soil chemistry/the nitrogen cycle in general (Zhang et al., 2024). Freshwater sources through surface and groundwater sustain water use (Zhao et al., 2024), but are often prone to nutrients leaching causing quality degradation, availability constraints and cost increases (Niazi et al., 2025).

To account for this nitrogen fertilizer, we plan to use GCAM, or the Global Change Analysis Model, which includes many multi-sector aspects of our world in an integrated assessment model which allows us to create useful forward-looking analysis (Niazi et al., 2024). Previously, no work had been done to include that organic nitrogen fertilizer into GCAM, such that the pathway for the nitrogen to be consumed by the animals then redeposited into the ground wasn't modeled (Kyle et al., 2023). To remedy this, we took data from the UN's Food Administration Organization (FAO) and interpolated the data such that most of the gaps in the data were filled, then created many graphs and maps such that the many trends and interesting/relevant points in the data could become visible (FAO, 2025 a,b). We believed that as the population increased, more manure would be produced and applied to soils, and that more rural countries would produce and apply more manure nitrogen than more industrialized nations (World Bank, 2025).

Methodology

The FAO data we used incorporates all countries, many areas (like island territories of France, the UK, and USA, and more provinces that are distinct from nearby countries mostly due to colonialism, like Hong Kong and Macau), and many former countries that existed during the data's time span, 1961-2022. For this time span and collection of countries/territories, the data we looked at included manure nitrogen applied to soils in dairy and non-dairy cattle, broiler and layer chickens, ducks, turkeys, breeding swine and market swine, sheep, and goats (FAO, 2025 a,b). To clean this data such that visualizations were possible, we used multiple R scripts, which were used to interpolate the data to fill in gaps, and were then used to create graphs and maps. Furthermore, we grouped those ten livestock categories into non-dairy, dairy, swine, poultry, and sheep/goats, and we compiled all countries/areas into the 32 GCAM land regions.

Results

As population increased from ~3 billion in 1961 to ~8 billion in 2022, the totals for manure nitrogen in soil increased significantly (Fig. 1). The totals for sheep & goats more than doubled, that of swine did the same, and that of poultry more than tripled. Similarly, but not nearly as much, that of beef and dairy cows increased by roughly 20%.

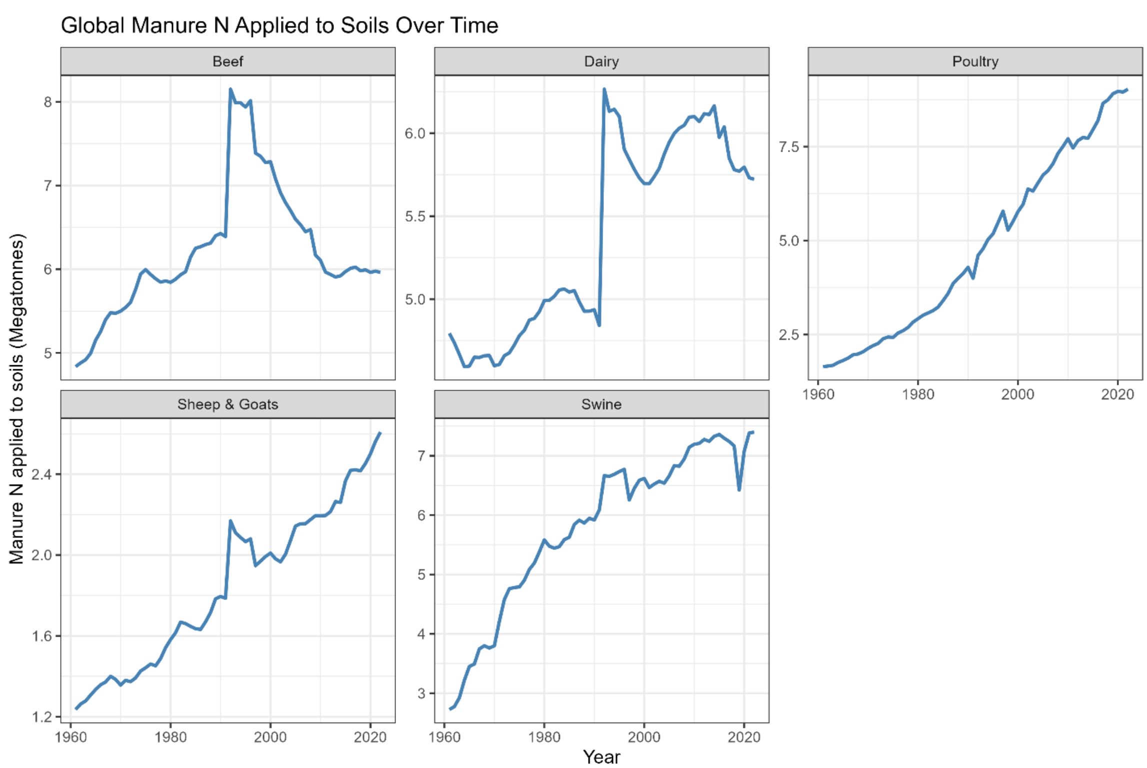

Figure 1. Global sums for manure nitrogen applied to soils per year by megatonnes

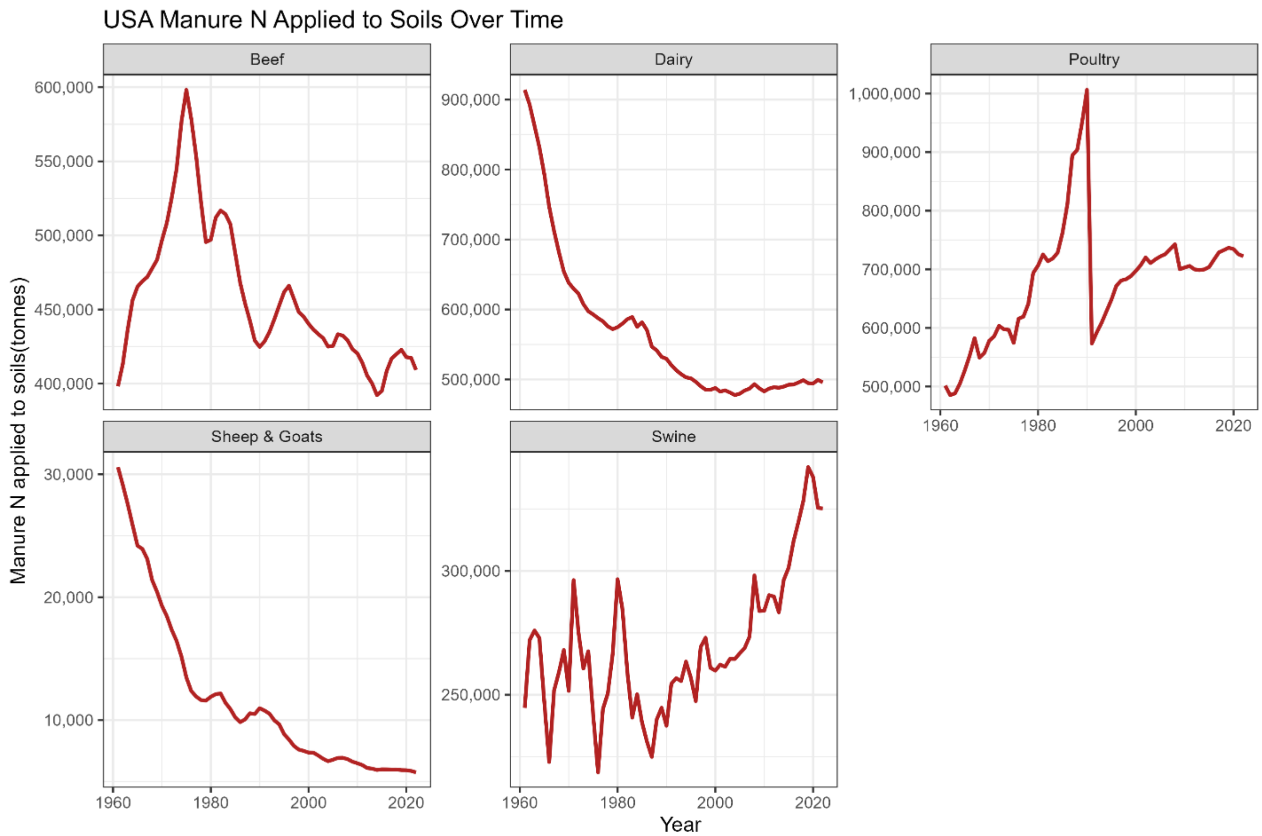

Figure 2. Manure nitrogen applied to soils per year for the United States

Despite the population of the United States increasing from ~180 million in 1961 to ~330 million in 2022, the manure nitrogen applied to soils has not gone up significantly like how it did for the world totals, with only poultry and swine seeing a significant increase, ~40% for poultry and ~30% for swine (Fig. 2).

Since Russia and Ukraine gained their independence in 1991, and since 1992 was the first full year they were sovereign states (at least since 1961), they first appear on the graph then (Fig. 3). Similarly to the United States, Western Europe, despite having a similar population increase, experienced slowed rates of growth, stagnation, and/or decline across the five livestock categories. For Russia, Ukraine, and Eastern Europe, they all experience a sharp drop down in about 1990 in all categories, with only some of their categories rebounding in recent years.

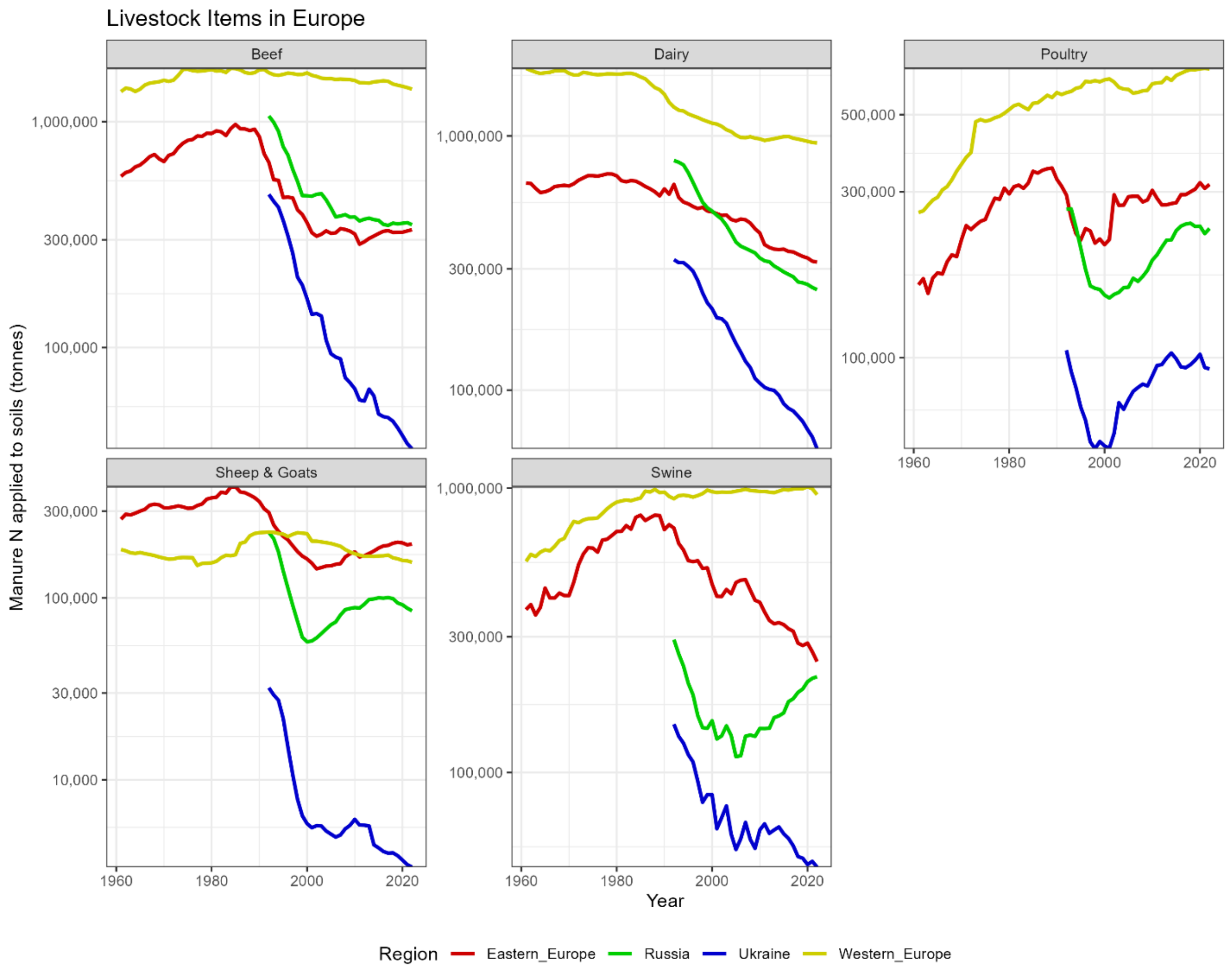

Figure 3. Manure nitrogen applied to soils in Western Europe (GCAM region EU-15), Eastern Europe (GCAM region EU-12), Russia, and Ukraine

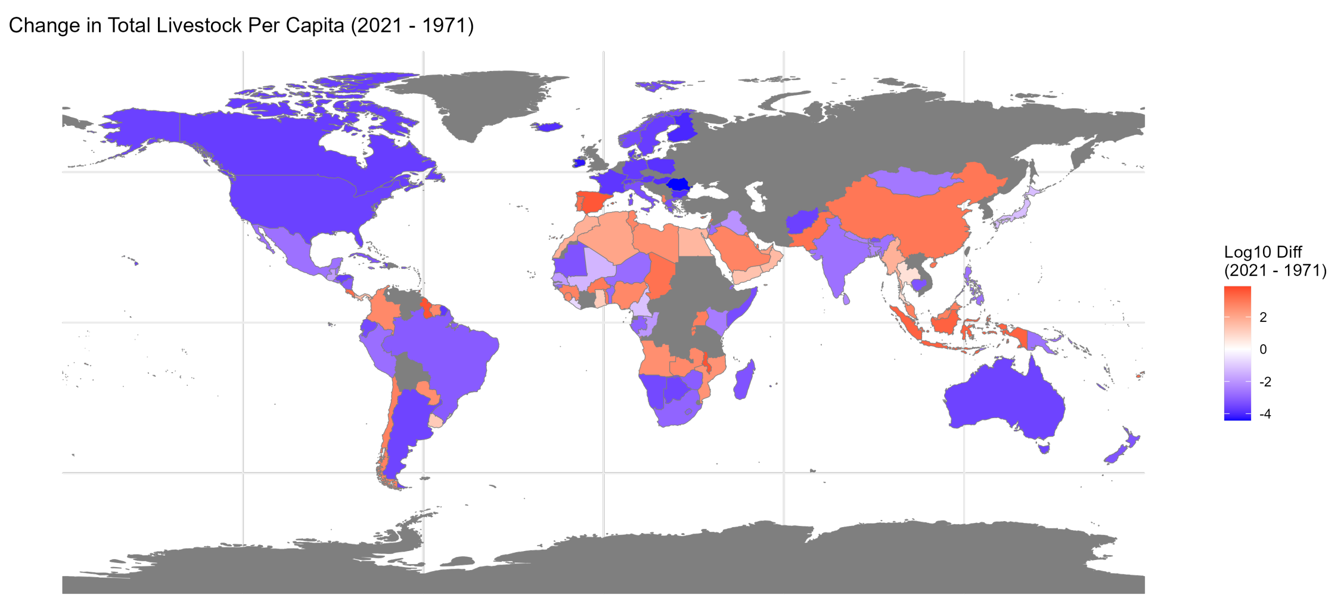

Figure 4. Change in manure nitrogen applied to soils per capita by country from 1971 to 2021

After adjusting for population, there is much diversity between countries that increased their nitrogen manure rates and those that decreased their rates (Fig. 4). Those countries, like those in North Africa, East Asia, Hispania, and Southern Africa relied more heavily on organic nitrogen fertilizer rather than synthetic nitrogen fertilizer in 2021 than they did in 1971.

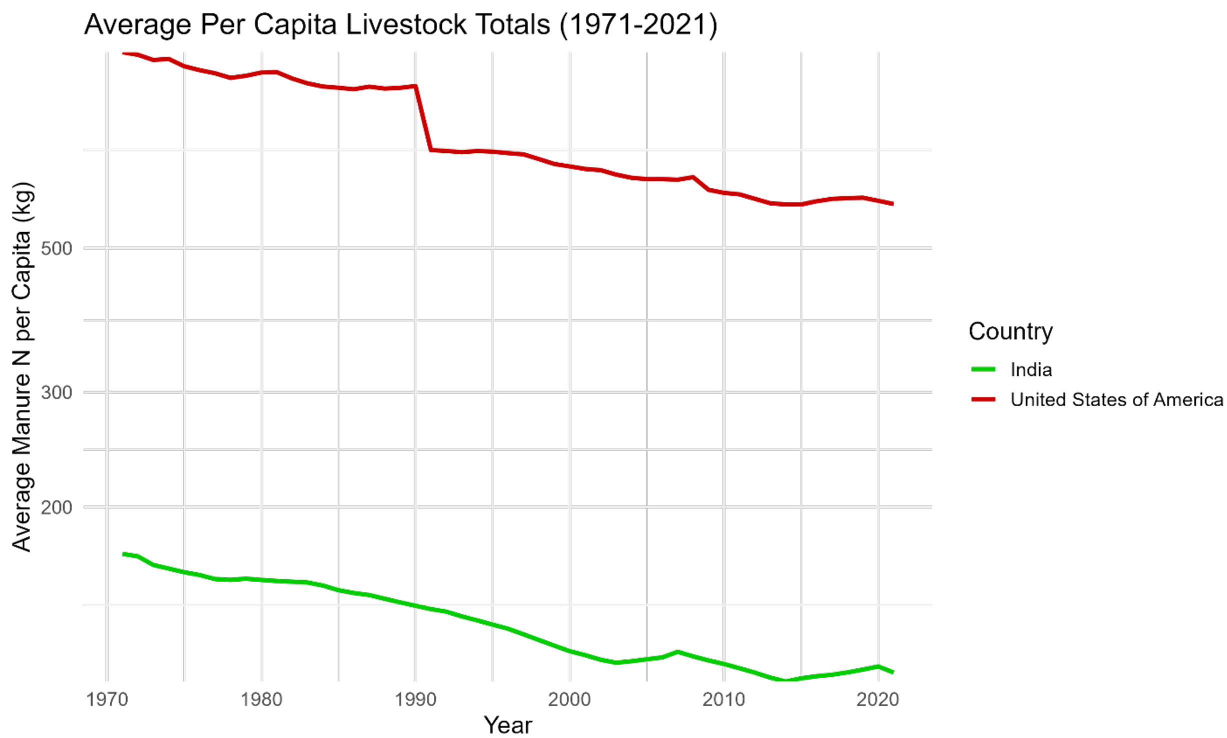

Figure 5. Manure nitrogen per capita in India and United States from 1971 to 2021

After adjusting for the expansive population growth in both the United States and India over the past fifty or so years, both countries are clearly moving away from the use of organic fertilizer in their agricultural sectors (Fig. 5).

Discussion

A trend that was discovered in the data was that development of a country was a strong indicator of how much organic nitrogen fertilizer they would use. Such a trend is logical, because to obtain synthetic fertilizer as a farmer there needs to be a factory that produces it, you must have the capital to purchase it, and there must be a capable infrastructure network to deliver it to you. Such requirements are seldom found in the most poverty-stricken and underdeveloped countries.

A great example of this is how the world totals in Figure 1 show massive increases in all five livestock categories, while in the USA most of the categories have decreased in their manure nitrogen. Since the USA is one of the most developed countries in the world, it can reasonably be assumed that this decline is because of an increased use of synthetic nitrogen fertilizer. This assumption is supported by the fact that the use of synthetic nitrogen fertilizers has exploded since

1961, supporting fewer than half a billion people that year, and supporting nearly half, about 3.5 billion people, of the world's population by 2015.

Furthermore, two things that are immediately present when analyzing Figure 1 and Figure 2 are the sudden spikes in cattle in Figure 1 and poultry in Figure 2. The roughly 30% increase in cattle manure applied to soils, as seen in Figure 1 in 1991, is the probable result of the FAO updating their estimation methods that year to a more dynamic model that incorporates cattle left on pastures (and not in enclosed farms) at a greater scale.

On the other hand, the more than 40% drop in poultry nitrogen manure applied to soils in the same year, 1991, in the United States, shown in Figure 2, is probably a result of more nuanced factors. When comparing the poultry graph of the USA in Figure 2 and that of the world in Figure 1, there is only a miniscule drop in the global totals in the same year. This drop is almost entirely composed of the more than 400,000 tonne drop in the United States, indicating that this change wasn't because of a change in methodology by the FAO, which would've affected the whole world similarly. This drop was most probably the result of a number of policy related changes, like increasing implementation of environmental regulations passed in the Reagan administration, the ongoing switch to factory farming (where poultry manure may be produced in high quantities with little nearby cropland to use), a regional shift in poultry production (as evidenced by the fact the rest of the world saw virtually no change in poultry manure production in the same year, and of course the FAO's data collection/estimation was far from perfect.

The trend of more developed and industrialized nations implementing the use of synthetic nitrogen fertilizer more and more remains true in most of Europe as well, as seen in Figure 3. Europe's trends of either stagnation or decline in most of the categories is symbolic of that development trend, but it's also quite apparent that the sharp declines in Eastern Europe, Russia, and Ukraine all occur simultaneously with the collapse of the Soviet Union and the Eastern Bloc. Due to their nascency, Ukraine and Russia don't have any data before the collapse of the Soviet Union, but their trend of decline in the 1990's aligns quite closely with that of Eastern Europe, which did have data from the communist era. Especially when looking at the poultry graph in Figure 3, all three regions have very similar rates of change in the 1990's, and they then have a similar rebound later in the late 2010's.

However, the general trend that development means more synthetic fertilizer used and less organic fertilizer used is not universal. For example, in China in Figure 4, it's apparent that China has massively expanded its organic fertilizer per capita over the past fifty years, even though it has seen some of the fastest development over that time, increasing its life expectancy by more than twenty years.

This is also further supported by the graph in Figure 5, as despite the United States having many times the GDP per capita and a much higher HDI than India, the United States has seen consistently higher rates of manure nitrogen fertilizer usage.

Conclusions

It was apparent that with an increased world population, there was a similar increase in the amount of manure nitrogen applied to soils. However, this trend has many holes in it, especially in the most developed nations. Overall, it seemed that industrialization had the greatest impact on the quantities of manure nitrogen applied to soils when normalizing for population. However, there are many conflating variables that were not addressed, normalized for, or accounted for in the data, like cultural practices towards animals and agriculture, that could paint a greater picture than simply development, industrialization, and population increase on their own.

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