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Estimating Future Global Needs for Nitrogen Based on Regional Changes of Food Demand

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Abstract

The use of synthetic nitrogen fertilizer is of great importance for global food supply, but it is also causing large environmental problems. The amount of fertilizer needed on a global scale is affected by the size of the population (more people more food), the type of their diets (luxurious diets require more resources) and the agricultural production system (intensive systems use more fertilizer than extensive systems). In the coming decades, global population will increase, diets will change and a strong intensification of agriculture is expected. In this paper, we assess how the changes in all these factors will affect future needs of fertilizers on both a global and a national scale. We developed a model that describes the various relations among population density, diets and production systems, and validated the outcomes with historical country level data. The variations over the globe are large. The model shows that in the regions with low population densities not much change in nitrogen applications is to be expected. On the other hand, in densely populated regions, with high population growth rates and expected changes in diets, the needs for synthetic nitrogen show an exponential increase. By using existing projections with respect to population growth and dietary changes, by 2050 over 70% of the global population will live in countries where an exponential increase of the nitrogen application is needed to feed the people. This may result on large impact for the global environment.

Keywords: Synthetic nitrogen fertilizer; Dietary changes; Population density; Historical trends; Global analysis

Introduction

The use of synthetic nitrogen fertilizer has had enormous global environmental impacts [1]. First, it is highly energy intensive. Globally, half of the energy use in agriculture is related to the production and application of synthetic nitrogen fertilizer and it is a major greenhouse gas emitter [2]. Secondly, its use has strongly affected the global nitrogen cycle [3-5] by doubling the emissions of reactive nitrogen into the biosphere [6] which has affected the global climate [4]. Third, large application of nitrogen has local effects on the environment such as acidification, eutrophication and loss of biodiversity [3,6,7]. However, the food for the present global population cannot be produced without it, and nowadays half of the world food consumption is based on its use [8,9].

The world population will reach nine billion people by 2050 [10], and food consumption per capita will increase as well [11]. Synthetic nitrogen fertilizer will play an important role in the increase of global food supply as well as in the environmental impacts related to the increase of food production [1,12-14] estimates that if the future global consumption of nitrogen fertilizer follows a linear extension of the past 50 years' trend, it will lead to serious global environmental consequences. So, achieving global food security while reducing environmental problems is one of the biggest challenges humanity will face in the next decades [15-17].

The use of nitrogen for food production has been widely studied. We have identified three lines of research addressing different drivers of its use.

First, population density drives the amount of nitrogen applied for a certain population. Smil [8] and Arizpe et al. [18] show that for several countries the increase of population density, due to population growth, has led to an increase in the nitrogen application per unit of area.

Second, food consumption patterns drive nitrogen requirements. Different types of diets require different amounts of nitrogen [19,20]. Food products of animal origin require more nitrogen than those of vegetal origin because of the inefficiency of producing animal proteins from vegetal proteins [21,22]. Also, differences exist among animal products [23], for instance the production of one kilogram of beef requires more nitrogen than the production of one kilogram of chicken [22].

Third, the type of agricultural production system drives the use of nitrogen fertilizer depending on the application rate level (kilograms of Nitrogen per hectare). Large regional variability exists in its use and in the corresponding local environmental impacts because of different application rates [24,25]. Some regions, like industrial countries and Eastern Asia, have an excess of reactive nitrogen in their environment due to high application rates [26-29]. Other regions, like most African countries, have a lack of nitrogen in their soil because of the low application rates which limits their agricultural production and affects their food supply.

So, changes in population, diets and agricultural systems affect the need for nitrogen fertilizer. The expected changes differ largely over the globe. In Western Europe, population growth has come to a standstill, their average diets already contain large amounts of animal products and agriculture is very intensive. So, no changes in nitrogen needs are expected in this region. In other parts of the world, population growth rates are still high (Africa) or large changes in meat consumption are taken place (China) and nearly everywhere agricultural production systems are intensifying. Based on these expected changes, we can expect an increase in global needs for nitrogen fertilizers. In this paper, we assessed the future needs of nitrogen fertilizer on global scale based on the existing regional variations of population, diets and agricultural systems, and the expected changes. First, we studied the historical changes in the drivers for different global regions from 1960-2010 (section 2). Then, we developed a model to integrate the impact of the various drivers of the nitrogen demand (section 3). The results of the model were validated with country level data (section 4), and finally we used the model to assess the global nitrogen demands in 2050 (section 5).

Historical Analysis of Regional Changes in Population, Diets and Nitrogen Use

In this section, we obtain insights on the trends of the main drivers for the global demand of nitrogen fertilizer. In order to do this, we look back in time. The main drivers are population density, the type of diet and the type of agricultural technology. These drivers differ throughout the world; therefore, we split the global population into six different regions with different characteristics of population dynamics, dietary patterns and agricultural technology. For these regions, we studied the changes on these parameters over the last 5 decades.

Methods and data

We obtained country level data of the main drivers for 1960-2010 from existing databases: population [11], food supply [30] arable land [31] and nitrogen fertilizer use. Population density was calculated by dividing the size of the population by the area of the arable land because we are interested in the availability of arable land per person which is, in general, where the nitrogen fertilizer is being used. The amount of animal products consumption in the diet of a person is the main factor in the requirement of nitrogen to produce the food of that person [21,32]. Therefore, we determined the total caloric intake of animal products per person per day. Finally, we used the application of nitrogen fertilizer as the indicator of the type of agricultural technology. This factor was calculated by dividing the total national consumption of synthetic nitrogen fertilizer by the amount of arable land of each country.

The countries were clustered in seven regions: A: Africa (with 950 million people in 2010), B: India (1210 million people), C: Southeast Asia (950 million people), D: China (1370 million people), E: Latin America (570 million people), F: North America (340 million people) and G: Western Europe (400 million people). These regions accounted for 85% of world population in 2010.

Results

In nearly all regions, population density, consumption of animal products and nitrogen application has been increasing over the last decades (Figure 1a). However, the absolute values differ per region. In 2010, Asia was the region with the largest population density, followed by Western Europe, Africa, Latin America and North America, see black bars of Figure 1b which indicate the values in 2010. So, Asia was the region with the smallest amount of arable land per person and North America with the largest. The population density in China was twice that of Western Europe, three times larger than that in both Latin America and in Africa, and as much as ten times larger than that in North America. During the last decades, global population density increased because global population doubled [10] while arable land only increased 10% [31]. Population density has changed differently among the regions due to different changes in both population numbers and arable land. Africa had the largest population growth and strongly increased its population density. But India, with a smaller population growth, ended up with a larger growth in population density because it did not increase their arable land as much as Africa. Western Europe increased its population density not because of a large population growth but because its arable land decreased.

The consumption of animal products differs amongst regions. Western Europe and North America consumed the largest amount of animal products per capita, followed by Latin America, China, Southeast Asia, India and Africa; see the values of 2010 of Figure 1c. During the last fifty years, the global consumption of animal products strongly increased, but the increase was not the same in all regions. North America, Western Europe and Africa were more or less stable, but Africa consumed much less than the former two. North America and Western Europe were large consumers and they show a levelling off in contrast with Latin America and parts of Asia which had the largest increase in consumption of animal products and they did not show a levelling off. Some of these regions still consume half the amount of animal products compared to that of Western Europe and North America.

Nowadays, the region with the highest application of nitrogen per hectare is Asia, and Africa has the lowest (Figure 1c). During the last five decades, mainly Asia but also Latin America strongly increased the nitrogen application rate. Africa did not increase

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substantially and by 2010 its average application rate was still very small compared to the rest of the regions. North America and Western Europe showed a leveling off from 1960 to 2010. North America increased its application rate until 1980, and then, it remained stable. Western Europe had by far the largest application rate in 1960. It increased until 1980, and then, it began to decrease (Figure 1).

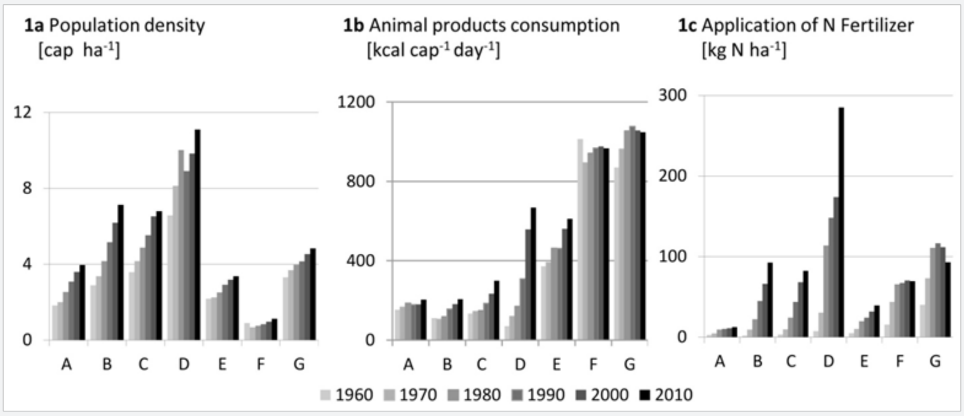

Figure 1: Drivers for the use of nitrogen fertilizer for the seven regions. The regions are: A: Africa, B: India, C: Southeast Asia, D: China, E: Latin America, F: North America and G: Western Europe.

Discussion

When we compare our regional results with relations mentioned in literature some striking differences can be seen. Figure 1 shows that large consumption of animal products is not always related with large nitrogen application as suggested by Smil [21,22] and Leach et al. [19]. The regions with the largest consumption of animal products did not have the largest nitrogen application rate. North America and Western Europe had the largest consumption of animal products but Asia had the largest application rate. In addition, Smil [8] and Arizpe et al. [18] show that countries with a high population density have high nitrogen application rates. Figure 1 shows that some regions follow this pattern like Asia (B, C and D). These three regions had relatively high population density and high nitrogen application rate. But Africa (A) and North America (F) do not follow this pattern. Africa has a larger population density than North America, but a smaller application rate. In addition, in Western Europe, population density increases over time while in the last decades a decline in fertilizer use is measured. So, the relations mentioned in the literature are not always found on regional scales. Therefore, in the next sections, we look in detail into the relationships among population density, dietary patterns and agricultural technology, the main trends of the last decades, and the differences throughout the world.

Integration of the drivers: model development

In section 2, we have shown that the general relationships between two drivers described in the introduction are not always valid for all regions (e.g. the highest nitrogen application is used in the region with the highest population density). Due to the close interrelationship of the three drivers (population, diets and agricultural technology), we believe that the solution to understand these deviations is by studying the three drivers at the same time. Therefore, we integrated the three drivers into a model. The model aims to understand patterns rather than calculate exact data. The three parameters are population density (by means of the inverse: ha of arable land cap^{-1}), consumption of animal products (kcal cap^{-1} day1), and nitrogen application rate (kg N ha^{-1}). Population density and consumption of animal products are independent variables, and nitrogen application rate is the dependent variable of the other two parameters. The model illustrates their interrelationships on a crop field scale.

Model description

We took the food consumption as starting point and we determined the amount of nitrogen needed to produce a certain amount of food. Under natural conditions (no fertilizer use) the natural nutrients available in the soil for uptake by the crop determine the amount of food that can be produced. If we want to produce more food two strategies exist: either more land should be put into production (land expansion) or the crop yield should be increased (the amount of food produced in a certain area: intensification). In this paper, we focused on the increase of food production by increasing crop yields, as intensification of the production is expected to play the major role in the global increase of food production in the coming decades Alexandratos & Bruinsma [11]. Nutrients have to be added to the soil in order to increase crop yields. The number of people we can feed from a certain amount of nutrients depends on their diets, and the amount of animal products plays an important role. We distinguished three hypothetical diets based on the Nutrition Transition Theory Chesnais [33] which describes the main trends and global differences in diets: a vegetarian diet *Dv* requiring N amount of nitrogen for its production, a more affluent diet *Da*, with a low amount of animal products, requiring

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50% more nitrogen than *Dv*, and a diet rich in animal products Da ext requiring twice the amount of nitrogen than *Dv*.

Our starting point is that in area A we can produce the food for one person with a vegetarian diet Dv using the natural nitrogen in the soil which is N. If the population doubles, we need 2N to produce the food for both people. Since the natural nitrogen in area A is N, then we need to apply another amount of nitrogen N. Column Dv of Table 1 shows the amount of external nitrogen that we need to apply if the population grows from one to ten people. The following columns show the amount of nitrogen application required for diets Da and Da ext.

Results

Figure 2 shows the results of the model. The application of external nitrogen increases exponentially with the decrease of availability of land per capita due to population growth. So, the increase of population density increases the application of nitrogen fertilizer, as shown by Arizpe et al. [18]. Also, diets rich in animal products require a larger nitrogen application rate. Our aim withthis model is only to show the relationships between the parameters, therefore we do not assign units of numerical values to the model, so (Table 1 & Figure 2) do not have units.

Table 1: Application of external nitrogen for different population numbers and diets on a crop field scale.

Population		Natural Nitrogen in the Crop Field [N]	Diet Dv (Vegetarian)		Diet Da (Low Animal Products)		Diet Da Ext (Large Animal Products)	
Number of people	Availability of land		External nitrogen required	Application of Nitrogen [N A-1]	External nitrogen required	Application of Nitrogen [N A-1]	External nitrogen required	Application of Nitrogen [N A-1]
	[A cap-1]		[N]		[N]		[N]	
1	1	1	1	0	1.5	0.5	2	1
2	0.5	1	2	1	3	2	4	3
3	0.3	1	3	2	4.5	3.5	6	5
...	...	...	...	...	...	...	...	...
10	0.1	1	10	9	15	14	20	19

Discussion

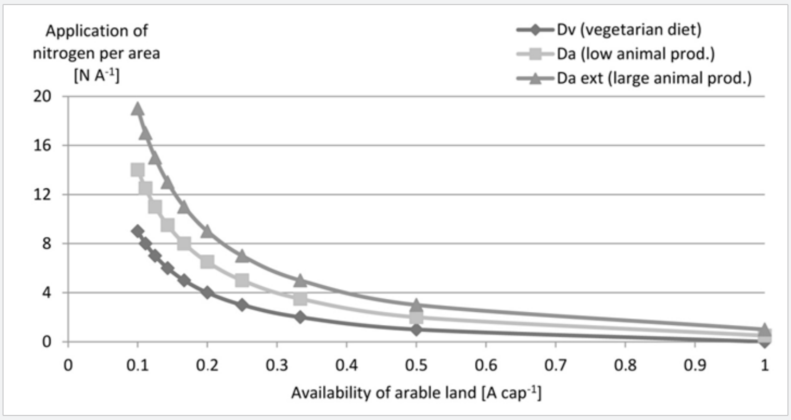

Figure 2: Model integrating the drivers of external nitrogen fertilizer use.

Figure 2 shows two things. First, the increase in consumption of animal products increases the application of external nitrogen much more in densely populated areas than in lightly populated areas. Second, the reduction of availability of arable land per capita increases exponentially the application rate of external nitrogen in densely populated areas. Thus, the nitrogen application rate tends to be much higher in densely populated areas than in low populated areas for a similar consumption of animal products per capita. This explains the deviations discussed in section 2 (Figure 1). For example, China and Latin America have a similar consumption of animal products in 2010 but China has a much larger nitrogen application due to a much higher population density. The same deviations are shown for Africa and India. This model explains these deviations, so we use it to analyse the global trends in section 4.

It is important to point out that in the model we determined the nitrogen needed by the crop to produce the food. This deviates from what a farmer should apply to obtain a certain yield. In agricultural practice, only a part of the fertilizer applied is taken up by the crop, the remainder is lost to the environment. In our analysis, we exclude nitrogen losses.

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Validation model outcomes with country data

In section 3, a model without values was developed showing the relations between the drivers and the nitrogen needed for food. In this section, we validate this model with country level data in order to use it to assess the future global use of nitrogen fertilizer (section 5).We used country level data from several databases of population numbers [10], arable land, food supply of animal products and nitrogen fertilizer use. With these data, we calculated population density, animal products consumption per capita and fertilizer application for each country. With this, we made the same graphs as the one in Figure 2, but now with values: Figure 3. Since drivers change over time (Figure 1) we did this for the years 1960, 1980 and 2010. In the model, three different consumption patterns are recognized. In this section, we distinguished four food patterns depending on the amount of animal products in the diet: 0-300, 300-600, 600-900 and 900-1200kcal of animal products per day. We referred to "poor diets" if the animal product's consumption is between 0-300kcal cap^{-1} day^{-1}, to "transition diets" is the consumption is 300-600 or 600-900 kcal cap^{-1} day^{-1}, and to "luxurious diets" if it is higher than 900kcal cap^{-1} day^{-1}. We were able to do this for 110 countries. We also determined the global averages on the consumption of animal products, population density and fertilizer's application.

Results

The global availability of land decreased from 0.4ha cap-1 in 1960 to 0.3ha cap-1 in 1980 and to 0.2ha cap-1 in 2010. At the same time, the global nitrogen application rate and the consumption of animal products increased; the former from 10kg N ha-1 in 1960 to 44kg N ha-1 in 1980 and to 75kg N ha-1 in 2010; and the latter from 350kcal cap-1 day-1 in 1960 to 390kcal cap-1day-1 and to 500kcal cap-1day-1 in 2010. This shows a linear increase in the nitrogen application rate. However, large variations exist between the global average and the country level data. Some countries have higher or lower consumption of animal products, nitrogen application and population density than the global average.

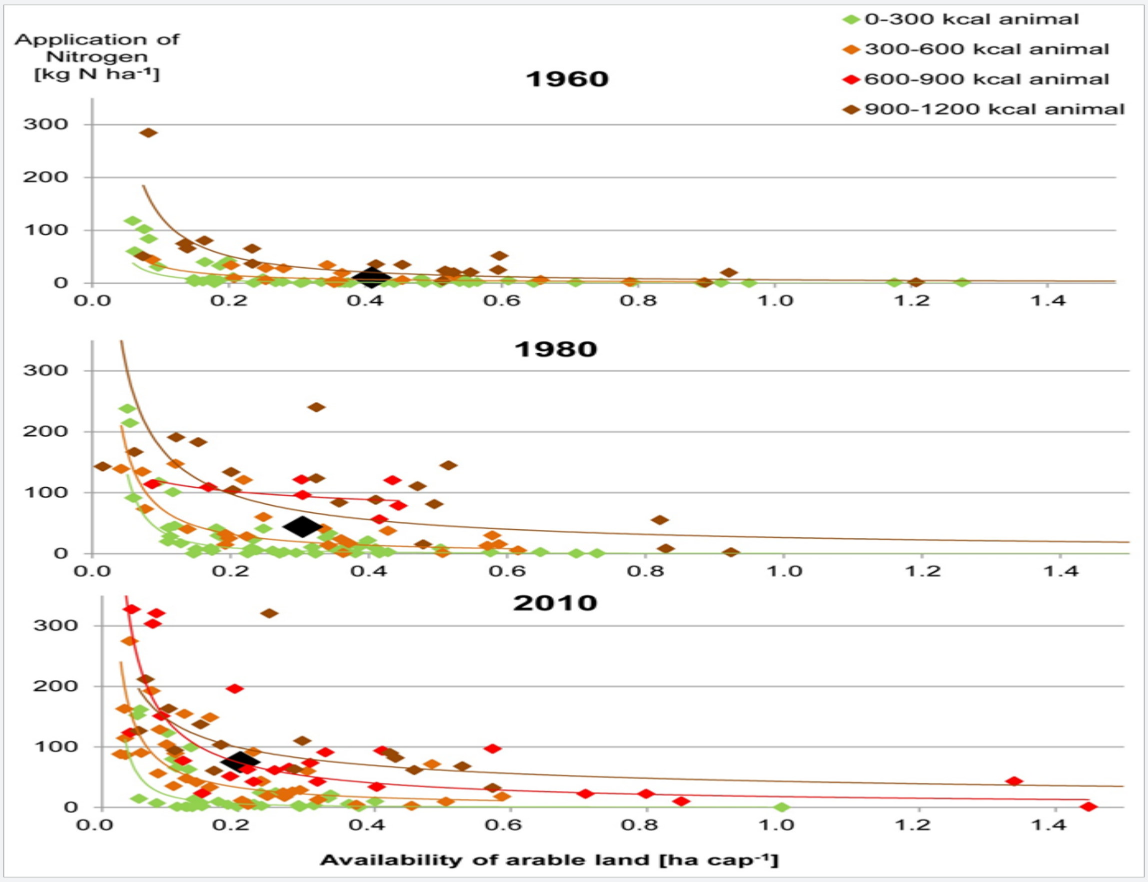

Figure 3: Country level data validating the model. The colors indicate the consumption of animal products per capita. The black diamond indicates the global average for each year. The average caloric intake of animal product for each year is indicated in the legend.

In Figure 3, the trend lines for the three diets in 1960 show a polynomial relation between availability of land and nitrogen application similar to the trend lines of our model, and the type of diet parallels this relation. So, the data of 1960 of Figure 3 fit with our model: countries with high amount of animal products in the diets used more nitrogen per ha than countries with both small amounts of animal products in their diets and a population density of less than 0.2ha/capita. Also, for the vegetarian diets fertilization is needed (green dots).The results for 1980 do not fit our model results. Especially the countries with high meat consumption values

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(red and brown dots) use far more nitrogen than the expectations based on the model. The data for 2010, however, fit with the model again.

Discussion

The nitrogen application rates in 1960 were generally lower for a certain population density than in 1980 and in 2010. One of the reasons is that during this period global population more than doubled: from three billion to seven billion people [10] and global arable land only increased 10%. In contrast, global use of nitrogen fertilizer increased eight times (Table S2 in the Electronic Supplementary Material), and crop yields strongly increased which lead to a doubling of the global food supply. The three billion people in 1960 were already using the natural nitrogen available in the soil, so for the new four billion people extra nitrogen in the form of synthetic nitrogen fertilizer had to be applied in the crop fields in order to produce their food by increasing the crop yields. This enormous population growth increased the population density of all countries (reducing the availability of arable land per capita). This pattern can be seen in Figure 3 where from 1960 to 2010 all countries moved to the left side of the graphs and also upwards showing that the increase of population density increased the nitrogen application rates, in accordance with our model. The population density increased the most for the countries with the lowest consumption of animal products (green dots in Figure 3). These countries are mainly in Africa.

During the 1960-2010 period studied, countries increased their animal products consumption and changed colour from green towards brown. In 1960, large differences in diets existed among countries showing large inequalities. More than two thirds of the global population had diets with only up to 300kcal of animal products (green group), one fifth had luxurious diets (up to 1200kcal animal products, brown group), and few countries had transition diets (orange group 330-600kcal). In 1980, many countries of the green group had moved towards the orange group and a new group emerged: the red group. By 2010, the inequality of diets decreased because of the large change towards luxurious diets in the transition countries. More than half of the world population had transition diets (red and orange diets), only one third had poor diets (green group) and one tenth had luxurious diets (brown group).

As mentioned earlier, in 1980 the red and brown countries do not fit in our model results. The nitrogen application rates of these countries were much higher for their values of availability of land, and so the data points exceed the trend lines of our model. This indicates that these countries were using more nitrogen per hectare than what we expected based on our model, which results in overuse of nitrogen fertilizer. In 2010, the country level data fits with our model again. The countries that did not fit with our model in 1980 reduced the nitrogen application rates by 2010. (See the values of the Netherlands, Greece, UK, Denmark and Bulgaria in the Table S1 in the Electronic Supplementary Material). In some of these countries, strict environmental regulations with respect to nitrogen applications were put in practice to reduce the environmental problems related to fertilizer use in agriculture (eutrofication) [34-36]. This phenomenon is also shown in Figure 1c where Western Europe reduced their application of nitrogen after the 1990's.

Our results showed that during the last fifty years the increase of both population density and consumption of animal products has increased the nitrogen application rates. These numbers are average country level data which should not be considered as strict values, but they help us to identify the different drivers to the use of synthetic nitrogen fertilizer and their interrelationships.

The combination of the population density and the diets makes it possible to explain the unexpected results in Figure 1. The fact that North America has high meat consumption levels but low fertilizer application rates can be explained from the fact that the population density is low. The fact that population density in Africa is much higher than in North America, while nitrogen application rates in Africa are much lower can be explained from the very low meat consumption levels in Africa.

Discussion of our approach and the consequences of our findings for the future needs for nitrogen

In this paper, we studied the use of nitrogen fertilizer from a demand perspective. We analysed the impact of the global differences in diets, population and agricultural systems on the use of nitrogen fertilizer. To do this, we linked data of food patterns and population densities with data of production systems. We used the average values of 110 countries as examples in order to have an overview of the global variations. By doing this, we have not calculated the exact use of nitrogen in each country. If we wanted to do this, we would have needed to consider the food imports and exports of each country; and to combine the data of one food pattern with the data of two or more production systems (the production system of the country itself and the country or countries where the food imports were produced). So, by including the food imports it is not possible to illustrate the relations of one diet with one production system, which is the aim of this paper. Therefore, including food imports and exports is outside the boundaries of our research. Thus, with our analysis it is possible to understand the relations of the global differences in diets, population and production systems to assess the future use of nitrogen.

An important finding of our analysis is that when population densities are below the 5 persons per ha arable land (p/ha) (0.2 ha of arable land per person) the relation population density and nitrogen demand is more or less linear, and it becomes exponential with higher values of population density. The present global population density is 5p/ha, and at global level we observed a linear increase of the nitrogen applications over the last decades. By 2050, the global population is expected to reach 9 billion people. If no major increase in arable land area is expected, 9 billion people will imply a population density of 7p/ha. (0.15ha/cap). This value is already in the exponential part of the curves in Figure 3. And so,

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the need for nitrogen can no longer be derived from the historical linear trend.

Next to this, the increase of the global population will not be evenly distributed over the globe. If we divide the projected 2050 population numbers for each country by the present arable land of each country, then by 2050 six billion people (or 70% of the global population) will live in countries with less than 0.1ha/cap arable land.

To make things even worse: the countries with the expected population increase are also the countries with the present low consumption of animal products in their diets. It is rather likely that meat consumption will increase in these regions which will increase the need for nitrogen even more. This double effect can be recognized in Figure 1 for China. In this country, both population density and meat consumption increased and the increase in nitrogen application rate was huge.

The existing estimates with respect to future needs for nitrogen fertilizer involve the doubling of the present use [37] which will result in major impacts for the global environment. Using our model with global average values, we could reproduce the estimates of Tilman et al. [37]. However, our model also shows that a large share of the global population will deviate from this global average to much higher nitrogen application due to both higher population density and higher consumption of animal products. Due to the non-linearity in this part of the graph (Figure 3), the future estimates of nitrogen fertilizer use could be larger with higher environmental impacts in the regions where 70% of the global population will live [38-41].

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