MODEL-BASED CONSTRAINTS ON NUTRIENT CYCLING IN THE GLOBAL ENVIRONMENT

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MODEL-BASED CONSTRAINTS ON NUTRIENT CYCLING IN THE GLOBAL ENVIRONMENT

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This dissertation has three chapters. Chapter 1 examines nutrient resupply patterns during decomposition in forest ecosystems, including tropical, temperate, and boreal, through meta-analysis. The hypothesis tested is that C, N, and P follow different prototypes in mineralization and be affected by the mean annual temperature and precipitation of sites. Results show that P will be preferentially released compared with C in mineralization, while C and N are coupled and released together. And C is more obviously affected by the higher the mean annual temperature (MAT), the higher the mineralization rate. C shows a significant increase in the mineralization rate with increasing temperatures. At the same time, N and P are not as strong as C. Thus, global climate change will aggravate the loss of C, further worsening the greenhouse effect. However, mean annual precipitation (MAP) has no significant effects on it.

Chapter 2 analyzes the nutrient (N and P) use efficiency, global fertilizer uses for 2015, and predictions for the year 2050 using models and scenario analysis. Country-level nutrient use efficiency was calculated based on crop yield and total nutrient inputs for each country, and global heterogeneity was studied. Five scenarios were applied for 2050 fertilizer demand prediction: business as usual (BAU), climate change mitigation, nutrient use efficiency improvement, dietary shift, and all methods. Results showed that some countries in Africa and South America have abnormally high nutrient use efficiency, which indicates nutrient

mining. Generally, nutrient use efficiency is higher in developed countries and lower in developing countries. For fertilizer use, by the year 2050, even population grows over 30 percent, with all scenarios applied, the fertilizer use can still reduce while feeding the population.

Chapter 3 studies technology and management that can increase the nutrient (N and P) use efficiency, and did a meta-analysis and scenario analysis. Meta-analysis results were applied as nutrients use efficiency increasing scenario to fertilizer application in the year 2050. The results show that technologies and management can reduce future fertilizer demand. If combined with the scenarios in Chapter 2, the fertilizer demand in 2050 can be even less than in 2015.

BIOGRAPHICAL SKETCH

Zhou has a BS in Environmental Science and is pursuing a Ph.D. in Quantitative Ecology. Her research interests focus on using models and data analysis to study sustainable food and climate change.

To my parents and everyone met in life

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I will cherish those fateful encounters forever, even if it's just a journey.

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PRELIMINARIES

Background on Carbon, Nitrogen and Phosphorus cycles

Carbon (C), nitrogen (N), and phosphorus (P) are essential nutrients for Earth's diversity of life and are critical to the global food system. These vital elements undergo biogeochemical transfers among plants, animals, and microbes across the atmosphere, geosphere, hydrosphere, and pedosphere [41]. The total global soil carbon pool is about 2,200 Gt, with two-thirds in the organic matter [13], more than three times the amount of carbon in the atmosphere. However, soil degradation depletes soil carbon, and changes in land use types and poor management can lead to its accelerated decomposition and emission of greenhouse gases into the atmosphere. Nitrogen mainly exists in the atmosphere in gaseous form. It must go through nitrogen fixation, nitrification, and denitrification processes to complete its cycle, be absorbed and utilized by plants, and then supplied to animals and humans. Understanding the connections and interactions between carbon and nitrogen is extremely important in understanding different soil properties and conditions and how soils serve as the basis for life, supporting fundamental human development. Because the carbon-nitrogen ratio of organic matter in the soil directly impacts soil residue decomposition and the nitrogen cycle. Phosphorus in the soil mainly comes from the decay of plant falls and the mineralization of organic matter. Agricultural soils it relies on fertilization. The main output of phosphorus is uptake by plants and the leaching of soluble phosphorus from the ground. Insoluble phosphorus can be lost through soil erosion processes, either. Therefore, when studying carbon and nitrogen, phosphorus is also a substance that cannot be ignored.

Plants require at least 14 mineral elements for nutrition, including macronutrients N, P, and K, widely applied as fertilizers to grow food. Crop production tends to be limited by low Phyto-availability of essential mineral elements or excessive concentrations of potentially toxic mineral elements, such as Fe, Mn, and Al [134]. For microbes, 50% of their dry weight is C, while N is an essential part of amino acids comprising cell protein, and P is a crucial component of nucleic acids and ATP. [79]. These nutrients are generally obtained from the soil, atmosphere, rock weathering reactions, and substantially via human interventions. My dissertation will focus on improving nutrient utilization efficiency in the biogeochemical cycle or food chain and reducing losses in natural and managed ecosystems.

Nutrient cycling significantly influences ecosystem functioning, climate change, food production, and environmental economics [59]. A significant interaction involves the role of nutrients in controlling global carbon sequestration on land. Current evidence suggests that nitrogen and phosphorus limitations of plant productivity are widespread. Whether and how terrestrial nutrient cycles will reduce the future carbon sink remains uncertain, with inputs, outputs, and plant-soil-microbe interactions all playing a pivotal role. In addition, nitrogen and phosphorus fertilizers are widely used to support global food production; however, inefficiencies in these nutrients can lead to widespread environmental issues as they escape cropping systems, including climate risks, biodiversity declines, poor drinking water quality, and air pollution. One of our biggest challenges is balancing global nutrient use to maximize the positive aspects of fertilizer applications and limit the negative consequences of inefficient fertilizer use on people and the planet.

Ultimately, the fate of nutrients in natural and managed ecosystems and processes centers on inputs and how such inputs recycle among diverse soil-plant systems. Nitrogen and phosphorus inputs occur via rock weathering, reactions, and deposition. In contrast, N has a substantially gaseous phase (78 percent of air is N2), unlike P, which does not exhibit a significant gaseous form on Earth. N fixation, the conversion of N2 into biologically available N forms, is feasible via free-living and symbiotic routes. However, this energy-intensive process limits global N fixation fluxes [60]. Once in an ecosystem, both N and P undergo complex mineralization reactions through which soil organic compounds are converted to inorganic forms readily available to plants and microbes, fueling terrestrial productivity and C sequestration worldwide [26].

Studies have shown that immobilization of nutrients by soil microorganisms, and chemical or mineralogical reactions, including precipitation and adsorption and ionic fixation within lattice structures of clay minerals [28], can limit the availability of N and P to plants. However, key questions and uncertainties surround how biochemical enzymes and geochemical reactions control the stoichiometry of N and P cycling across terrestrial environments. As N and P cycle through the soil, two principal factors determine nutrient availability: decomposition efficiency and preferential release of N or P vs. nutrient use efficiency of plants. Approximately 90% of total soil N is composed of organic forms [75], and 30% to 65% of complete soil P is organic P [29]. Microbes decompose a variety of natural materials into soluble nutrients, making them plant available. Decomposition (mineralization) regenerates nutrients at a much faster rate than external inputs of either N or P in natural ecosystems. Plants acquire and assimilate available nutrients from soil or atmosphere (like legumes) and store them as proteins or other forms to feed animals and human beings. Managing these processes properly could help to balance nutrients in a way that maximizes the positive benefits of fertilizers.

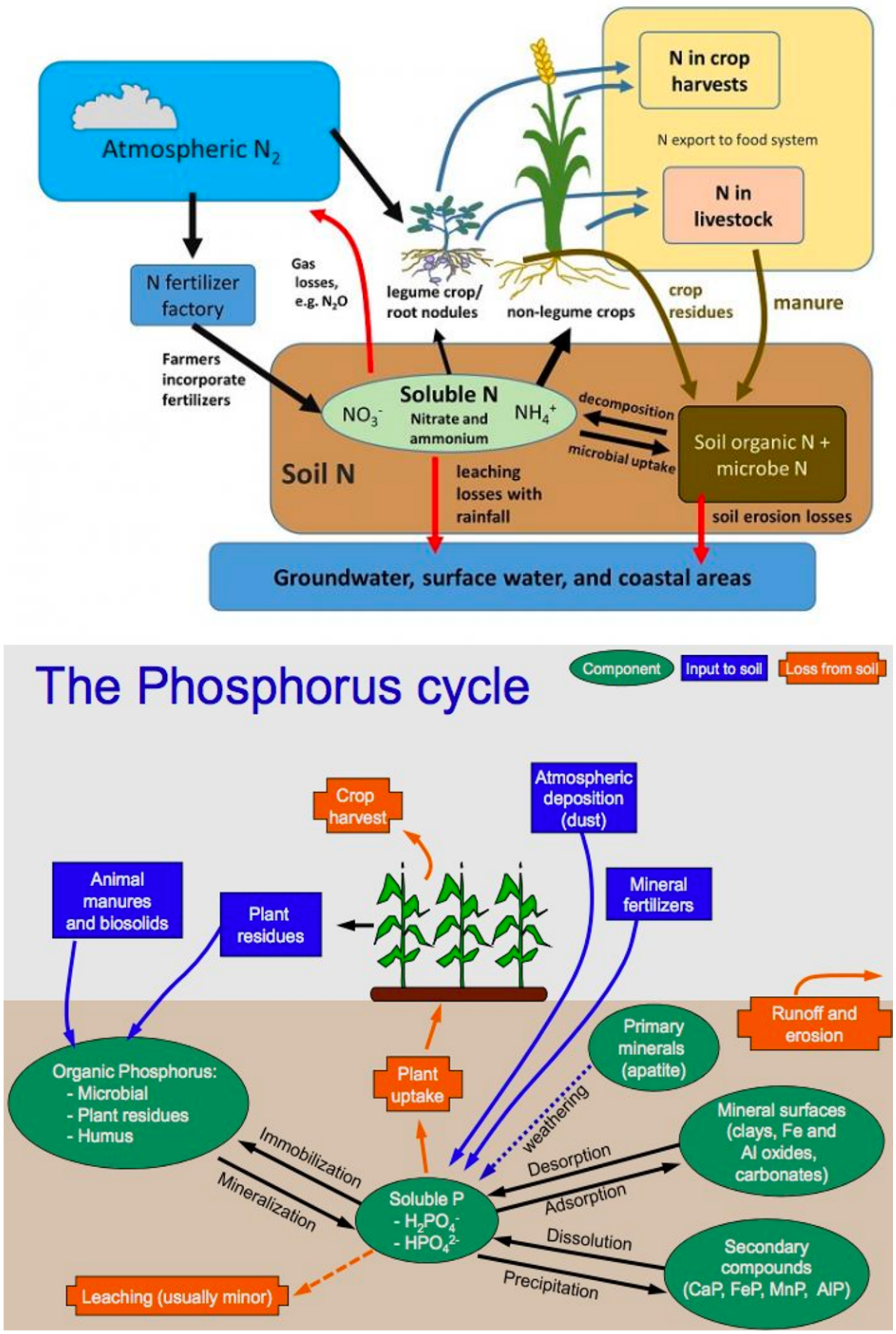

Figure 1: (a) Conceptual Model of Nitrogen Cycle. (b) Conceptual Model of Phosphorus Cycle

CHAPTER 1

NATURAL ECOSYSTEM —— NUTRIENTS RESUPPLY PATTERN DURING DECOMPOSITION

1.1 Abstract

Terrestrial ecosystems are a major reservoir of carbon, sequestering around 25% of anthropogenic CO2 emissions each year. However. The sustainability of the terrestrial carbon sink is uncertain. A key question concerns the role of nutrients in regulating plant productivity, given the widespread importance of nutrient limitation across Earth's ecosystems. Models and experiments suggest that nitrogen and phosphorus could reduce the size and sustainability of the terrestrial carbon sink in the future, leading to more CO_2 emissions remaining in the atmosphere, and thereby increased climate risks. Here I investigate global patterns of carbon, nitrogen, and phosphorus mineralization across the litter decay process in terrestrial ecosystems. Results of the litter decay experiments show that the mean C/P of the initial litter is lower than the final C/P in the global average, implying rapid P cycling that is decoupled from C respiration. In contrast, the C/N shows the opposite pattern with C/N initial values closely linked to final C/N ratios in litter decay, revealing strong relationships between N mineralization and C respiration. The climate is shown to play an essential role in mineralization rates: mean annual temperature increases are positively related to C, N, and P mineralization, whereas changes in precipitation did not show a coherent relationship with litter decay. The mineralization rate of C is most affected by temperature when compared to N and P, indicating that global warming will aggravate the loss of C from the forest ecosystem, consistent with

global models.

1.2 Introduction

Litter decomposition of plant matter has been studied for decades, especially in individual sites and at species to stand levels [30, 3, 50]. More recently, studies have shifted focus to include roots and wood decomposition in addition to foliar litter rates [122, 113, 99], emphasizing comparative analysis across ecosystem types and different areas of the earth system. Factors that regulate decomposition rate have been identified as (i) climatic factors such as mean annual temperature (MAT), mean annual precipitation (MAP) and actual annual evapotranspiration (AET) [15, 33, 84]; (ii) litter quality, e.g., nitrogen content (N) [138], carbon: nitrogen ratio (C: N) [34, 16], lignin content (LIGN) [49] and lignin: N ratio (LIGN: N) [3, 105]; (iii) vegetation and litter types [49, 50, 98]; (iv) geographical variables such as LAT and altitude (ALT) [114] and (v) changes in microbial community composition [108]. Zhang et al. revealed that the k value decreased with latitude (LAT) but increased with temperature, precipitation, and nutrient concentrations of experimental sites at a large spatial scale [142].

Stoichiometric relationships hold power for connecting communities to ecosystems and disentangling the complex array of controls on nutrient cycling during litter decomposition. N:P (the nitrogen–phosphorus ratio) of ecosystem pools have been used to examine relationships between nutrient supply and demands in marine and terrestrial ecosystems [36]. Alfred Redfield showed that the molar N:P of inorganic nutrients was c. 16/1 across ocean basins, consistent with marine organic matter [103]. Nutrient mineralization ratios are defined as the N:P released from decomposing substrates over the time course of decomposition [8], and nutrient mineralization ratios in the ocean have been used to understand patterns of N fixation, denitrification [53], and nutrient limitation of marine phytoplankton [31]. Likewise, terrestrial ecologists have discovered coherent patterns of N:P in live and dead plant pools [51, 83, 104], plant resorption [118, 128], soil microbial biomass [27, 137] and extracellular enzymes [116] across terrestrial ecosystems. Previous analyses have shown negative correlations between litter decomposition rates and litter C: N and C: P [92, 141]. Marklein et al. demonstrated that there is no singular N:P of net mineralization across global forests; rather, the N:P ratio mineralization can be well-predicted by the N:P of initial litter substrates [80].

While the pattern and regulation of C-N-P interactions are essential to global C and climate forecasts, key uncertainties remain over the relative rates through which C, N, and P are released from decomposing litter. In traditional ecological models, decomposition rates of organic phosphorus and organic nitrogen are not sufficiently differentiated, which challenges the robustness of model predictions [63]. Fundamental concepts suggest that P can be more rapidly released from litter than N, owing to phosphatase enzymes, which are ubiquitous and can be secreted by both plants and microbes to directly cleave phosphodiester-bonded P, which is the primary organic P form found in biomolecules, including litter [82]. By contrast, N is typically bonded to C in organic substrates, with a suite of different enzymes needed to release N from litter, and CO2, in principle, released during decomposition along with N [82]. If P and N are differentially decoupled from C during decomposition, this could affect net CO2 capture by terrestrial ecosystems, depending on changes in the stoichiometry of C: N and C:P during the decay process. Identifying global patterns of net nutrient mineralization and interactions with C is critical to understanding how nutrients regulate plant CO2 capture and terrestrial feedback to climate change [61, 132, 139].

Manzoni et al. showed that N loss occurs slower than C loss for most litter decomposition [78]; however, their study did not systematically address interactions of C, N, and P, and how their stoichiometries are coupled across ecosystems and climates. McGill and Cole (1981) proposed a conceptual model that differentiates the factors regulating nitrogen (N) and phosphorus (P) mineralization in soils, resulting in differential connections to C[82]. They pointed out that carbon (C) and nitrogen(N) are bonded together in soil organic matter, and thus, N mineralization is coupled to the respiration of C by soil organisms. In contrast, most organic phosphorus is bound in phosphate esters and is mineralized independently of C through catalysis by phosphatase enzymes. Finally, Zhang et al. hypothesized that decomposition rates decrease with increasing latitude (LAT), but the mechanisms beyond this concept remain poorly resolved [142]. Understanding the stoichiometric connections between C, N, and P and their differential responses to climate is vital for advancing theoretical ecosystem concepts and global projections of carbon-climate feedback.

Here I examine C, N, and P loss and resupply patterns during litter decomposition across forest ecosystems spanning tropical, temperate, and boreal zones. Data were collected from fields studied in previous literature by using meta-analysis techniques. I test the hypothesis that P mineralization from litter is more decoupled from C than N, with solid climate dependencies in mineralization rates.

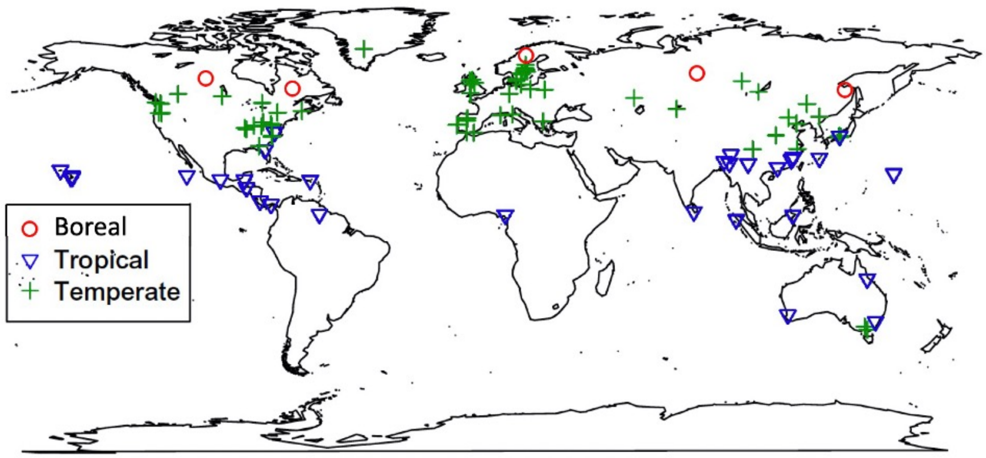

Figure 1.1: Field sites of meta-data.

1.3 Methods

1.3.1 Data Collection

Our method based on the analysis by Marklein et al.[80], which was focused on N and P patterns, I compiled and analyzed data from the primary literature on net mineralization rates from 193 litterbags in 89 separate experiments spanning 95 different forest ecosystem sites worldwide, covering boreal, temperate, and tropical forests. Fig 1.1. shows the field sites included in the dataset (see all literature in Appendix B).

1.3.2 Data Analysis

Net nutrient mineralization was calculated as losing a given nutrient from the litterbag during decay at a given site. Initial C: N or P ratios were calculated as the average of all litterbags' substrates prior to in-situ mineralization studies. Final C: N or P ratios were taken from the average C: N or P ratios observed at the termination of the decay experiments. As many stoichiometric relationships are non-normal, data were log-transformed prior to the analysis [27]. Net mineralization rate, k, was calculated through equation [81],

$$\frac{dN}{dt} = -kN \Longrightarrow A = Be^{-kt} \Longrightarrow \log A = \log B - kt \Longrightarrow k = \frac{\log B - \log A}{t}. \tag{1.1}$$

where A is the initial mass while B is the final mass of a given nutrient of net mineralization; t is the number of days of litterbag incubation, which is a time of mineralization and immobilization. Therefore the unit of k is log(mmol)/day.

Mean annual temperature (MAT) and precipitation (MAP) were collected from the literature were reported. WorldClim subsequently estimated studies that did not report MAT and MAP. WorldClim is a database of high spatial resolution global weather and climate data. According to the year, altitude, latitude, and longitude of the field experiment in the literature, WorldClim was used to obtain the corresponding MAT and MAP.

1.4 Results

Fig 1.2(a) and Fig 1.2(b) are relationships between the initial and final C:N and C:P of litter substrates over the course of the experiments across the global data set. The x-axis represents the mass of the C/N and C/P ratio, and the y axis is the density (%) of litterbags (total $n = 193$) within a specific ratio range. The blue curve is the initial mass ratio of nutrients, while the orange curve is the final mass ratio after net mineralization. The blue and orange line is the mean of the C: N and C:P ratio of litterbag substrates. All units are in mmol.

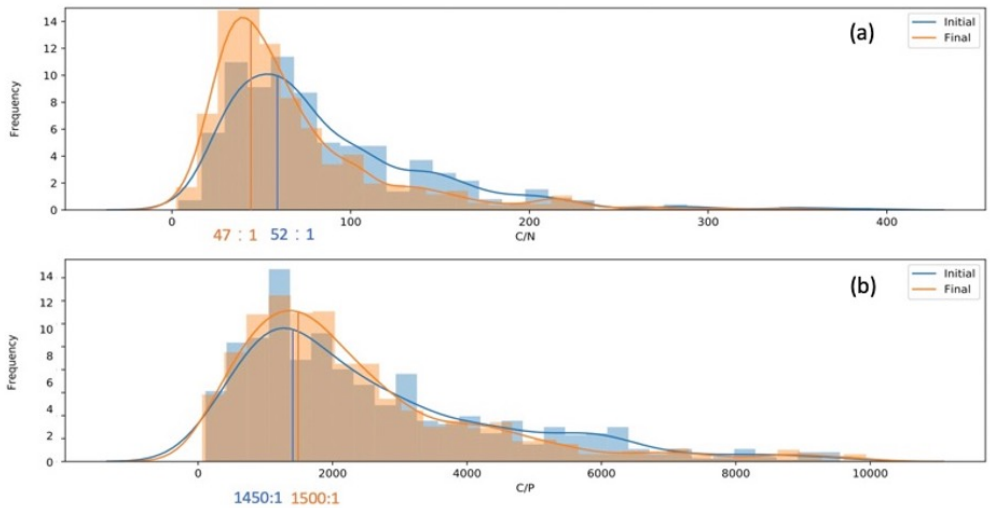

Figure 1.2: Distribution of C:N and C:P of litter substrates before and after mineralization

The mean C: N and C:P ratios before and at the end of the litter decay continuum across sites showed a systematically skewed distribution, particularly for C/P ratios. The mean C: N of the initial litter ($47 : 1$, $SD = 93.78$) was slightly lower than but similar to the final C: N ratios ($52 : 1$, $SD = 71.66$), In contrast, the mean C:P of the initial litter ($1450 : 1$, $SD = 450.45$) was lower than the final ratio ($1500 : 1$, $SD = 509.17$), deviating by 50 units total.

Because the data is non-normally distributed, all data are log-transformed. The x-axis and y-axis in Fig 1.3. (a) and Fig 1.3. (c) represent log(N loss) and log(C loss) of net mineralization, whose units are mmol. The color bar in Fig 1.3. (a) is mean annual temperature (MAT, unit $^{\circ}C$) of experimental or field sites while in Fig 1.3. (c) mean annual precipitation (MAP, in millimeter units). The redder the color, the higher the MAT and MAP, while the bluer, the lower. The x-axis and y-axis in Fig 1.3. (b) and Fig 1.3. (d) represent log (phosphorus loss) and log (carbon loss) of net mineralization, whose units are mmol. The color bar in Fig 1.3. (b) is mean annual temperature (MAT, unit $^{\circ}C$) of experimental or field

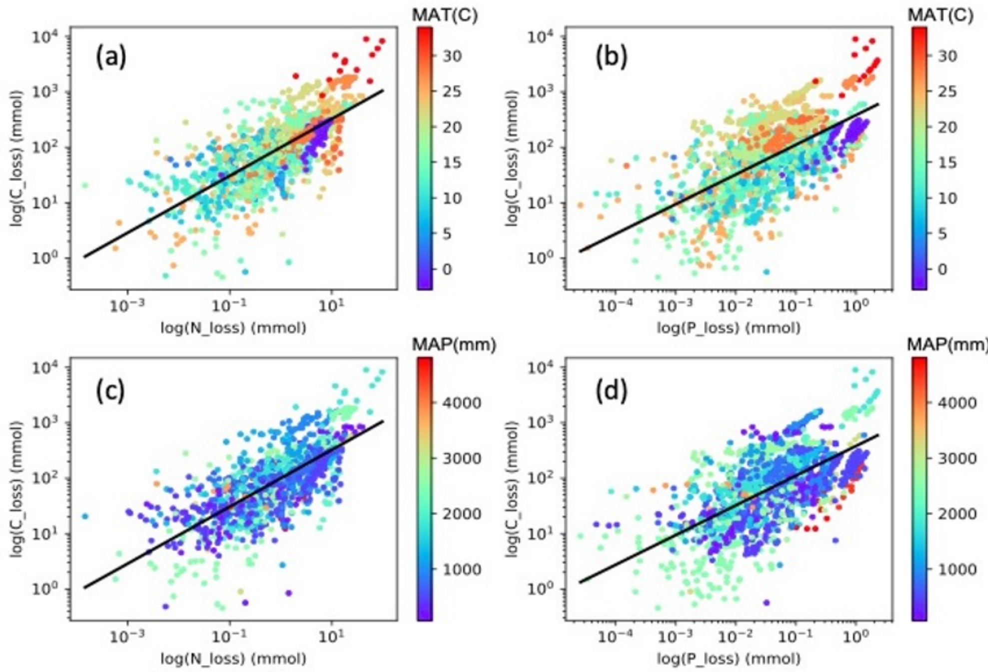

Figure 1.3: The relationship between C, N, and P loss from litter during decay as a function of the climate factors of the site, MAT (mean annual temperature), and MAP (mean annual precipitation).

sites while in Fig 1.3. (d) mean annual precipitation (MAP, unit: millimeter). Each dot is one litterbag (total n = 193). The solid black line is the fitting line of nutrient loss.

The bivariate relationships between fractions of C and N and C and P that were lost from the litter during the decay process was highly correlated across the compiled global data set (Fig. 1.3). The relationship between the log-transformed C vs. N data revealed a slope of 0.50 with an r^2 of 0.48. This was almost identical to the slope for C vs. P (0.49), although with a slightly lower Rsquared of 0.38. MAT was related to the increase in C, N, and P losses and their relationships across biomes, whereas MAP did not show a similarly coherent role.

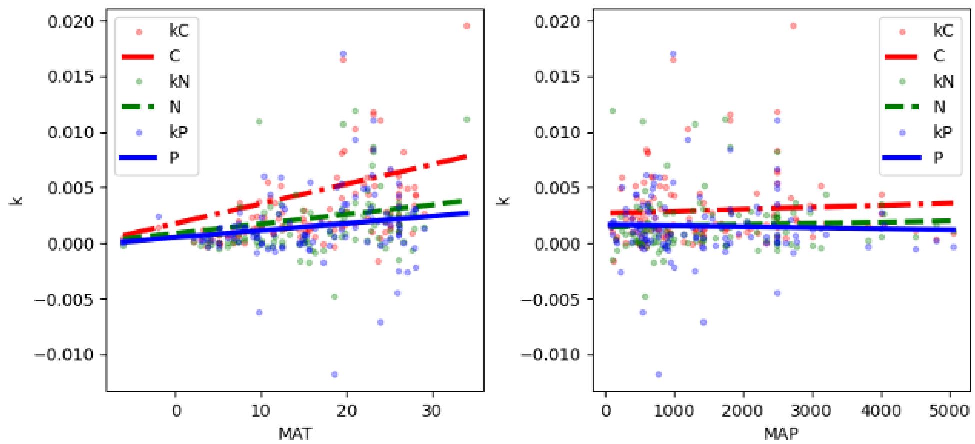

Figure 1.4: Relationship between net mineralization rates of nutrients and climate factors (MAT and MAP)

k is the rate constant derived from litter decay experiments expressed in units of 1/time. Each dot is one litterbag (total $n = 193$). Fig 1.4(a), the x-axis is mean annual temperature (MAT) whose units are $^\circ C$ and in Fig 1.4(b) is mean annual precipitation (MAP) whose units are millimeter (mm) respectively. The red dots are net mineralization rates (k) of carbon, the green dots are net mineralization rates (k) of nitrogen, and the blue dots are net mineralization rates (k) of phosphorus for each litterbag.

In Fig 1.4., additional analysis of the rate constant ($1/t$) of litter decay for C, N, and P revealed an influence of climate that was most pronounced for C losses from litter, which was faster in warmer climates (Fig 1.4). A fitting linear mixed-effects model using `lm4` was used as: `model <- lmer (k ~ MAT + MAP + (1|Time) + (1|Litter), data=decomposition, REML=FALSE)`. Residual shows that the length of the Time (experimental period) has no effect on k value while Litter (litter quality, initial C/N, and N/P) does. From Anova test, MAT ($p = 0.0063$) has a significant effect on k value and MAP ($p = 0.15$) has no significant effect on k value. The rate of C loss from litter showed a slope of 3.356×10^{-4} and r^2 of 0.375 when regressed against MAT. The slope of this relationship was not as steep for N loss from litter ($m = 1.389 \times 10^{-4}$), although the correlation was stronger than observed for C ($r^2 = 0.513$). Finally, the rate of P loss from litter showed the shallowest slope ($m = 1.471 \times 10^{-4}$) that did not differ substantially from that of N, and which showed more scatter in the relationship that for either C or N ($r^2 = 0.314$). All these relationships were significant at the $p < 0.05$ level). In contrast to the statistically significant relationships with MAT, the role of MAP in the rate of C, N, and P losses from the litter was lacking (Fig 1.4(b)).

1.5 Discussion

1.5.1 Evidence for globally explainable patterns of C, N, and P losses from litter

I tested the hypotheses that C, N, and P are strongly coupled through the litter decay process, with important differences in rates of N and P losses from litter vs. C, which are consistent with global ecological models and theory. The finds of my compilation support the Magill and Cole model of the preferential release of P compiled to C, given the role of phosphodiester-bonded forms of P, which do not include C compounds. On average, the final C:P stoichiometry of litter was lower than the initial substrates, meaning that P was mobilized from litter more quickly than C, with a slight decoupling. In contrast, the C: N of initial and final litter was similar across global data. This suggests these elements are strongly coupled, given the fundamental biochemistry of C-N bonds in plant matter. These C, N, and P patterns were apparent in the global data set, which provides strong evidence for widespread Magill and Cole-type dynamics across terrestrial ecosystems.

While these results are consistent with theoretical predictions, the strong correspondence between C/N during the litter decay continuum across sites reveals the net influence or N fixation in litter, immobilization, and mineralization losses of N during decomposition. Marklein et al. estimated that asymbiotic N fixation only accounts for 0.7% of net N mineralization, implying that this would have minor control over the findings compared to the influence of immobilization and mineralization.

Another factor could involve the physical leaching of N versus P from litter beyond biological-driven influences on mineralization of C, N, and P showed that the solubilities of different elements in dissolved organic matter vary, but with considerable uncertainties in stoichiometric effects [90]. The preferential leaching of P from litter has been observed [35, 109], which is likely driven by differences in the chemical bonding of P and storage pools. P, which is decomposed and leaches from litter, may be geochemically bound to mineral surfaces of soils rather than leave the ecosystem immediately [80]. Such geochemical solid sinks can limit the immobilization of P into litter by microbes during decomposition.

1.5.2 Climate dependencies on C, N, and P interactions during litter decay

The results of this study support the hypothesis that temperature influences rates of litter decay and C, N, and P losses from litter across global ecosystems. The stoichiometric connections between C: N and C: P held across a global range of temperatures, with rates of losses of each of these elements increase in the hottest climates. However, there was a tendency for the coldest sites to exhibit elevated C/N and C:P loss ratios compared to temperate climates, which likely originated from the planned litter collected from the boreal sites or changes in the optimal rates through which microbial enzymes can accelerate decay processes. This argues from strong climate effects affected by litter quality and microbial enzyme activities at high latitudes.

Liu and others have revealed that the rate constants (k) for net mineralization and decomposition increase significantly with increasing temperatures[76]. C, N, and P decay rates increased with mean annual temperature (MAT), which is consistent with previous researchers [77, 145, 142]. The rate of P loss from litter responded less to changes in MAT than N or C, which could reveal a strong sink for P in the tropical litter, as microbes seek to immobilize P from the external environment. Ċarbon showed the fastest net mineralization rate that was strongly affected by temperature. (MAT). That C is progressively decoupled from N, and P suggests that respiration from the litter can drive ecosystems towards positive feedback on climate change because C is disproportionately compared to N and P recycling with increased MAT. However, the steady

CHAPTER 2

FERTILIZER USE BY 2050: ANALYSIS OF HUMAN DIETS, TECHNOLOGY AND CLIMATE RISKS WORLDWIDE

2.1 Abstract

Commercial fertilizer use has dramatically improved crop yields since the early 20th century, underpinning the caloric nutrition of more than ~ 3 billion people worldwide. However, wholesale inefficiencies and regional disparities in nitrogen and phosphorus fertilizer use have negative consequences, including widespread environmental challenges, such as reduced groundwater and air quality, rising greenhouse gas emissions, biodiversity losses, and economic burdens on farmers. As Earth's human population continues to expand to projected 9 to 10 billion people by 2050, it is critical to optimize agricultural fertilizers and understand the impact of human diets, climate change, technology, and land use change on global fertilizer demands. Here I examine nitrogen and phosphorus use efficiency globally and across countries to investigate systemic controls over fertilizer demands vis-a-vis model-based scenario analysis in 2050. A business-as-usual scenario, which assumes that the world's human populations growth, nutrient use efficiency, and dietary choice follow current trends, demonstrates 31.77% and 17.21% increase in nitrogen and phosphorus fertilizer use, respectively, by mid-century. In contrast, climate change mitigation, human dietary shifts favoring the EAT-LANCET diet, and improving nutrient use efficiency portend a reduction of nitrogen and phosphorus fertilizer use in 2050 compared to 2015. The most critical factor in determining these potential reductions in nitrogen and phosphorus applications is based on assumed increases in

nutrient use efficiency, particularly for nitrogen, where essential changes in crop breeding, fertilizer management, and precision agricultural approaches have resulted in improvements over the past several decades. Much of the increase in fertilizer demands by 2050 will occur in the global South and Asia, implying an intentional focus on optimized fertilizer access that considers climate change mitigation, economics, environment, and food security in these areas. The role of large-scale systematic factors implies the potential to support 9 to 10 billion people with less fertilizer, offering agricultural and environmental sustainability opportunities.

2.2 Introduction

Fertilizers have had a profound impact on modern agricultural progress and human survival. However, world nutrient imbalance is a significant and growing threat to agricultural sustainability, climate change, and the environment. Most major developed economies have benefited from widespread access to fertilizer inputs [37]. However, many countries in Africa, Asia, and Latin America still suffer from inadequate nutrient supplies due to economic, trade, cultural, and political constraints [59]. On the other hand, excessive fertilizer use beyond crop demands economically disadvantaged farmers. This leads to nutrient losses and environmental pollution, such as global warming caused by N2O emissions and eutrophication resulting from leaching. Therefore, it is essential to study the opportunities to radically improve fertilizer use worldwide for the mutual benefit of agriculture and the environment.

Nutrient use efficiency is a commonly used metric in agriculture defined as the nutrient content of yield divided by fertilizers inputs [123]. Nitrogen and phosphorus limit macro-nutrients for crop, animal, and human health. They play a critical role in the food supply chain and agricultural ecosystems. Understanding nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) is a priority because these nutrient fertilizers have contributed much to the remarkable increase in food production that has occurred during the past 50 years of the "green revolution" [119].

There are two major factors influencing nitrogen and phosphorus use efficiency, including 1) uptake efficiency, or the ability of the plant to remove N/P from the soil, ordinarily present as nitrate or ammonium ions or soluble P, and 2) utilization efficiency, or the ability of the plant to transfer the N/P to the grain, predominantly present as protein [10]. In the absence of direct molecular biology methods, it is challenging to disentangle these two influences mechanistically. Nevertheless, simplified models based on mass-balance constraints can be used to draw larger-scale inferences of NUE and PUE at country scales, an essential unit of agricultural policy and food security.

Fertilizers are applied preferentially in regions with available irrigation water and soil and climatic conditions favor plant growth. With increasing fertilizer application rates, the possibility of nitrate and phosphorus pollution of surface and groundwater has become strongly linked with nutrient use efficiency [111]. Researchers have been working on ways to improve NUE and PUE for many years. Adesemoye and others have found that microbial inoculants, such as plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhiza fungi (AMF), can enhance nutrient uptake, especially N, P, and K from the field [2]. Fan and Liao believed that slow/controlled release fertilizers (SRF/CRF) would increase nutrients use efficiency [40]. Cao and others revealed that biochar will increase NUE, and the nitrogen-enriched amendment will increase PUE [22]. Van de Wiel et al. believed that PUE could be improved through crop breeding [126].

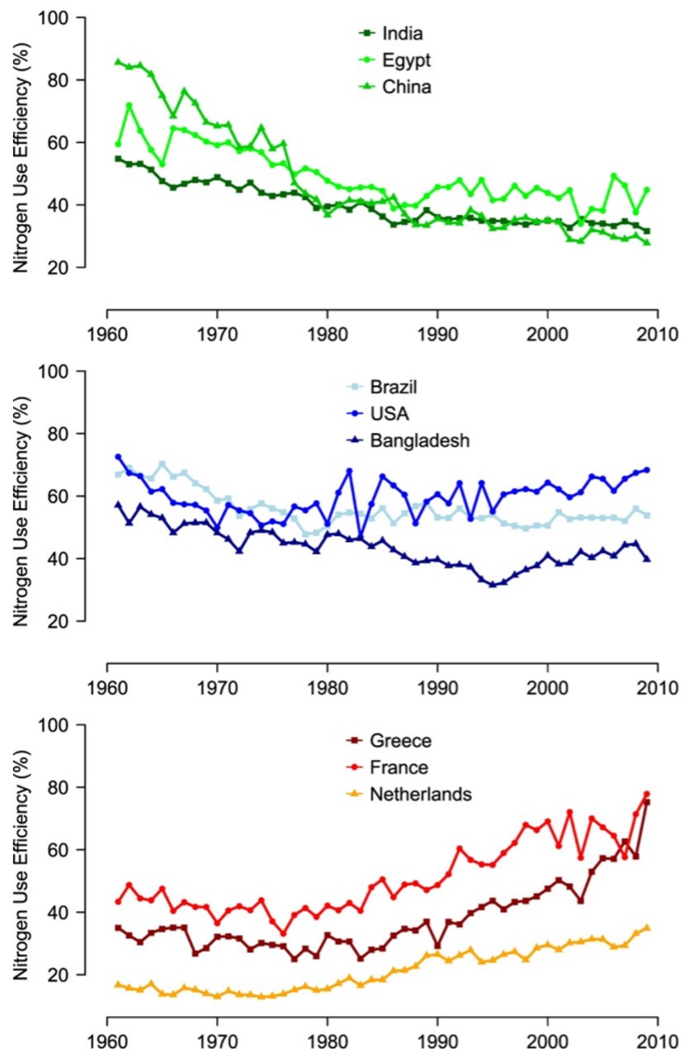

Figure 2.1: Trend of nitrogen use efficiency for nine countries from 1960 to 2010 based on Lassaletta et al., 2014Different color represents a different country, and each dot represents the NUE value for a specific country in a specific year. [74]

Past analysis has collated information on country-scale fertilizer use to construct various degrees of downscaled spatial distribution estimates of fertilizer applications and nutrient use efficiencies in croplands. The changing trend of NUE in the past 50 years varies from country to country because of climate and economic factors, fertilizer, and cropland management (Fig 2.1). In developing countries such as India and China, with the heavier use of fertilizers year by year, the nutrients use efficiency has been continuously decreasing, while in developed countries in Europe such as France and Netherlands essential gains have been observed [74]. However, previous analyses have been lacking in understanding both the high-fertilizer and low-fertilizer regions of the world and their responses to systemic change. This includes a robust assessment of both N and P fertilizers and how they are affected by critical controls on agricultural production and food-growing practices worldwide, including in Global South communities where soil nutrient deficiencies are widespread, and population growth is expected to rise.

This study examines global and regional nitrogen and phosphorus fertilizer demands in the year 2050 in response to systemic change factors. A global model is developed to forecast future nitrogen and phosphorus fertilizer application globally and spatially. The factors investigated include population growth, climate, cropland change, dietary shift, and NUE increasing into the model as inputs.

2.3 Methods

2.3.1 Nutrient use efficiency

Conceptually, I analyzed systemic effects on nitrogen and phosphorus use through a global model analysis that considers crop nutrient use efficiencies, which span several definitions (Table 2.1). Here NUE and PUE are defined as the nutrient use efficiency of crops (bold in Table 2.1) rather than including the entire crop-soil system. This approach focuses on the number of nutrients recovered in the grain compared to the amount of fertilizer added, which connects the nutrients added to the food systems directly annually and is amenable to global estimates, given data and parameter constraints. Moreover, while the inclusion of global soil nutrient accumulation is insightful, such an analysis is secondary to the primary focus on nutrients in crops compared to fertilizer added; it is focused on fates beyond the initial year of fertilizer application, beyond the scope of this study.

2.3.2 Model and calculations

175 types of crops were used in the analysis based on the dataset "Harvested Area and Yield for 175 Crops". For each crop, the production (Yield) is estimated following FAO data, and the nutrients content (N content (%) and P content (%) of production is estimated following Hong et al., Lander et al., and FAO data [57, 73]. NUE and PUE maps contain 130 countries together. These countries represented 99.2% of the world population and 99.6% of the cropland surface in 2015. NUE and PUE were calculated by two below equation:

$$
\begin{aligned}
NUE &= \frac{Yield \times NContent(\%)}{FertilizerN + ManureN + FixationN + DispositionN}, \\
PUE &= \frac{Yield \times NContent(\%)}{FertilizerP + ManureP}.
\end{aligned}
\tag{2.1}
$$

Data on annual nitrogen and phosphorus fertilizer and manure application rates for each country were derived from the FAO dataset (see Fertilizer N and Manure N in the equation above). The yearly atmospheric N depositions (NH_x-N and NO_y-N) during 1860–2015 were from the International Global Atmospheric Chemistry (IGAC)/Stratospheric Processes and Their Role in Climate (SPARC) Chemistry–Climate Model Initiative (CCMI) N deposition fields. CCMI models explicitly considered N emissions from natural biogenic sources, lightning, anthropogenic and biofuel sources, and biomass burning [38]. The transport of N gases was simulated by the chemical transport module in CCMI models. Data were on a 5 minute by 5 minutes ($\sim 10 \times 10\ km^2$) latitude/longitude grid and were summed up by each country, in other words, upscaled to country level. Units are tons (Deposition N in the equation above).

Cropland N fixation was estimated following the procedures described in Hong et al., [57], which relates N fixation rates to crop yield in specific production areas. Coefficients used in the estimation of N fixation by major crops were based on Han and Allan, 2008. Units are tons. (Fixation N in the equation above)

Creating a 2015 fertilizer map follows methods from Potter et al. [95]. [95]. Monfreda et al. have collected the data of the harvested area and yields of 175 different crops of the world (M3-crops) [88], and the latter was merging satellite-based land-cover data with global subnational cropland inventory data by Ramankutty and others [102]. The data represent the year 2000 and are available at 0.5° spatial resolution in latitude by longitude. The global maps of N and P input through fertilizer were developed by merging the harvested area from the M3-crops database with national-level fertilizer-use data for the same crops. The following equation downscaled fertilizer application rates:

$$F(i, j) = \sum_{c} F_{IFA}(k, c) A_{M3-crops}(i, j, c) \frac{A_{IFC}(k, c)}{A_{M3-crops}(k, c)} \quad kg\ ha^{-1}, \tag{2.2}$$

Where $F(i, j)$ are the spatially explicit fertilizer maps of N and P (units = kg of N or P ha^{-1} of gridcell area), with a spatial resolution of 0.5° in latitude by longitude; i and j are the longitude and latitude indices, c is an index indicating different crops, and k is the country index (and we use a 0.5° resolution spatial map relating countries to latitude–longitude indices); $FIFA(k, c)$ are the crop-specific IFA national fertilizer statistics (units = $kg\ ha^{-1}$ of crop area); AM3-crops (i, j, c) is the spatially explicit crop harvested area data from Monfreda et al. [88] (with unit ha of crop area, ha^{-1} of gridcell area); $AIFA(k, c)$ is the national total harvested area reported in the IFA statistics (with unit ha of crop area); and AM3-$crops(k, c)$ is the national total harvested area calculated from the M3-crops database (with unit ha of crop area).

2.3.3 Data sources

Multiple anthropogenic N input databases were integrated to generate the data sources for the models. Annual country-level statistics data were obtained from the FAOSTAT "Land, Inputs and Sustainability" domain (FAO, 2021); N fertilizer applied to soil data were obtained from the "Fertilizers by Nutrient" subsection; and manure applied to soil data were obtained from the "Livestock

Manure" subsection.

The FAOSTAT agricultural use of N fertilizer and manure referred to the N use for crops, livestock, forestry, fisheries, and aquaculture, excluding N use for animal feed. The use of N fertilizers and manure for forestry, fisheries, and aquaculture was minor compared with that for crops and livestock, so the former was assumed to be negligible. The N fertilizer application partitioning ratio to cropland and pasture was adopted from Lassaletta et al. [74]. As the Lassaletta et al. ratio values only covered the period from 1961 to 2009, values in 2009 were used to calculate the N application partitioning for 2015. According to the FAO definition, manure applied to soil was equal to the difference between all treated manure and N loss during the storage and treatment processes. Therefore, I assumed that the total quantity of manure applied to soil was equal to that of manure applied to cropland and pasture. The fraction values for cropland were from Zhang et al. [143], who assumed that the fraction value ranged between 0.5 and 0.87 for European countries, Canada, and the USA, whereas it was 0.9 for other countries.

The `HYDE3.2` dataset [70] provides historical spatial distributions of cropland, pasture, and rangeland at a 5 arcmin resolution and at an annual time step after 2000 but a decadal time step before the 1990s. In contrast, the `LUH2` dataset (Hurtt et al., 2020), derived mainly from `HYDE3.2`, has an annual time step from 1860 to 2019 but at a relatively low spatial resolution of. To reconcile these two datasets, I first conducted a linear interpolation to `HYDE3.2` before 1999 using the data from every 2 neighboring decades. Then the fraction of crop, pasture, or rangeland of a `LUH2` grid was partitioned into all grid cells of `HYDE3.2` that fell in the `LUH2` grid, according to their shares in `HYDE3.2`. Using this routine, I obtained a land use dataset that both kept the spatial information of `HYDE3.2` and was consistent with `LUH2` with respect to the total area for each land use type.

2.4 Model Scenarios

Systematic factors that regulate fertilizer demands are examined, including population growth, dietary shifts, changes in nutrient use efficiency, and climate change. The model was used to determine the relative effect of different factors compared to a 2015 baseline year and a business-as-usual analysis for the year 2050. Consequently, the scenarios were built to separate factors and evaluate their individual and collective impacts through a combined scenario. The following describes the scenarios tested with the global and regional models:

i) **2050 Business as usual**

This scenario assumes that the human population grows with dietary adoption following existing trends without additional climate mitigation or nutrient use efficiency changes. No extra measures are taken to mitigate climate change, increase crop yields or nutrient use efficiency, and human historic dietary trends continue from the 2015 baseline in the year 2050.

This scenario examines the role of population growth and its effect on global fertilizer demands. Using the population growth model of Kohli et al.[71], the fertilizer application prediction model divides the population of 185 countries into three types: lower income class, middle class, and higher income class, and predicts country-scale 2050 populations according to moderate rates of growth for different classes. Low-income status refers to households with less than 2/3 of the national median income. The middle class is defined as households whose income is between 2/3 and twice the country's median income. High-income households are those whose income is more than twice the median income of the country in which they live. In this scenario, population growth follows middle-of-the-road development trajectories [107].

This scenario includes the effects of climate change on crop distributions and yields and uses this information to estimate global fertilizer demands by 2050. It refers to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. Under the RCP8.5 emissions scenario, the global temperature is projected to increase by $1.5°C$ from 2015 to 2050. RCP8.5 is a high-emissions scenario, assuming that the world continues to emit greenhouse gases at a high rate without significant mitigation efforts. It is suitable for forecasting 2050 in a pessimistic climate change scenario. Model IMPACT is used to quantify the impact of $1.5°C$ global temperature rising on crop distributions and yields, and results are incorporated into my 2050 BAU scenario.

The diets transition in this scenario includes more calories in total (an ~89% estimated increase in global food production from 2015 to 2050) as well as more calories from animal-sourced foods as populations become wealthier [135].

ii) **Climate change mitigation**

The Intergovernmental Panel on Climate Change (IPCC) Report summarizes and sorts out measures to mitigate climate change, such as increasing the use of renewable energy sources, improving energy efficiency, and reducing deforestation, and concludes that if these measures are adopted, the global temperature can be 1.5 degrees Celsius lower than in 2015. Therefore, this scenario adopts their assumptions and predicts the fertilizer needs when the global temperature is lowered by $1.5°C$.

iii) **Dietary shift**

The dietary shift scenario used a food system model incorporated into the EAT-Lancet analysis [135] assuming the diet changed to more plant-based protein while meeting human nutritional requirements standards. Referring to Perignon et al. [93], this study also assumes that by 2050, diets of different income classes will switch from animal protein to plant protein in different proportions. The EAT-Lancet model is derived from IMPACT, a global partial equilibrium economic-based food system model that estimates food demand, production, etc., in > 150 regions from 2010 to 2050. The EAT-Lancet food system model is widely used in the study of dietary shifts, so it is more convenient to use this model to compare the results of this study with other studies. The EAT-Lancet food system model provides food system projections for each region.

The diet in the dietary shift scenario assumes the population slowly transitions to a flexitarian diet by 2050. The flexitarian diet, as described in the EAT-Lancet report[1], is such that dietary composition meets best recommendations from epidemiological and nutritional literature, the assumption is current rates continue. For crop yields to increase, I assume that yield gaps will be closed by 2050. This assumption is commonly used in food system models, such as Springmann et al.[121] (2018); and Willett et al.[135].

iv) **NUE and PUE Improvements**

[1] https://eatforum.org/eat-lancet-commission/eat-lancet-commission-summary-report/

According to the historical changes of NUE in different countries, this scenario uses the machine learning prediction algorithm in Candanedo et al. study to ascertain improvements in NUE by 2050[21]. Since there is a lack of historical data on PUE improvements in the baseline data (the year 2015), this P fertilizer use by 2050 in this scenario is assumed to follow the efficiency of 2015.

v) **All methods scenario**

This scenario combines all the scenarios for 2050, including population growth, adoption of climate change mitigation methods, NUE growth over time, and a shift in the human diet to more plant-based protein and less animal-based protein.

Table 2.3. Summarize assumptions of all scenarios.

2.5 Results

2.5.1 2015 baseline for N and P fertilizer use

For the baseline year of 2015, there was a significant regional imbalance of global fertilizer N application rates (Fig. 3a). In eastern Asia, most of India, especially the northern portions, western and central Europe, eastern North America, and Central Valley of the United States, the amount of fertilizer used exceeds 20kg N/ha/yr. The highest rates were estimated for eastern China, where the application of N in fertilizer exceeds 200 kg N/ha/yr. In contrast, there were vast areas where N fertilizer use was below 5 kg N/ha/yr, such as parts of sub-Saharan Africa, South America, and Oceania. The total amount of N fertilizer added to global croplands was 121.99Tg/yr for the year 2015.

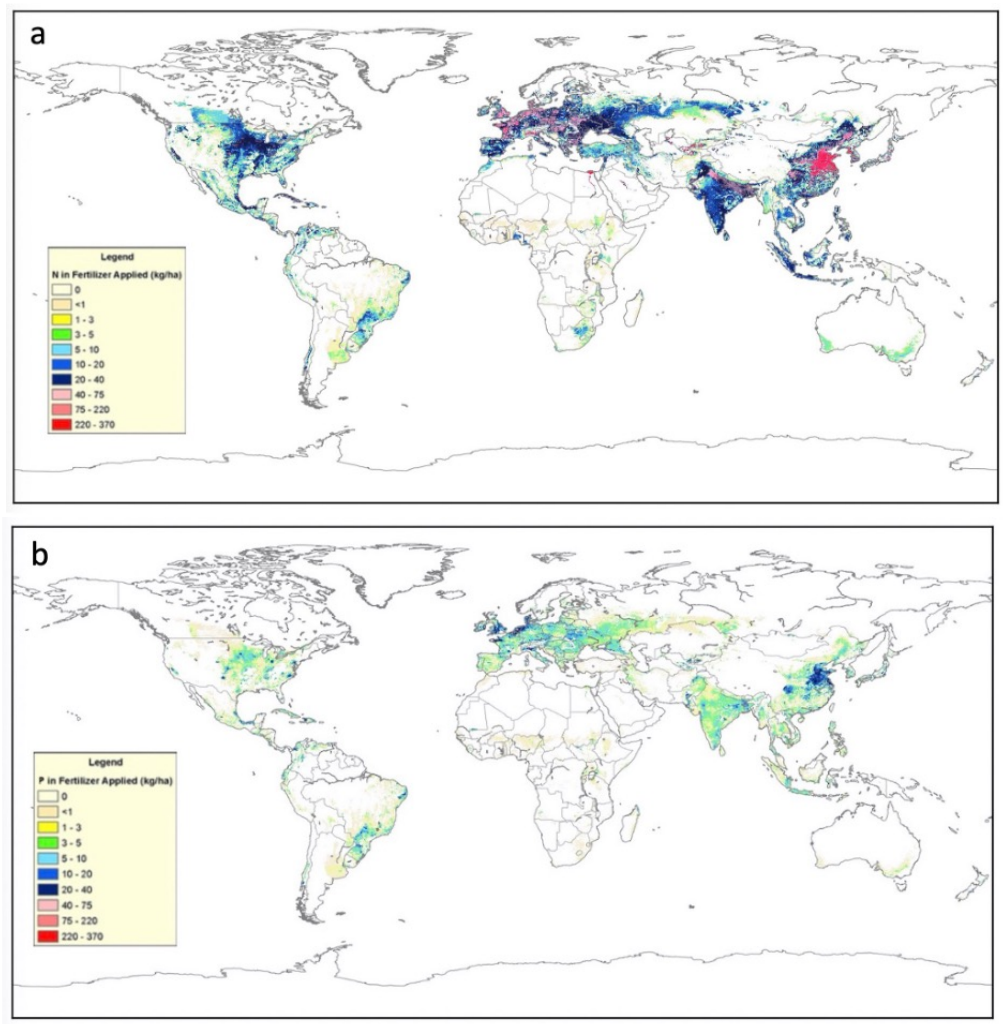

Figure 2.2: Global fertilizer applications rates for 2015. a, Estimates for N fertilizer application rates (kg/ha). b, Estimates for P fertilizer application rates (kg/ha).

The variation in P fertilizer application rates was less significant than for N. However, there was a considerable range, with the highest rates of application of P in the Global North compared to the Global South (Fig 2.2b). The amount of phosphorus fertilizer application in Europe, Asia, North America, and the southeast coastal area of South America was relatively high. In contrast, the application of P fertilizers in Africa and Oceania was relatively low. Across all areas, China, India, and most European countries use an enormous amount of phosphorus fertilizers, followed by North America. The total amount of P fertilizer added to global croplands was 22.00 Tg/yr for 2015.

Fig 2.3a shows the baseline year of 2015 variations in country-scale NUE worldwide, with lowest average values of < 20%) in most African countries, except for Nigeria (> 100%) and Ethiopia (~50%). NUE> 100% demonstrates higher N in crop yields than N inputs, which indicates loss of soil N capital to support crop production. The NUE of South American countries was also high, particularly in Argentina (> 100%), with lower NUE (< 30%) in the western coastal areas of South America. The NUE in Asian countries fell within the average NUE range of crops (30.2%~53.2%, Muhammad et al., 2020), except for Mongolia, which was less than 15%, and Kazakhstan and Cambodia, which were higher than 100%. The major economies in Asia, China, India, Japan, and Australia displayed NUEs between 28% and 40%. NUE was generally higher in North America, with 41% in Canada and 58% in the United States. Russia's NUE was 62%.

Similar to NUE, PUE showed country-scale variations around the world in the 2015 baseline year (Fig 2.3b). In North America and Central America, PUE was generally above 30%, while that of South American countries showed lower fractions of 17% except for Argentina, where the PUE was 36%. The national PUE in African nations showed two distinct patterns. The PUE in the northern and southern regions was around 30%, while the PUE in the central inland countries exceeded 100%. The PUE in Europe and Oceania was like North America, mainly varying between 20% and 35%. Among Asian countries, the PUE of China and India was 18% and 19%, respectively. Mongolia, Kazakhstan, Bhutan, Cambodia, and Myanmar were above 100%, and Afghanistan's nationwide PUE was 93% in the 2015 baseline.

2.5.2 2050 business as usual scenario

Fig 2.4a shows the model-based forecast of N fertilizer application rates in 2050 for the BAU scenario. Compared with Fig 2.2a (2015 baseline), fertilizer application forecasts were significantly higher in almost all regions worldwide, especially China, India, southern South America, and eastern North America. In contrast to the global pattern, fertilizer application forecasts remained relatively unchanged in Western Europe, primarily because of a lack of population growth. The predicted total N fertilizer application in 2050 is 31.77% higher than in 2015, reaching 160.75 Tg/yr (Fig 2.2b).

Fig 2.4b. shows the distribution map of phosphorus fertilizer application rates across global regions by 2050 under the BAU scenario. Phosphorus fertilizer in eastern and southern Asia is projected to increase by more than 30% compared with 2015. Similarly, large regions in South America and Africa are projected to increase phosphorus fertilizer rates by 25% compared to 2015 in the BAU analysis. However, North America, Europe, and Oceania did not project such growth levels. In total, the amount of P fertilizer application is projected to increase by 17.21% compared to 2015, reaching a global value of 25.79 Tg/yr (Fig 2.2b).

2.5.3 Effects of Diets, Climate Change, and nutrient use efficiency on N fertilizers

The climate change mitigation scenario (Fig 2.5a) resulted in a 3.83% reduction from the 2015 baseline, leading to 117.32 Tg/yr N fertilizer needed (Fig 2.2a). The fertilizer need in Eastern Europe and South America is significantly affected by climate, while the opposite is true in North America and Eastern Asia.

For the dietary shift scenario (Fig 2.5b), N fertilizer application rates decreased in Australia, central and eastern Europe, and South America. Assuming no population growth, the predicted total N fertilizer application in 2050, which is 95.67 Tg/yr, is 21.57% lower than in 2015 (Fig 2.2a). In Asian countries, especially India, changes in the diet significantly affect the expected demand for fertilizers in the future. Europe and America have also decreased with dietary shifts.

Considering the effect of increased NUE resulted in the most significant reductions in N-based fertilizers (Fig 2.5c). The predicted total N fertilizer application for 2050 was 10.52% lower than in 2015 (Fig 2.2a), which is 109.16 Tg/yr (Fig 2.2a). Changes in NUE have the most pronounced impact on fertilizer demand in Africa, Asia, and Oceania.

All factors combined resulted in 136.75 TgN/yr by 2050, which is 12.10% more than the 2015 baseline but 14.93% less than the 2050 BAU scenario (Fig 2.2a) compared with 2015 (Fig 2.2a), Africa, Oceania, and South America are estimated to increase fertilizer demands to feed the 2050 population. The amount of fertilizers needed in North America will remain the same as in 2015, while the demand for fertilizers in Europe will decrease. Compared with 2050

BAU (Fig 2.4a), fertilizer demand is reduced in all regions, but the reduction in Africa is insignificant.

2.5.4 Effects of Diets, Climate Change, and nutrient use efficiency on P fertilizers

The climate change mitigation scenario resulted in a 4.5% reduction from the 2015 baseline, leading to 21.01 Tg/yr P fertilizer needed (Fig 2.5b, 2.2b). The demand for fertilizers in Europe and the Americas is greatly affected by the climate, of which there is a slight increase in Europe and the Americas but a decrease in South America. Asia is less affected by climate change mitigation.

For the dietary shift scenario (Fig 2.6b), the demand for P fertilizers in Asia and North America has decreased significantly, especially in China and the United States. Combining all the systematic factors, P fertilizer use is predicted to be 24.12 Tg P/yr by 2050, 9.64% higher than the 2015 baseline estimate but 6.48% less than the 2050 BAU scenario (Fig 2.2b). Compared with 2015 (Fig 2.2b), fertilizer needs to be increased slightly, but regional differences were insignificant. Compared with 2050 BAU (Fig 2.4b), fertilizer demand is reduced, especially in India and central Europe.

[Fig 2.2a-b. The total amount of fertilizer use prediction (Tg/yr) for 2050 under different scenarios. a, 2050 N fertilizer use in each scenario. b, 2050 P fertilizer use in each scenario.]

Individual and combined factors affected total N and P fertilizer use on a global scale compared to the 2015 baseline and 2050 BAU scenario. Fig 2.2

shows that fertilizer N for 2015 is 121.99 Tg/yr. The business as usual (BAU) predicted N fertilizer use for the year 2050 was estimated to be 160.75 Tg/yr. 117.32 Tg/yr, while for the dietary shift, 95.67 Tg/yr and nitrogen use efficiency increasing 109.16 Tg/yr. If all methods are adopted, the predicted fertilizer use will be 136.75 Tg/yr, which is 12.10% more than the 2015 baseline, which drops 2050 BAU by 14.93%. The bottom plot demonstrates that using fertilizer P for 2015 is 22 Tg/yr. The business as usual (BAU) predicted P fertilizer use for the year 2050 with no mitigation act will be 25.79 Tg/yr. The result for the climate change scenario is 21.01 Tg/yr, while for a dietary shift, 19.33 Tg/yr. If all methods are adopted, the predicted fertilizer use will be 24.12 Tg/yr, 9.64% higher than the 2015 baseline and 6.48% lower than the 2050 BAU.

2.6 Discussion

This study demonstrates markedly different outcomes for mid-century fertilizer use globally and regionally in response to climate change mitigation, advances in nutrient use efficiency, population growth trends, and consumer dietary choices. This follows previous work examining such systematic factors in regulating GHG emissions and environmental impacts of the food system [25, 23] and advances understanding by including both N and P fertilizer demands worldwide. A key conclusion is that bundled influences of factors can potentially reduce global N and P use in 2050 by 14.93% and 6.48%, respectively compared with taking no actions while keeping pace with population growth, with critical spatial differences across regions.

2.6.1 Global trends of NUE/PUE

Lassaletta et al. investigated trends in nitrogen use efficiency of 9 countries before 2010, revealing areas of improvement and challenges across countries[74]. This study expands to more countries and considers future scenarios as the world population moves to a projected 9 or 10 billion people, including N and P fertilizers. The average crop nitrogen use efficiency in most countries is between 30.2%~53.2% [7]. But in reality, many countries are far from reaching the optimal efficiency.

While these projections suggest opportunities to improve nitrogen management and reduce fertilizer demands in the future, NUE is controlled by many factors, which could influence the likelihood of such improvements materializing. Texture and other properties are essential to control NUE, as the retention of nitrogen in organic matter and textural controls on leaching and denitrification affect the amount of N available to crops. Another control is climate and weather, including rainfall, temperature, and sunshine, affecting the efficiency of crops using nitrogen. And how much fertilizer is applied also affects crop nitrogen use efficiency, and proper fertilizer management can maximize nitrogen use efficiency. Different countries are at different economic and agricultural development stages, and there are considerable differences in the types, quantities, and fertilizer application methods. Finally, different crop species have entirely different nitrogen use efficiencies.

Extreme NUE values can be explained by many factors affecting NUE. The interannual differences in agricultural performance observed in some of these countries can be explained by weather, such as continuous floods and droughts, socio-political issues, or sometimes even inaccurate fertilizer data: especially in countries with crop rotation does not take t agricultural estimation, into account the nitrogen accumulated in fallow forest soils for fertilizing agricultural soils [74]. Taking Argentina as an example, their main nitrogen fertilizer is urea. Granulated urea is in demand, particularly for use in mixtures. The mixing effect of these mixtures may affect the application and absorption of nitrogen fertilizer (Fertilizer use by crop in Argentina, 2004). At the same time, in the agricultural production of these countries, due to the relatively small use of chemical fertilizers and pesticides, biological activities such as microorganisms in the soil are relatively active. These organisms transform organic matter in the soil and convert fixed N into N that plants can absorb. This part of the value is not included in the calculation.

Crop phosphorus use efficiency is similar to nitrogen, but PUE in the overall agricultural production system ranged from 22 to 76%, a more significant gap than NUE [24]. Because the PUE of different crops varies greatly, for example, the phosphorus use efficiency of soybean ranges from 30% to 90%, while rice ranges from 10% to 60%, [91]. In developed countries such as the United States and Russia, the NUE is more significant than 30%. Countries with better economic development in Asian countries are slightly lower, such as China, India, and Japan, generally around 20%. The problem of P mining is more severe than that of N, and the PUE of some countries in central Asia and most countries in central Africa with poor economies is more significant than 100%. This shows that in the agricultural systems of many countries, to maintain healthy soil and ecosystems, the amount of P needed is much greater than the actual input, which is also consistent with the conclusion in the first chapter.

In general, factors such as soil, climate, crop, agricultural management, and economy all affect the nutrient use efficiency of crops in a country. And in general, economically developed countries will have healthier nutrient use efficiency. Plants have higher absorption and utilization efficiency while maintaining soil sustainability. The soil health in economically underdeveloped areas and how to maintain high crop yield to feed the growing population will be an issue that needs attention in the future. However, it is not advisable to blindly increase the input of N and P for yield because excessive nutrients that plants cannot absorb will become pollutants and pollute water sources, causing huge environmental problems [69]. Therefore, how to estimate plant nutrient use efficiency and fertilizer demand more accurately is the only way to reduce pollution while increasing yield to feed the growing population. Knowing the nutrient use efficiency of crops in different countries can provide a baseline for fertilizer use and help us predict future fertilizer applications.

2.6.2 Impacts on fertilizer use of 2050 and regional differences

Findings show that, although according to the United Nations forecast the global population will increase from 7.37 billion in 2015 to 9.72 billion by 2050, an array of technological and human behaviors can reduce fertilizer use by 2050 compared to the business-as-usual path. If no additional mitigation measures are taken, in 2050, the nitrogen and phosphorus fertilizers needed by humans will increase by 31.77% and 17.21% respectively compared to 2015. However, when climate change mitigation measures are considered, changes in human diets and measures to increase nutrient use efficiency in crops are adopted, predicted N and P fertilizer use for the year 2050 with no mitigation act can be lower than doing nothing respectively 14.93% and 6.48%. Among the factors analyzed, the contribution of dietary shift is the largest, followed by improvements in nutrient use efficacy, and finally climate change mitigation, both for nitrogen and phosphorus. Importantly, given the paucity of data on improvements in P use efficiency, future technological approaches that reduce P use and maintain food production should be viewed as a high priority that could greatly alter the future projections for mid-century fertilizer demands.

There are significant regional differences in the application of N fertilizers. kinds of improvements that have been seen in other regions. For example, regions with diverse crop types that are more affected by climate, such as South America, are likely to show reductions in fertilizer use, as cropland production is limited by water and other resources. Areas with faster population growth will fuel more fertilizer demands in the future, and at the same time, these areas are mostly economically underdeveloped areas, where plant-based protein accounts for a large proportion of the diet, so the impact of dietary shifts is less significant in these areas. In areas with more developed countries such as Europe, changes in diet will significantly reduce fertilizer demands.

Regional differences in the application of P fertilizers are also apparent, with the largest potential reductions estimated for are linked to Asia and Europe, followed by the Americas, and the least in Africa and Oceania, but the overall amount is far less than that of N. Because there is a large demand for food in densely populated areas, the demand for fertilizers is also large. Conversely, areas with poorer economies and less population have less demand [54]. If nothing is done, Africa and Asia will need more phosphorus fertilizers due to faster population growth. If action is taken, Europe is mainly affected by climate change mitigation measures, Asia is mainly affected by the dietary shifts, and

America is affected by both, so the forecast reduction of phosphorus fertilizer use is obvious. This is related to the current PUE, crop distribution, diet, and future population expectations of each region.

2.7 Uncertainties, limitations, and future work

While the modeling scenarios examined to provide insights into systemic factors of change and their influence on regional and global N and P demands in the future, several limitations and uncertainties in the model could result in more robust projections. In particular, the calculation model of NUE and PUE is very simplified, and some inputs are not taken into account, such as rock weathering. And the data of some countries is not accurate, for example, it is difficult to accurately record the manure inputs in some areas of China. In addition, incomplete or inaccurate fertilizer application estimates in African countries mean that results for these regions are less certain than for other areas of the world. In addition, when predicting the fertilizer map in 2050, the machine learning algorithm can only estimate the future fertilizer usage in each scenario based on the existing fertilizer and data of the past few years: it cannot predict new factors that may appear in the future, such as emerging fertilizers and fertilization methods.

Furthermore, although estimating crop yields based on the fixed nutrient content of each crop is a standard way to calculate nutrition budgets [123], the actual nutrient content of crops varies with genetic diversity, different management practices, and local environmental conditions. However, these variabilities are difficult to examine in large-scale modeling studies.

2.8 Conclusions and implementations

In conclusion, optimizing fertilizer use globally is essential to ensuring food security, economic growth, and environmental sustainability in the face of an expanding global population. While fertilizers have played a critical role in improving crop yields and feeding billions, excessive and inefficient fertilizer use has resulted in widespread environmental challenges, including groundwater and air quality degradation, rising greenhouse gas emissions, and biodiversity loss. However, human taking efforts can significantly reduce fertilizer demands and mitigate the negative impact of fertilizer use. Large-scale systematic factors, such as climate change mitigation, and dietary shifts to more plant-based protein, will influence global fertilizer demands in the coming decades, with a particular emphasis on optimizing fertilizer access in the global South and Asia. The potential for supporting 9 to 10 billion people with less fertilizer offers an opportunity for sustainable agricultural and environmental management. Overall, research and innovation in nutrient use efficiency will continue to play a vital role in balancing agricultural needs and environmental sustainability.

Definition	Expression	Unit	References
Agronomic N Efficiency AE_N	Crop Yield Increase*/ Fertilizer Application Rate	kg.ha -1 /kgN.ha-1	Cassman et al. 2002; Dobermann et al. 2005; Spiertz et al. 2009.
Crop Recovery Efficiency of Applied N RE_N	Increase in N Uptake/ Fertilizer Application Rate	kgN.ha -1 /kgN.ha -1	
Physiological Efficiency of Applied N PE_N	Crop Yield Increase*/ Increase in N Uptake	kg. ha -1 /kg N.ha -1	
Apparent N Use Efficiency ANUE	N in Grain / Fertilizer Application Rate	kgN.ha -1 /kg N.ha -1	
Crop Recovery Efficiency of Total N input	**N in Grain / (Fertilizer + Manure + Fixation + Deposition)**	**kgN /kgN**	**Lassaletta et al. 2014**
P Use Efficiency	**P in grain/Fertilizer + Manure**	**kgN /kgN**	**Schroder et al. 2011**
P Use Efficiency $_{B\&A}$	Biomass production per unit P per unit time * P residence time	mol g-1 s-1	Veneklaas et al. 2012

Table 2.1: Definitions of nitrogen and phosphorus use efficiency in the primary scientific literature (The increase* is compared to a zero-fertilizer application scenario)

Data source	Dataset	Reference
FAOSTAT	Annual country-level fertilizer and manure inputs (1961-2019)	FAO (2021)
EARTHSTAT	Fertilizer and manure application rates for major crops	Mueller et al. (2012) West et al.(2014)
EARTHSTAT	Harvested area and yield for major crops	Monfreda et al. (2008)
HYDE3.2/LUH2	Cropland, pasture, rangeland (1860-1960)	Holland et al. (2005)
Holland et al. (2005)	Global fertilizer and manure N (1860 - 1960)	Nishina et al. (2005)
Nishina et al. (2017)	Annual NH4+ and NO3- fraction in total fertilizer (1961 - 2014)	Nishina et al. (2017)
GLW3	Livestock distribution maps	Gilbert et al. (2018)
Eyring et al. (2013)	Monthly atmospheric N depositions (NHx-N and NOy-N) Yearly atmospheric N depositions (NHx-N and NOy-N) (1860 - 2015)	Eyring et al. (2013), IGAC, SPARC

Table 2.2: Summary of main data source

Scenarios/Assumptions	Population growth	Climate change	Dietary shift	Nutrients use efficiency increase
BAU 2050	Follow current trend	Follow current trend	Follow current trend	Follow current trend
Climate change mitigation	Fixed as 2015	Take mitigation method	Fixed as 2015	Fixed as 2015
Dietary shift	Fixed as 2015	Fixed as 2015	EAT-Lancet	Fixed as 2015
NUE increase	Fixed as 2015	Fixed as 2015	Fixed as 2015	For N, follow current trend. For P, fixed as 2015
All methods	Follow current trend	Take mitigation methods	Change the diet	For N, follow current trend. For P, fixed as 2015

Table 2.3: Summary of scenarios and assumptions

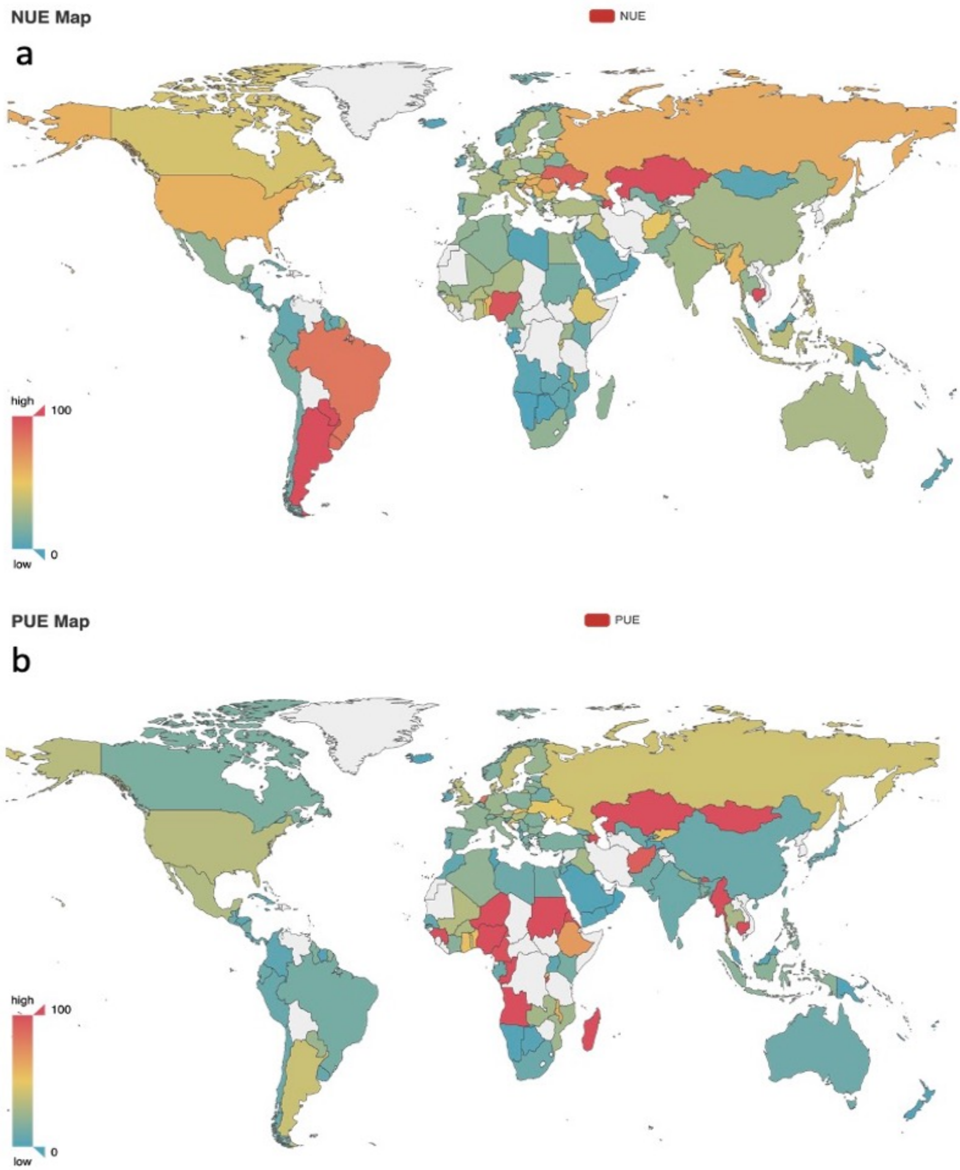

Figure 2.3: Global nutrient use efficiency at the country scale for year 2015. a, Nitrogen use efficiency map in global croplands for the year 2015. Different colors represent the value of NUE from 0% to 100%. The darkest red color represents a value larger than 100%. b, Phosphorus use efficiency map in global croplands for the year 2015. Different colors represent the value of PUE from 0% to 100%. The darkest red color represents a value larger than 100%.

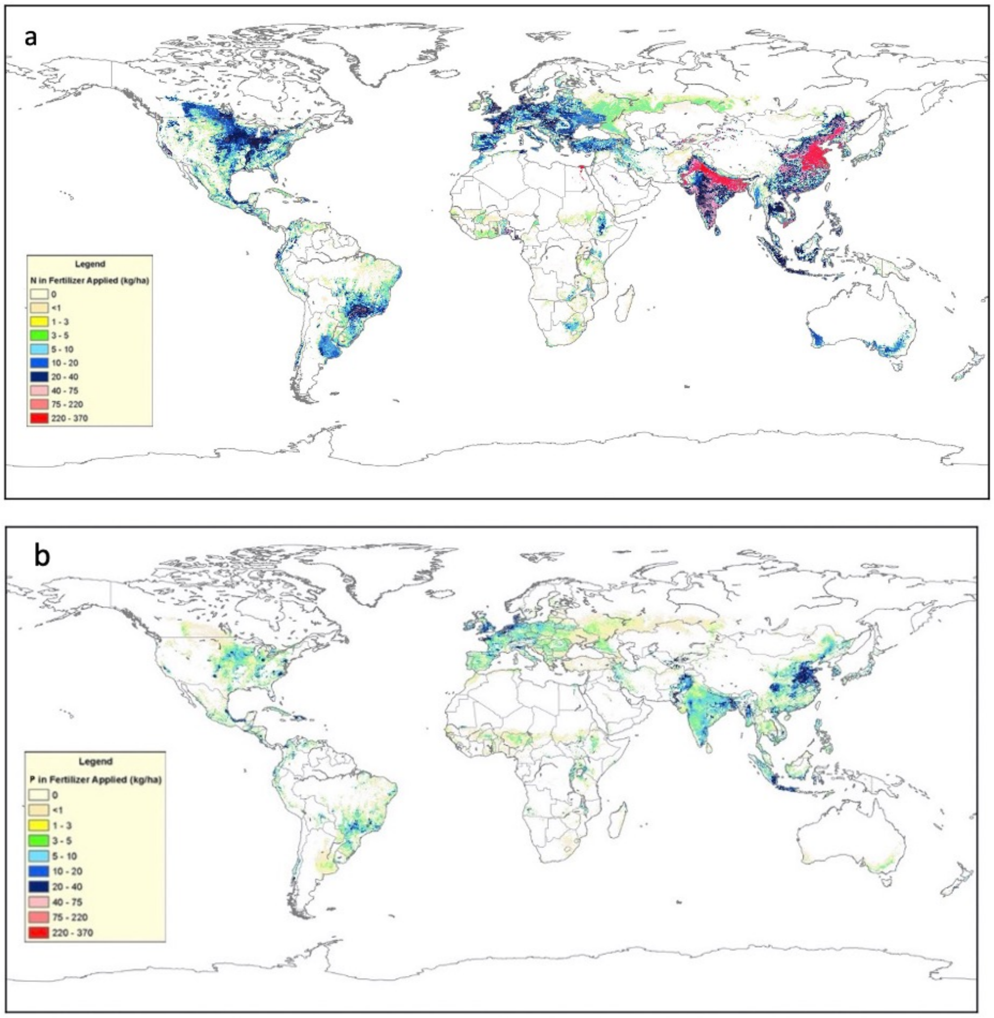

Figure 2.4: (a) Nutrients input map for 2050 under the BAU scenario. a, N input map. (b) P input map

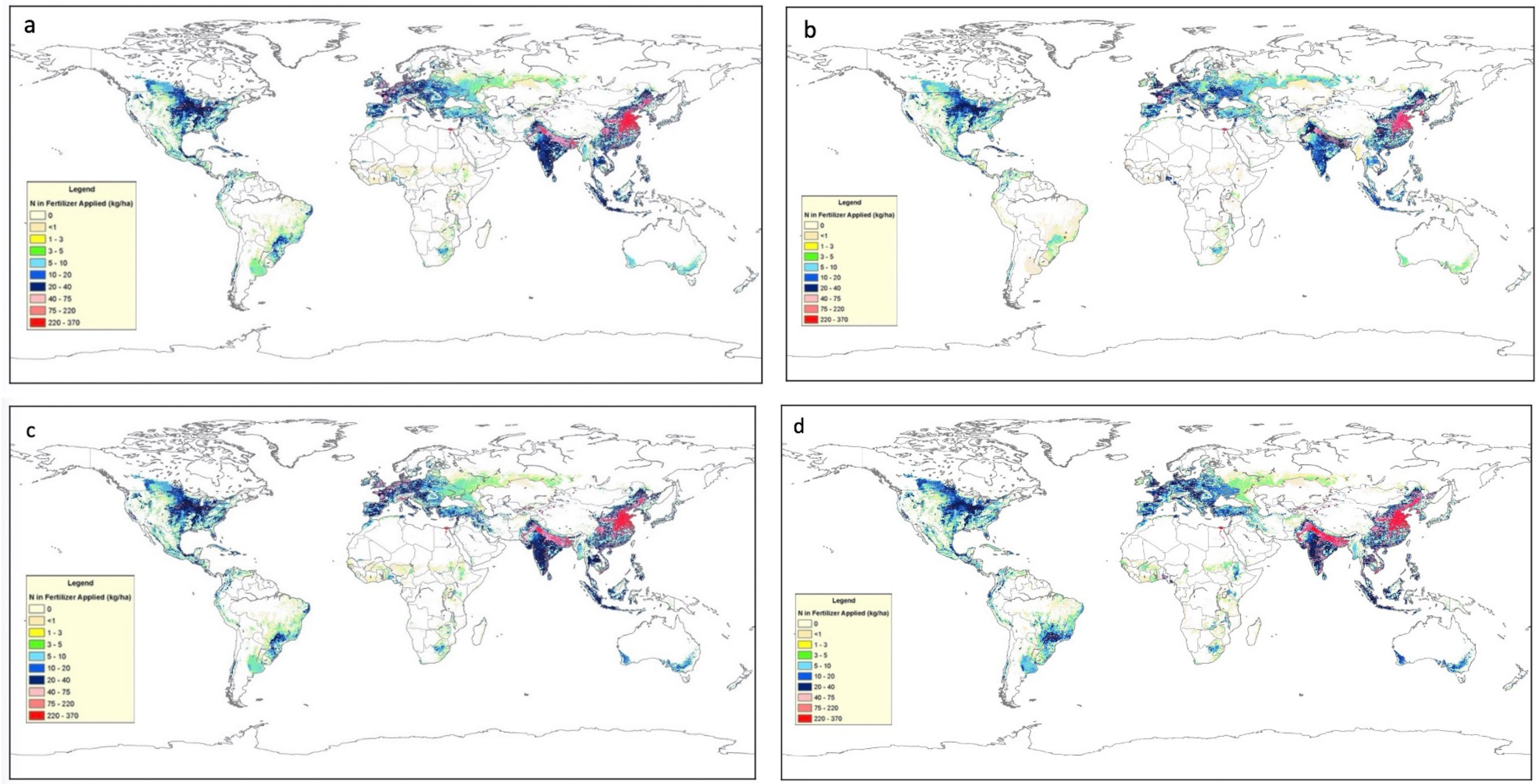

Figure 2.5: Scenarios showing the influence of climate change mitigation, dietary shifts, improvements in NUE, and all combined systemic influences, on global and regional nitrogen fertilizer applications in the year 2050. (a) Climate change mitigation. (b) Dietary shifts. (c) Nitrogen use efficiency improvement. (d) All systemic influences combined.

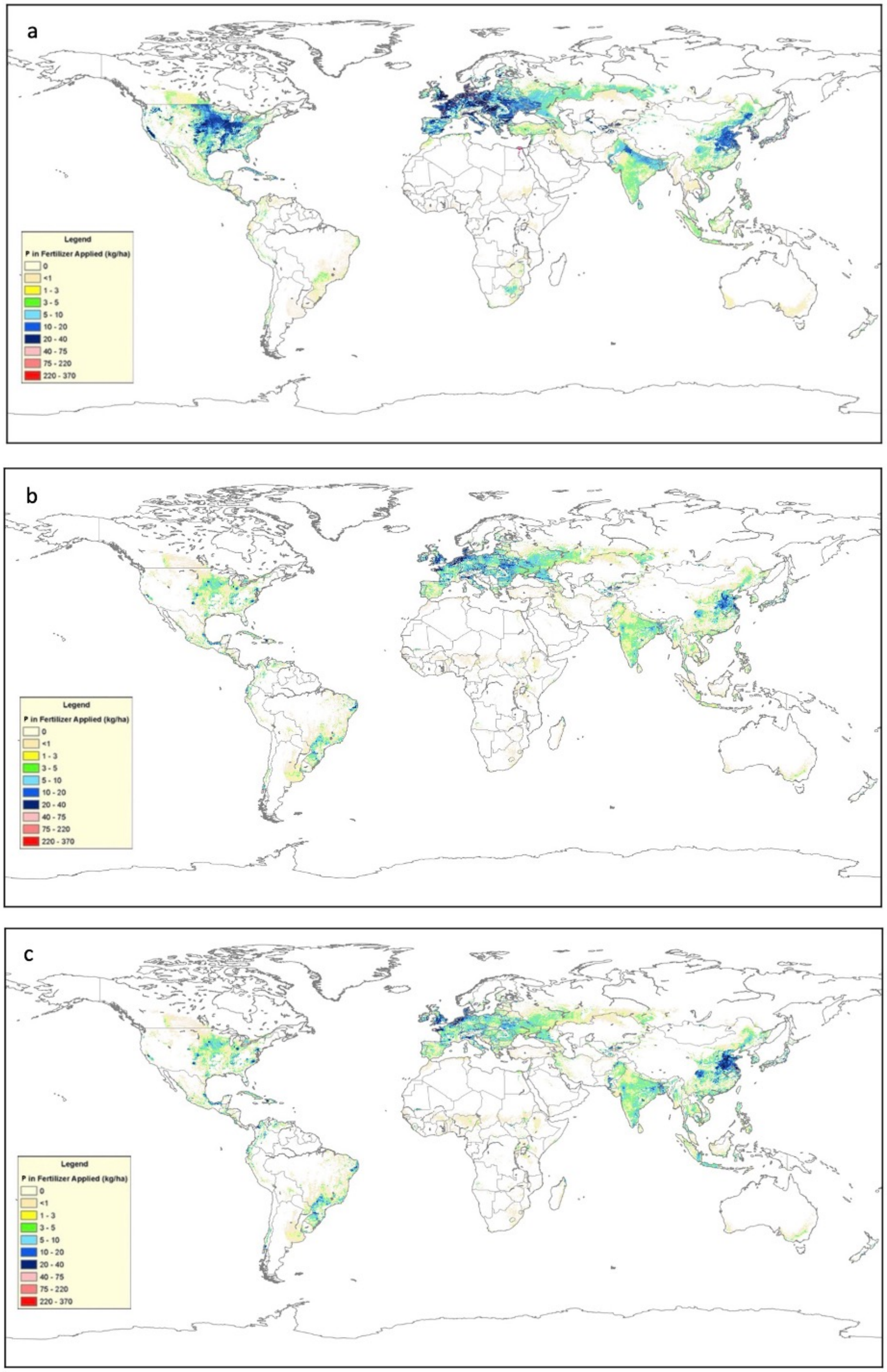

Figure 2.6: Scenarios showing the influence of climate change mitigation, dietary shifts, and all combined systemic influences on global and regional phosphorus fertilizer applications in the year 2050. a, Climate change mitigation. b, Dietary shifts. c, All methods (systemic influences combined).

CHAPTER 3

TECHNO-MANAGEMENT IMPROVEMENTS IN NUTRIENT USE EFFICIENCY MAY SUBSTANTIALLY REDUCE AGRICULTURAL FERTILIZER DEMANDS BY MIDCENTURY

3.1 Abstract

Fertilizers are critical to maintaining high crop yields thereby meeting the food demands of an estimated 3 to 4 billion people globally. However, large regions of Earth's croplands continue to suffer from sub-optimal fertilizer use, which has resulted in economic burdens on farmers, climate change risks, and environmental damages. This paper examines the capacity for improvements in nutrient use efficiency to reduce fertilizer use while supporting future crop production as the world's human population expands to 10 billion people by 2050. I combine meta-analysis and global modeling to ascertain the capacity of existing technologies to global improve fertilizer use via quantitative assessment of nutrient management, water management, soil amendments, biotechnology, and nanotechnology approaches. The effect of all technology and management approaches demonstrates a ~30% improvement of fertilizer use efficiency and compared to 2015, assuming 100% adoption and deployment in Earth's croplands, resulting in 34.52 Tg (21.47%) of N and 2.85 Tg (11.05%) of P fertilizer savings by 2050 BAU. Among the various interventions examined, biotechnology approaches (46.4%) and soil amendments (30.8%) have the most considerable positive effect on nutrient use efficiency. Water management (24.5%) and nanotech (14.7%) have a more minor but significant impact globally. If combined those technologies and management approaches with climate mitigation

and diet change methods (see Chapter 2), the N and P fertilizer demand for 2050 can reduce more to 102.56 Tg/yr (15.93%) and 19.06 Tg/yr, which is 19.43 Tg/yr (15.93%) and 2.94 Tg/yr (13.36%) less than 2015 baseline, and 58.19 Tg/yr (36.2%) and 6.73 Tg/yr (26.10%) than 2050 BAU. This study reveals the potential for current approaches to have profound benefits for farmer economics, environment, and food security, but social-economics factors, private sector and university/NGO partnerships, and policy innovations will be needed to realize such gains.

3.2 Introduction

Today, the Earth's human population has reached 7.7 billion people. According to world bank data, the total population of the world will exceed 9 billion people by 2050 (Fig 3.1). Currently, the world's seven most populated countries (China, India, United States, Indonesia, Pakistan, Brazil, and Nigeria) represent a total population of 4.0 billion, or more than half of the world's human population [94], with significant growth projected in such regions. Due to the limitation of arable land area and substantial natural habitat loss, sustainable intensification of agriculture is viewed as one approach for meeting the growing food demands worldwide while protecting the planet from continued losses of biodiversity and growing greenhouse gas emissions. Sustainable intensification is based largely on the model of technology deployment and innovation for improved water and fertilizer use efficiency.

Agricultural land use in many countries has exceeded 60% of the total geopolitical area, with especially large proportional areas of croplands and rangelands in Asia and Africa (Fig 3.2). Some ecosystems cannot be transformed into agriculture, limiting further land use change for food production. In addition, expanding arable land has led to the destruction of forests and other natural ecosystems [42]. This can negatively impact biodiversity and the environment, including soil erosion, water pollution, and climate change [85]. Finally, expanding arable land is not a sustainable solution to increasing food production. It does not address the root causes of food insecurity, such as poverty, inequality, and access to markets and technology [11].

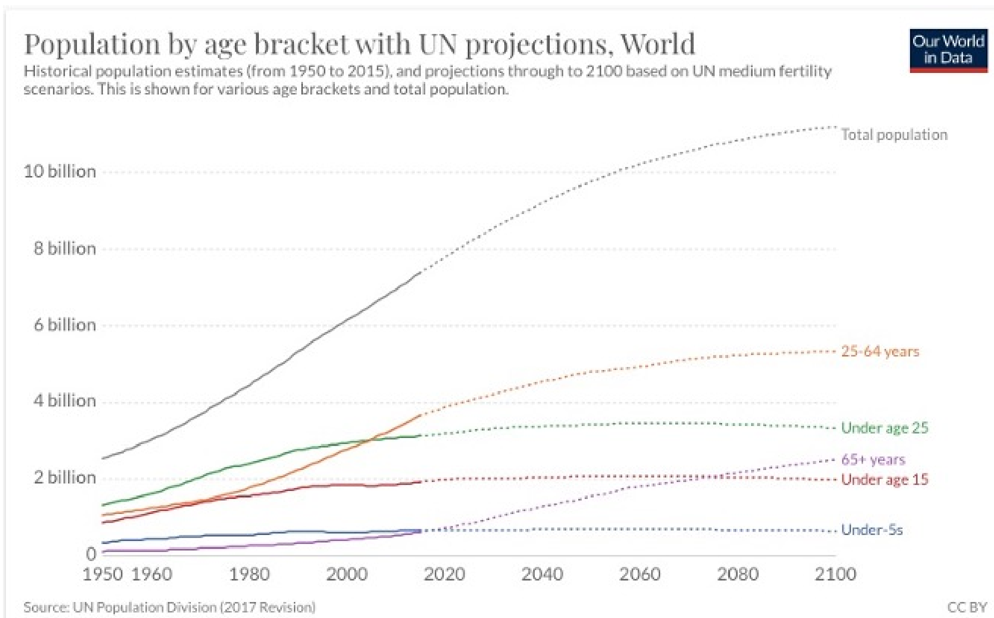

Figure 3.1: Population by age with UN projections from World Bank (2017)

In Chapter 2, the role of systemic controls of the global food systems was examined, including climate change mitigation and human diets, on global fertilizer demands in the year 2050. A question remains over the adoption of technological and fertilizer management practices to complement, which could spur additional fertilizer savings and improve food security and the environment via sustainable intensification. Based on existing approaches that have been ana-

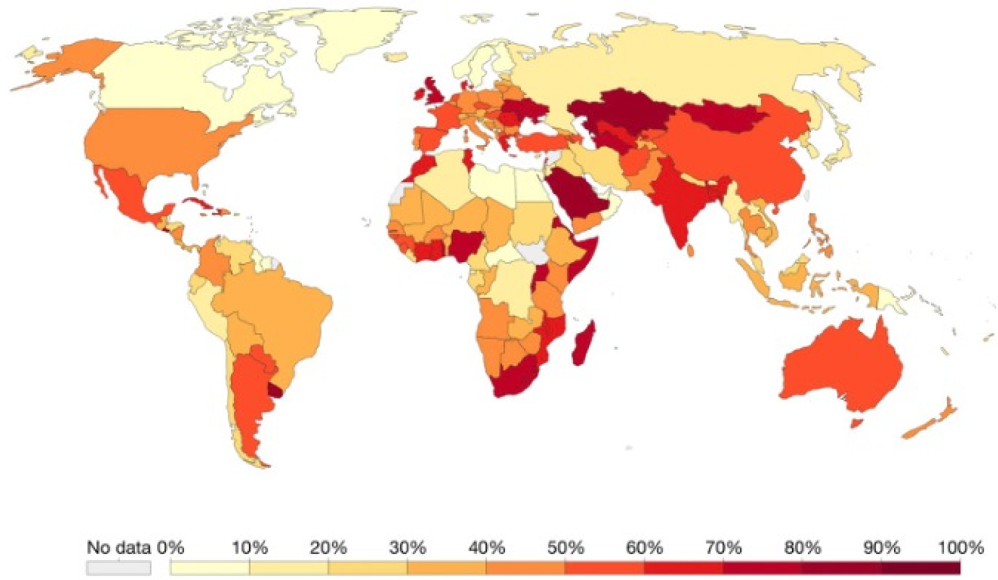

Figure 3.2: Land use for agriculture from World Bank (2014). The share of land area for agriculture is measured as a percentage of total land area. Agricultural land refers to the share of land area that is arable, under permanent crops, and permanent pastures

lyzed in the peer-reviewed literature, here I use meta-analysis to quantitatively determine the capacity for future improvements in nutrient use efficiency to affect fertilizer demands and explore the global impact of scale-up on nitrogen (N) and phosphorus (P) fertilizers.

Nutrient use efficiency refers to the ability of plants to effectively acquire, utilize, and retain nutrients from the soil to support their growth and development [10]. The two most important nutrients for plant growth are N and P, which are essential for photosynthesis, protein synthesis, and cell division [106]. Nitrogen is typically the most limiting nutrient for plant growth, as it is often in limited quantities in the soil [17]. Nitrogen use efficiency is, therefore, a critical factor in plant productivity and sustainability. Plants have developed an array of strategies to optimize N use, including adjusting root architecture, regulating nitrogen uptake and transport, and increasing the production of nitrogen-fixing symbiotic bacteria [39]. Phosphorus, on the other hand, is often abundant in soil but present in forms that are not readily available to plants [127]. As such, plants have evolved a suite of mechanisms to enhance P uptake and utilization. These include increasing root growth and branching, producing P-mobilizing enzymes, and forming associations with mycorrhizal fungi [110].

The methods for improving nitrogen use efficiency can be broadly classified into the following categories: (1) fertilizer management, including application method, timing, and location, such as fertigation [58, 67, 48, 131, 52, 9] and slow-release fertilizers [136, 125, 65, 112]; (2) water management [87, **?**]; (3) amendments, including soil amendments [66, 133, 97, 63] and foliar application [124, 32, 89, 6]; (4) genetic approaches [46, 44, 55, 62, 117], such as transgenic crops; and (5) nanotechnologies, such as nano fertilizers [4, 72, 100] and nanocarriers [96, 68].

While these methods form classes that are similarly used to support improvements in P use efficiency, technology-driven efforts to improve P use in crops have historically received less attention than for N. Among the approaches for improving P use efficiency, fertilizer management [106, 115], water management [120, 144], soil amendments [143, 86, 1], genetic approaches [47, 19], and nanotechnology [12, 101] have all been found to improve phosphorus use efficiency to varying degrees across past studies. However, in the case of both N and P, a systematic analysis of the capacity for existing technology and management approaches to improve fertilizer use efficiency is hitherto lacking.

In this study, technological and management approaches that can be used to improve N and P fertilizer use worldwide were examined. The approaches I analyze are divided into five categories: biotechnology, soil amendments, fertilizer management, water management, and nanotechnology. I use quantitative meta-analysis combined with a model to explore the global and spatial effect of combined technology bundles on N and P use by 2050. Individual and combined effects of the technologies on regional changes and global magnitudes by adopting a modeling scenario that includes population growth, climate mitigation efforts, and dietary shifts are studied, thereby building on the findings of Chapter 2.

3.3 Methods

3.3.1 Meta-analysis data gathering approach

Peer-reviewed publications (Attached in Appendix C) (and the reference lists from these publications) were searched on Web of Science, Scopus, and Google Scholar with the following keywords "nutrients use efficiency", "nitrogen use efficiency", and "phosphorus use efficiency". Studies were only included for which a pairwise comparison between the treatment and control was conducted under the same pedo-climatic conditions (e.g., temperature, precipitation, soil texture, and type). Studies were filtered into those that analyzed the mean effect of nutrient use efficiency change, its standard deviation (SD), and the number of replications (n) to calculate the nutrient use efficiencies and effect sizes of response. If the paper reported yield but not nutrient use efficiency, the same method used in Chapter 2 was employed to estimate nutrient use efficiency. Field trials were not included when the soils were previously fumigated or heat sterilized to obtain a control without soil biota, given the influence of such experiments on microbial processes and how that obfuscates the field application of results. When data was only supplied in a summarized format, the study authors were contacted to obtain individual data. Plot Digitizer Version 2.6.6[1]) was used to quantify the effects if the data were only available in graphical format.

3.3.2 Data analysis and statistics

A total of 104 studies met the criteria for this meta-analysis, resulting in 375 pairwise comparisons. The meta-analysis was conducted with R-Studio using the "metafor" package [129]. Selection bias was assessed via Egger regression. Because of the heterogeneity of the meta-data, a random effects model was chosen. An analysis of the studies shows the broad representation of crops (Table 3.1) across the different studies and methods. To explore whether crop effects had an impact on the resultant efficacy of the mitigation approaches explored, a correlation analysis was performed. This approach revealed a small effect of crop type compared to the overall dominant control of a given intervention to improve nutrient use efficacy. Consequently, the meta-data was applied to all crop types to explore the capacity for fertilizer use changes rather than using a crop-specific approach.

Crops in this meta-data were divided into five categories according to Table 3.1.

[1] http://plotdigitizer.sourceforge.net

Crop category	Crops included
Cereals	Barley, durum wheat, rice, spring wheat, winter wheat, pearl millet, maize, sorghum, kamut, silage maize, ryegrass, finger millet
Legumes	Blackgram, chickpea, peanut, horse gram, kidney bean, mung bean, fenugreek, lentil, snap bean, soybean, runner bean, pigeon pea
Root crops	Garlic, potato, turmeric, sugar beet, cassava
Vegetables	Eggplant, tomato, cabbage, watermelon, pepper, okra, cucumber, melon
Other crops	Dill, anise, rapeseed, cotton, sesame, fennel, coriander, sunflower, mustard, sugarcane

Table 3.1: Crops grouping included in this meta-analysis

3.3.3 Global model analysis

A global model was developed to analyze the magnitude of the fertilizer use effects of individual and combined technologies and management approaches. The "All Methods" scenario in Chapter 2 was used for this purpose, which considers human population growth, adoption of climate change mitigation methods, and adoption of the EAT-LANCET diet in 2050. The model was run assuming additive effects under the condition of independence, rather than assuming subtractive, multiplicative, or synergistic effects (see Discussion). Five scenarios are included: 2015 Baseline (see Chapter 2), 2050 BAU (see Chapter 2), 2050 All Methods (see Chapter 2), 2050 Techno-management (Chapter 3), and 2050 Combined (Chapter 3, combine 2050 All Methods from Chapter 2 and 2050 Techno-management from Chapter 3).

3.4 Results

3.4.1 Meta-analysis of interventions for improved fertilizer use efficiency

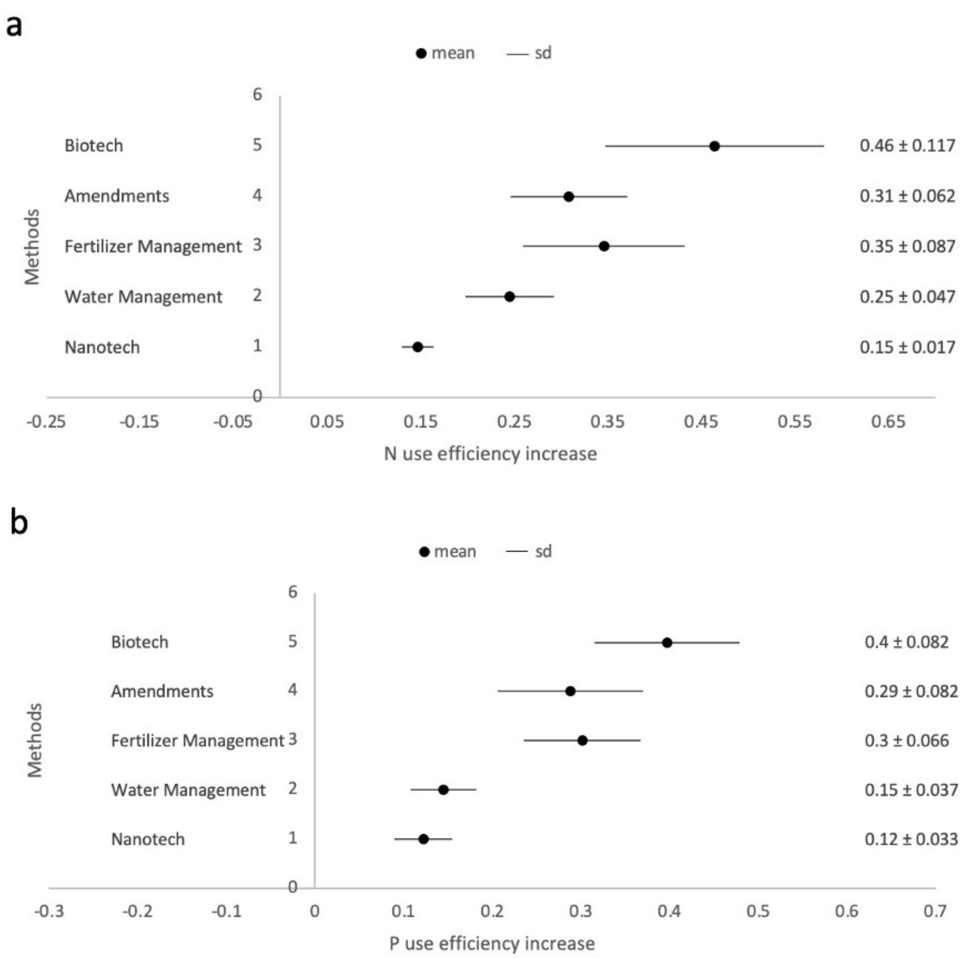

Figure 3.3: Meta-analysis of existing technology and management practices on fertilizer use efficiency based on a global compilation of peer-reviewed literature. a, effect on N use efficiency. b, effect on P use efficiency. Symbols are mean responses and error bars are standard deviations.

Interventions to improve NUE varied widely across the classes of approaches (from 12~46% vs. controls), with especially strong effects observed for biotechnology for both N and P fertilizers (Fig 3.3). The rank order of improvements tracked well across N and P: biotech > fertilizer management > soil amendments > water management > nanotechnology. While biotechnology yielded the most significant improvement in N and P use efficiency vs. controls, differences among target genes resulted in more variation than for other interventions (Fig 3.3).

Fig 3.4 shows the global modeled impact of the intervention classes at different levels of worldwide adoption in the year 2050. In the case of N fertilizers (Fig 3.4a), global adoption of biotechnology translated from 126.2 (100%) to 134.1 Tg N/yr (25%); soil amendments from 129.8 (100%) to 135.0 Tg N/yr (25%); fertilizer management from 128.9 (100%) to 134.8 Tg N/yr (25%), water management from 131.2 (100%) to 135.4 Tg N/yr (25%), and r nanotechnology from 135.9 (100%) to 133.4 Tg N/yr (25%). In the case of P fertilizers (Fig 3.4b), the model predicted 22.5 (100%) to 23.7 Tg P/yr (25%) for biotechnology, 22.9 (100%) to 23.8 Tg P/yr (25%) for soil amendments, 22.9 (100%) to 23.8 Tg P/yr (25%) for fertilizer management, 23.5 (100%) to 24.0 Tg P/yr (25%) for water management, and 23.6 (100%) to 24.0 (25%) for nanotechnology adoption.

The 2015 Baseline scenario is the fertilizer use estimates from available data and represents the NOW, 2050 BAU scenario from Chapter 2, assuming climate, diet, and nutrient use efficiency change and population growth follow historical trends for each country. The 2050 ALL Methods scenario is also from Chapter 2, assumes taking climate mitigation methods, changing the diet to more plant-based protein as EAT-Lancet model, and the population keep growing following the historical trend which is the same as the 2050 BAU scenario. 2050

Techno-mgmt represents technologies and management, this scenario assumes climate, diet, and nutrients use efficiency change and population growth follow historical trends for each country but adopt nutrients use efficiency improvement technology and management at 100% (Fig 3.4). The 2050 Combined scenario assumes adopting technologies and management to improve nutrient use efficiency, taking climate change mitigation and dietary change methods in 2050 ALL Methods, and combining them, population growth follows the same trend as the 2050 BAU scenario and 2050 ALL Methods scenario.

The global forecasted fertilizer demands were sensitive to not only the interventions examined, but the combination of systematic factors of change and the technology and management approaches (Fig 3.5). Worldwide adoption of the EAT-LANCET diet coupled with climate mitigation and continuous population growth can reduce global N fertilizers from 160.75Tg/yr to 136.75Tg/yr in 2050 (Fig 3.5a), which is still 25 Tg N/yr more fertilizer than in 2015 (see Chapter 2). The maximum capacity (100% adoption) of the techno-management interventions in this scenario results in further reductions to 126.23 Tg N/yr. Similarly, assuming 100% adoption of techno-management approaches, total P demands projected for 2050 fall to 22.94 Tg/yr. If combining those technologies and management approaches with climate mitigation and dietary shift, the predicted fertilizer demand for 2050 will go down further to 102.56 Tg N and 19.06 Tg P, which is less than 2015 by 19.43 Tg N and 2.94 Tg P.

Spatially, the patterns track the global scenarios, given that the model is applied uniformly for all crops (Fig 3.6). Areas that show the greatest reduction potential are those with the highest N and P inputs, clustered in Southeast Asia and India, where N and P fall to levels that are lower than estimated for 2015.

3.5 Discussion

3.5.1 Effects of techno-management on global N and P fertilizer demands in 2050

This meta-analysis and modeling study demonstrates potential N and P fertilizer reductions via the adoption and deployment of existing approaches for improving the nutrient use efficiency of crops, including biotechnology, fertilizer management, water management, soil amendments, and nanotechnology. When scaled with a global model, my findings suggest that N fertilizer demands can be reduced to 102.56 Tg N/yr and P fertilizers to 19.06 Tg P/yr in 2050. Both mid-century projections are lower than the 2015 baseline, yet allow for the world's human population to grow to 9 billion people, with food demands increasing accordingly. Researchers have previously examined the potential for both technologies and social change factors to reduce GHG emissions in the future [18, 5, 121], and the technologies explored have many overlaps with those in this study. That fertilizer reductions are achievable through the adoption of existing approaches is economically essential for farmers, with many additional co-benefits for GHG emissions, biodiversity conservation, and air and water pollution, given the role of N and P in these areas of global biogeochemical change [59, 140, 43]. This study highlights the substantial capacity of technology and management to promote planetary health and sustainability, which is consistent with a growing body of evidence for the impact of combined socio-techno assessments.

3.6 Barriers to adoption

While the capacity for large-scale reductions in N and P fertilizers is evident from this global analysis, many barriers to adoption need to be considered to realize such gains. These include social, cultural, knowledge transmission, policy, economic and market forces [20]. First, from a social perspective, farmers may be reluctant to try new approaches, especially if they are departing from traditional practices [56]. New technologies may also be subject to resistance from the traditional fertilizer industry. Second, from a cultural perspective, some countries and regions may value the importance of tradition and the need to maintain cultural practices that have been passed down through generations. The belief that new technologies may disrupt traditional ways of life or lead to cultural homogenization is critical to consider when exploring adoption. Third, from the knowledge transmission perspective, if farmers lack access to information and training on new technologies, they will not know the benefits or may mistrust the novel technologies. For example, some farmers believe that GMOs have negative effects on human and soil health [64], which limits the broader uptake of biotechnology, we need clear and effective communication to bridge the gap between researchers and farmers and to ensure that knowledge is effectively transmitted and understood. Fourth, from an economic perspective, high costs associated with acquiring and adopting new technologies, such as the cost of purchasing equipment - like drip irrigation system [14] - training and maintenance are huge barriers. There are also questions about whether the economic benefits of adopting these technologies are more significant than the cost. Technologies with the substantial initial investment and slow returns will be difficult to implement unless they get external support, such as policy innovation and coordination of public-private partnerships [59].

3.7 Uncertainties, limitations, and future work

This study has several uncertainties and assumptions, which can be addressed through additional field-based research and modeling tool development. A base assumption is that the technologies are independent and thereby additive rather than subtractive, multiplicative, or synergistic. There is a paucity of information and field-testing of multiple techno-management approaches, which is a critical gap in understanding co-benefits and possible pitfalls of mixing interventions and exploring combinations. In addition, the existing literature tends to report methods that can improve plant nutrient use efficiency in the greenhouse or small plots, which limits understanding of larger multi-acre effects. Carrying out demonstrations of technologies and management approaches at scale and across heterogenous bio-climatic conditions is critical for improving the model and understanding realized benefits for farmers and the environment.

Also, at present, there are many ways to improve the nutrient utilization efficiency of plants, with gene-editing approaches the most promising and the fastest developing tool. But genetic modifications can carry unknown natural and ethical risks, so much research is needed on the safety and environmental ethics of biotechnology (Robinson, 1999). Soil amendments are effective and often scalable, but adding exogenous substances to the agricultural system may affect soil health and sustainability, and even cause air pollution, such as PM2.5 produced when biochar is applied [45]. Many technologies require life cycle assessments to evaluate their potential use in agriculture. For areas where fertilizer application is insufficient, such as most countries in Sub-Saharan Africa, increasing the nutrient capital of soil is a priority, and using the most sustainable approaches should be considered a global imperative [130].

Finally, there are many complex factors that affect plant nutrient utilization efficiency, such as climate, soil physical and chemical properties, etc. The metadata used in this study are derived from different soil types and climatic conditions, but more research is needed on crop-specific effects across growing practices.

3.8 Conclusions and implementations

This study demonstrates the potential benefits of adopting nutrient-use efficiency-improving technologies to reduce fertilizer demands, particularly in regions with high population growth and intensive fertilizer use. Biotechnology and soil amendments are the most effective approaches, while water management and nanotechnology have localized benefits. However, social-political factors such as traditional beliefs, lack of knowledge transmission, and high economic costs may present barriers to the widespread adoption of these technologies. Future research should focus on the interaction among different technologies, the gap between reported benefits and practical applications, and the safety and environmental ethics of genetic modification. Overall, measures to improve nutrient use efficiency are promising but require global cooperation and support to realize their potential benefits for the environment, food security, and economic growth.

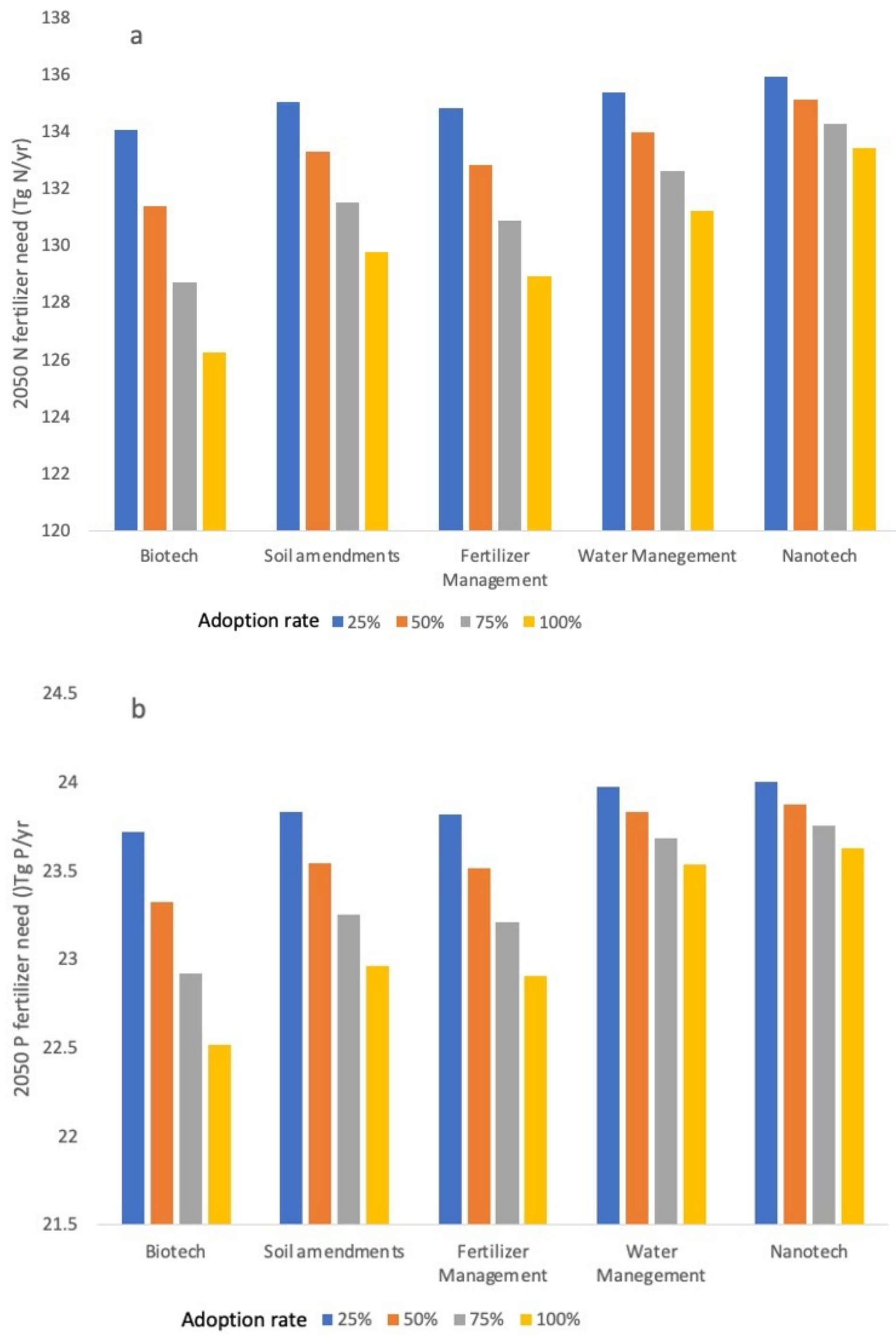

Figure 3.4: Modeled global fertilizer demands in the year 2050 at different levels of adoption for N (a) and P (b).

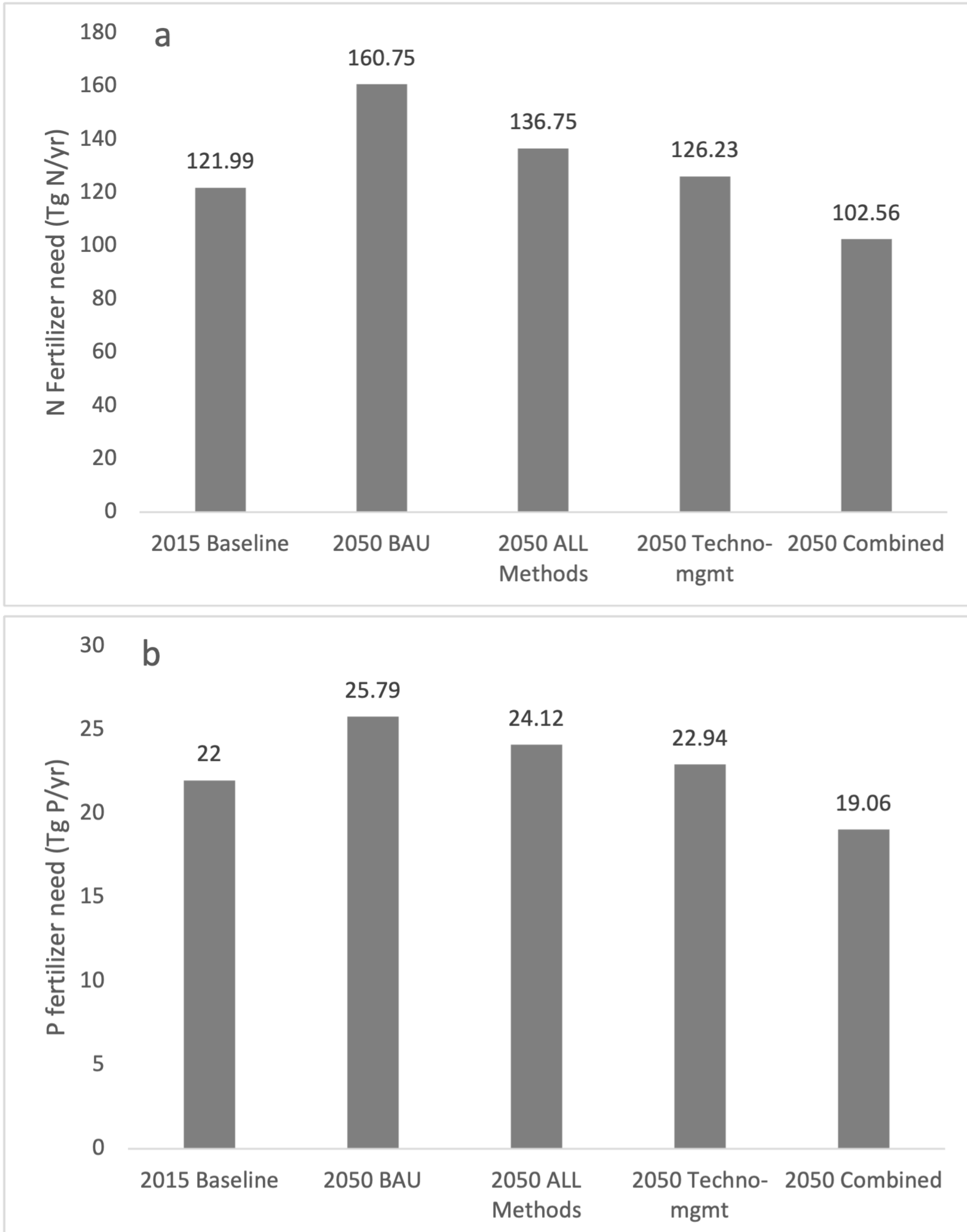

Figure 3.5: Fertilizer demand for N (a) and P (b) across different scenarios for the year 2050. Baseline = 121.99 Tg/yr for N (a), 22 Tg/yr for P (b). 2050 BAU = 160.75 Tg/yr for N (a), 25.79 Tg/yr for P (b). 2050 All Methods = 136.75 Tg/yr for N (a), 24.12 Tg/yr for P (b). 2050 Techno-mgmt = 126.23 Tg/yr for N (a) and 22.94 Tg/yr for P (b). 2050 Combined = 102.56 Tg/yr for N (a), 19.06 Tg/yr for P (b).

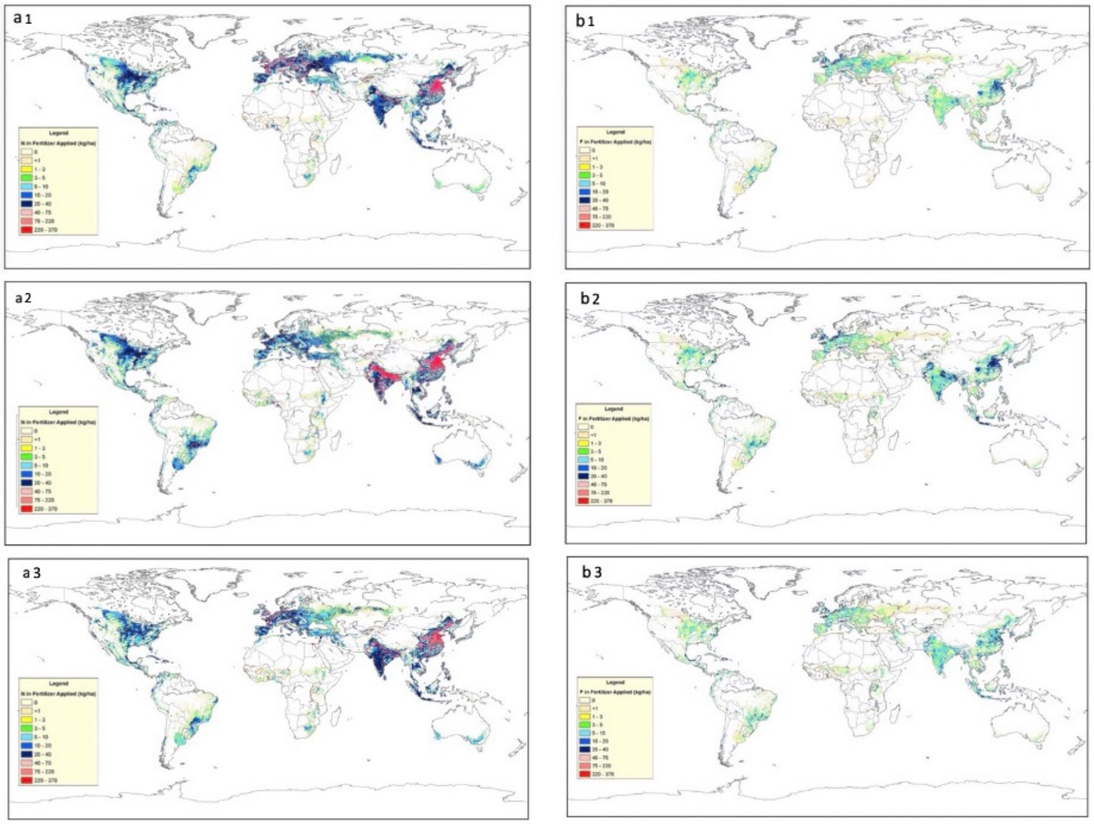

Figure 3.6: Nutrients input map under different scenarios. a1, N fertilizer applications rates for 2015. b1, P fertilizer applications rates for 2015. a2, N input map for 2050 under the BAU scenario. b2, P input map for 2050 under the BAU scenario a3, N input map for 2050 adopting N use efficiency improving methods (100%). b3, P input map for 2050 adopting P use efficiency improving methods (100%)

APPENDIX A

LIST OF ABBREVIATIONS

Abbreviation	Definition
NUE	Nitrogen Use Efficiency
PUE	Phosphorus Use Efficiency
GHG	Greenhouse Gas
BAU	Business As Usual
GMO	Genetically Modified Organism

Table A.1: List of Abbreviations and acronyms used in this dissertation.

APPENDIX B

DATA SOURCE OF CHAPTER 1

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APPENDIX C

DATA SOURCE OF CHAPTER 3

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APPENDIX D

APPENDIX 2

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