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Research Article

INCREASED FERTILIZER USE INDUCES DIET CHANGE AND IS LINKED TO INCREASED OVERWEIGHT AND OBESITY

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ABSTRACT

Through theHaber-Boschinvention of fertilizer production, we have increased rates of food production to help feed a growing population. This has led to a livestock revolution, and we are now eatingmany animal products.At the same time we have roughly equal populations of malnourished and obese people. The strong increase in mineral fertilizer use and livestock production is known to cause many negative environmental impacts.Here we show that there is a strong correlation between mineral fertilizer used on a national scale with calorie consumption and with obesity and overweight. While no direct causality should be implied, we derive important insight in the relations between diets, health and the disruption of the nitrogen cycle. An important diverging point between fertilizer use and obesity/overweight rates was identified. Up to national average per capita consumption levels of 3,000kcalthere is an increase in the share of the population that is obese or overweight; after 3,000 kcal, the obese/overweight population levels off. However, the average national fertilizer use continues to increase linearly with kcal consumption beyond 3,000 kcal. This suggests that the availability of N fertilizer enabled a boost to food production to reduce malnourishment in the world, but a major part of this fertilizer enabled a shift towards diets that can affect human health in a negative way and has a cost for society both in health care and in environmental consequences. This study can serve as a foundation for making new connections between how fertilizer use feeds different populations of the world.

INTRODUCTION

In 1913, the first large-scale ammonia production started in Ludwigshafen, Germany, using the Haber-Bosch (HB) process to fix atmospheric nitrogen (N_2) in a reactive form such as ammonia [Smil 2001; Hager 2008; Gorman 2013]. The chemical industry regards this as a major achievement especially because it was the first time that chemical reactions could be completed in a controlled way under pressure and at high temperatures. It was the basis of the Green Revolution and the enormous increase in population up to the current 7.5 billion (e.g. [Erisman *et al*. 2008]).In addition to the increase in food production and population growth, NH_3 produced by the HB process forms the basis of many products we use in daily life, such as nylon [Gu *et al*. 2013]. Meanwhile the process of producing NH_3 has advanced such that the consumption of fossil fuel energy has almost reached the thermodynamic minimum and production costs have dropped to make fertilizer affordable in large parts of the world (e.g. [Smil 2001; Gorman 2013]).

The production of grain and other food products has kept pace with population growth due to the use of mineral fertilizers (Fig. 1;Also quantifies the other key processes of fixing atmospheric N_2: human induced biological nitrogen fixation

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and NO_x from combustion processes).Globally, three stages of per capita fertilizer use can be distinguished: a strong increase until 1990, a decrease until1995, and stabilization until now [Galloway *et al.* 2014].The production of meat (including fish) shows a steady per capita increase of about 0.5 kg per person per year from 1950 to present. The production of grain was more stable until around 2005 when it started to follow the increase in meat production while the vegetal into animal conversion efficiency is still increasing (Bouwman *et al*. 2013).

The conversion of N_2 into biologically relevant nitrogen forms (reactive nitrogen, Nr) has, together with the exploration and use of fossil fuels, enabled a new food industry and resulted in the availability of more calories, protein, sugar and fat per person [FAO 2013]. This has resulted in diets with increased animal protein, which is less efficient to produce in terms of nitrogen and other resource use compared to plant protein. Animal protein is 2-6 times less nitrogen-efficient for protein production than crop protein [Smil 2001; Bouwman *et al.* 2013]. Although the Haber-Bosch process enabled the Green Revolution and therewith the strong increase in population, it has also allowed for a change in diets, reduced efficiency of resources (e.g. food waste) and the associated negative environmental consequences [Erisman *et al* 2008; Gorman 2013]. In fact only about half of the increase of global animal protein consumption during the last 50 years was due to population growth—the rest was due to dietary changes (Lassaletta *et al*. 2016).

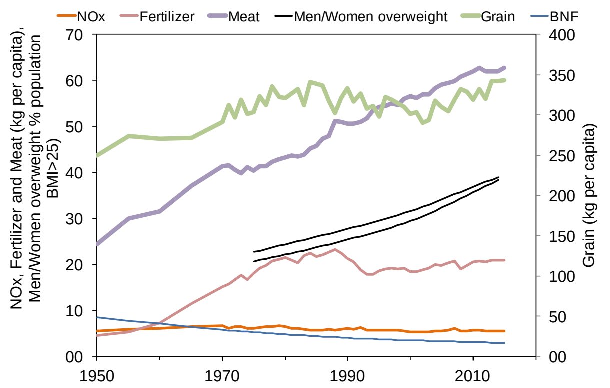


Figure 1 Global trends in food production (meat and grain, kg N per capita) and formation/use of newly created Nr(mineral fertilizer consumption, biological nitrogen fixation, combustion NOx,all in kg N per person)since 1950 (data from International Fertilizer Association, Earth Trends, IPCC). Data of men (upper line)/women (lower line) overweight (BMI > 25) are given as % of total population (NCD-RisC, 2016)

Environmental and societal impacts

With agricultural intensification and expansion, increased fertilizer use has occurred along with increased water use, loss of soil carbon and loss of biodiversity (e.g. [Isbell *et al*. 2013; Sutton *et al*. 2013]). There are serious side effects caused bythe loss of Nr to the environment, including the following: water quality impacts (e.g., groundwater pollution, freshwater eutrophication, estuary eutrophication and hypoxia); air pollution and the associated human health impacts (e.g., NOx, O_3, particulate matter [PM]); ecosystem and crop yield impacts; deposition to ecosystems (e.g., with affects to biodiversity, ecosystem services); climate change and stratospheric O_3depletion (N_2O);(e.g. [Sutton *et al*. 2011; Reid *et al*. 2005; Galloway *et al*. 2003, 2008; Diaz *et al*. 2013; Erisman *et al*. 2013; Sutton *et al*. 2013]).

Nr is highly mobile through the environment. Over time, one molecule of Nr can contribute to several of these environmental effects in space and time as it cascades through the environment [Galloway *et al*. 2003]. The endpoint of the cascade is at some place and time the release of N_2 or long-term sequestration in biomass, soils or rocks. N_2O is the longest living reactive form and contributes to climate change and stratospheric ozone destruction [Ciais *et al*. 2013].

The importance for proper management of nitrogen in order to safeguard the environment has been widely recognized (e.g., Zhang *et al*., 2015). There are huge societal costs associated with the loss of Nr to the environment. Recent cost-benefit analyses of Nr have been presented for the Chesapeake Bay in the US [Birch *et al*. 2011], for Europe [Brink *et al*. 2011, Van Grinsven *et al*. 2013] and as a broad overview for the US [Compton *et al*. 2011; Sobota *et al*., 2013]. The costs in Europe have been estimated to be 70-320 billion Euros annually for Europe [Brink *et al*. 2011]. The global costs of human use of Nr are estimated at 800 (200-2000) billion US dollars per year [Sutton *et al*. 2013]. These estimates do not include the additional health costs associated with changes in diet and overconsumption such as obesity and cardiovascular diseases.

Objectives

Given the increasing rates of fertilizer use coupled with a growing population and environmental impacts, this paper aims to explore the question: Who eats the fertilizer? The specific objectives addressed are:

1. Explore global trends in food consumption by food category.
2. Compare national rates of obesity and overweight populations with the following:
   a. Kilocalorie consumption
   b. Plant protein consumption
   c. Animal protein consumption
   d. Fertilizer application rates
3. Discuss potential connections between fertilizer use, the types of protein consumed, and obesity/overweight populations.

Who eats the fertilizer?

Fertilizer use in the agricultural system can never be 100% efficient and the efficiency generally decreases with increasing application: the law of diminishing returns [e.g. Smil 2001; Sutton *et al*. 2011]. The large-scale availability of relatively cheap and in many cases subsidized fertilizers along with the strong increase in meat production has decreased the nitrogen use efficiency (NUE) to globally no more than 15% in agriculture including livestock[Gorman 2013; Davidson *et al*. 2015; Sutton *et al*. 2013; Erisman *et al*. 2017].In 1961 29% of the new reactive nitrogen (considering also crop and grassland fixation) finished in the human food (vegetal + animal protein discounting fish) while in 2009 this amount decreased to 18% (Lassaletta *et al*. 2016). With an average NUE of 18% over the whole production chain, most of the N_r (82%) used in producing food products is lost. The NUE of animal protein production is lower because N_r is lost at two different stages (Gerber *et al*. 2014; Galloway and Cowling, 2002; Bouwman *et* al. 2013). The first loss occurs while producing the feed for the animals. The second loss occurs while the animals are raised and fed, as most of the N in their feed is lost in manure (but may be reclaimed for agriculture).

Several authors have attempted to determine what share of the global population's whose diets depends on fertilizer inputs to food production (e.g.[Smil 2001; Erisman *et al*. 2008]). They estimated how much food the current agricultural land could produce without fertilizer as an indicator for the rest of the population which should then depend on fertilizer. This approach took the pre-fertilizer agricultural production level and corrected it for an increase in the agricultural area and an increase in production efficiency due to mechanisation, different management practices and crop breeding. Erisman *et al*. [2008] estimated that currently 48% of the people consumes food produced with the aid of synthetic fertilizer. Stated another way, we could not produce enough food for 48% of the current global population without the production of synthetic fertilizer

To determine how much fertilizer eventually reaches the consumer we have to consider information about trends in diets, especially the consumption of animal protein, food waste and the people who over-consume or who are malnourished. Some general observations to inform this study are the following:

- About 10% of the produced food (sweets, snacks, wine, etc.) does not contribute to the daily nutritional requirements (FAO, 2012). This does not include the use of corn (syrup) for food additives instead of direct consumption
- Over the whole food chain, 40-50% of food is wasted, mainly as 'wet foods' (vegetables, fruits),estimated at 25% of all calories [FAO 2013; Gustavsson *et al*. 2011]
- About805 million people suffer from malnutrition and about 750 millionareconsidered obese and 2.35 billion people are overweighed in 2012-2014 [Fig. 1; FAO 2015; Ng *et al*. 2013; NCD-RisC 2016]
- 67%% of cereal production is currently allocated to animal feed (expressed in terms of protein and including bio-energy byproducts such as DDGs) [Lassaletta *et al*. 2016].

These factors allow us to derive the amount of 'effective' fertilizer which is consumed per person in food, provided that information on diets and food waste is available. Because food consumption and therewith fertilizer use is not evenly distributed over the world, we expect that a relatively small share of the population consumes most of the fertilizer.

Diets, obesity and N fertilizer use

We hypothesize that there are people who--through their diets--consume more than average fertilizer and thus are more responsible for polluting the environment through a higher share of nitrogen losses.

Obesity and overweight is a growing worldwide concern. It affects the health and well-being of many people and leads to increased health care costs. In a recent publication Ng *et al*.[2013] present an overview of the national share of obese (defined as adults with a body mass index above 30) and overweight(body mass index above 25) people. The national percent of the population that is overweight ranges from the lowest in North Korea (4.4%) to the highest rate in the Tonga (86%) in Tonga (adults over 20 years old). Trends of obesity and overweight in the Organization for Economic Co-operation and Development (OECD) countries show a steady increase of 0.5% per year over the past 20 years [OECD 2013]. Global obesity and overweight trends are given by NCD-RisC (2016; see Fig. 1). We collected data on protein consumption rates, fertilizer consumption, population numbers, obesity and overweight populations, and nitrogen use efficiency (Table 1).

Table 1 Data collected to compare fertilizer use, protein consumption, and obesity and overweight rates in countries.

Data set	Data source
Protein consumption by food category at national scale	FAOSTAT [FAO 2015]
Mineral fertilizer consumption on national level	FAOSTAT [FAO 2015]
National populations	United Nations Department of Economic and Social Affairs, Population Division [United Nations Population Division of the Department of Economic and Social Affairs, 2015]
National obesity and overweight populations	Ng et al. [2013]: World Population Prospects: The 2012 Reivision, and obesity data
Nitrogen use efficiency	Lassaletta et al. [2014a] and Sutton et al. [2013], Our Nutrient World

These statistics were used to study the correlations between the different variables. Central to this is the per capita kcal consumption which we classiefied and per class averaged the national consumption. Per kcal class we then averaged obesity, overweight, fertilizer and protein consumption for different food groups. The results are discussed here. We observe a strong correlation among the different indicators, e.g.,national population strongly correlates with fertilizer use just as national calorie and protein consumption also correlate with fertilizer use(Figures not shown here). We first compare food classes with calorie consumption, then relate obesity/overweight to calorie consumption and finally introduce fertilizer into the equation.

Comparing food classes and kcal consumption

Our current consumption pattern can be grouped by food category, reported as food class expressed as kcalconsumption per person in different countries. By using FAO national data on food supply we grouped the food components according to Rivas [2015]: staple food (cereals, root and pulses), affluent vegetal (sugars, vegetable oils, vegetables and fruits), meat (bovine, pig, poultry and fish), other animal (milk, eggs and animal fats) and other (alcoholic beverages, tree nuts, stimulants and spices). Staple food consumption is the highest share in the kcal consumption and is independent of the average national kcal consumption (Figure 2). The other 4 food components, however, increase with increasing kcal food. Apparently the staple food consumption is a basis in all the diets averaged over the countries and therefore not increasing with increasing calorie consumption. However, this does not mean these correlations represent causal relationships. Especially, the use of national data obscures in-country differences between affluence and related diet patterns, or the influence of trade in the Nr budgets of some countries. While trade patterns of Nr have been investigated (Lassaletta *et al*., 2014b), these do not allow proper allocation of fertilizer use. Finally, in this analysis we were not able to single out fertilizer use for applications other than food production (e.g., biofuels), which may be an important element for some countries.

Connecting fertilizer and overweight/obesity

Up to a 3,000 kcaldiet there is an increase in the share of obese and overweight people; above 3,000 kcalboth shares level off, suggesting that the obese/overweight shares of the population do not continue to increase above a national average of 3,000 kcal per capita consumption (Figure 4).

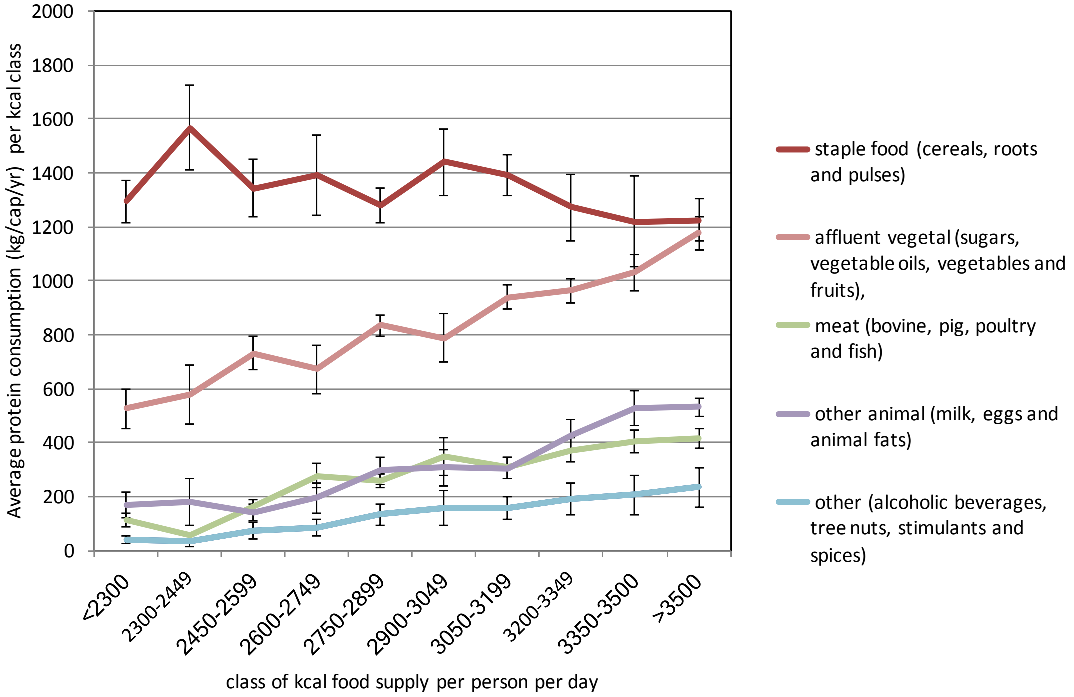


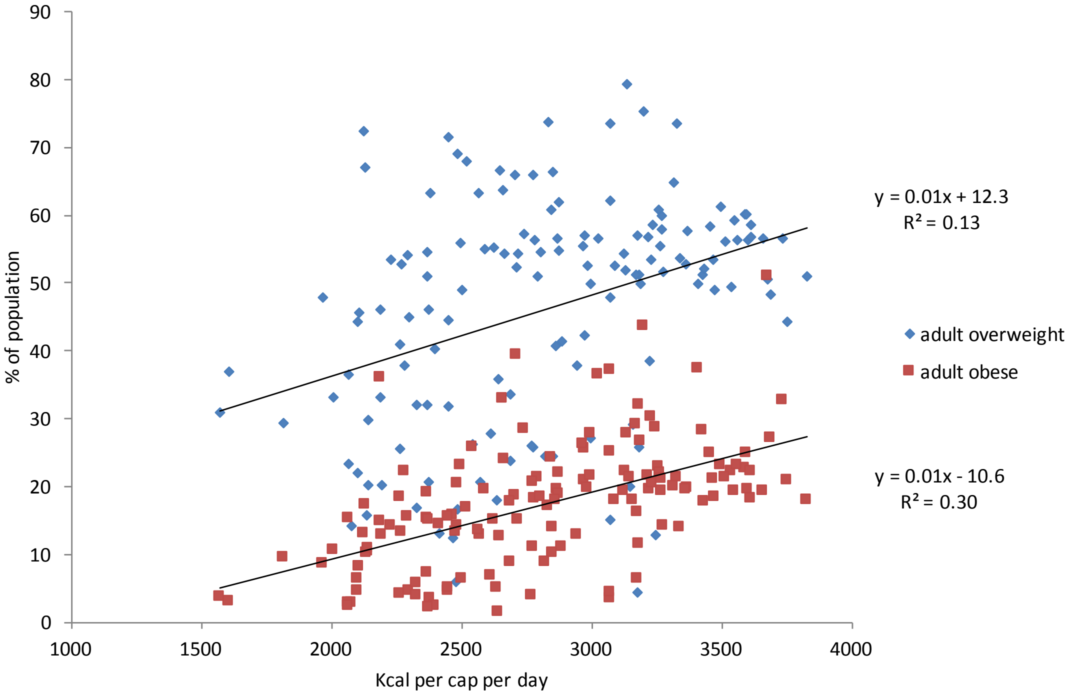
Figure 2 The change in food consumption (kcal) by five food categories in different classes of kcal consumption across countries. Countries are allocated into a kcal class across the x-axis based on per capita consumption, and that diet is then shown across the five food categories (staple food, affluent vegetal products, meat, other animal products, and other food products). The average and standard error is calculated based on the range of kcal consumption for the countries that fit into a given kcal class.

Comparing overweight/obesity rates to protein and kcal consumption

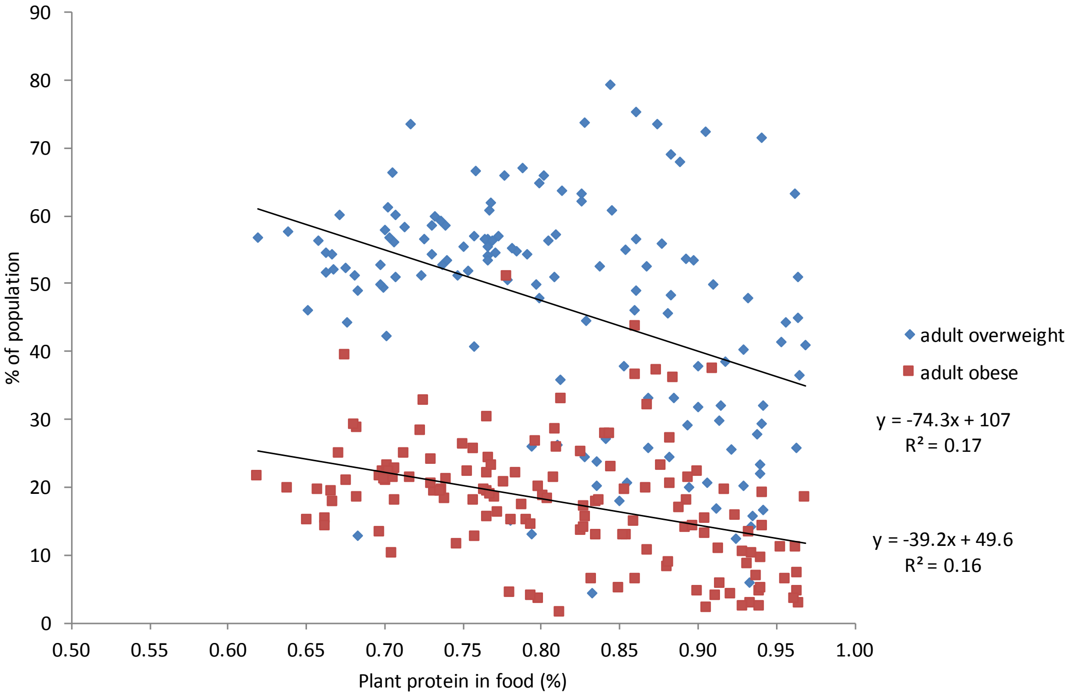
Within each country there is a share of the population that is identified as overweight or obese [Ng *et al*. 2013]. A change in diet towards more animal protein and more processed food is one of the major causes of increased overweight and obesity in many parts of the world [Ng *et al*. 2013; Ljungvall and Zimmermann 2012]. There is a strong correlation between the trend in obesity and per capita calorie supply for the nations of the world as shown by Vandevijvere *et al*., (2015). and supported by our data in Figure 3A, although the correlation is low. Furthermore, when the share of plant protein in the diet increases, the obesity and overweight percent decreases (Figure 3B). However, there might be other factors that changed with the same intensity over the years such as a decrease of everyday physical labor, only part of which is substituted by volunteer sport exercises. Furthermore, there are differences in age, size, culture, calories used, waste, import and export of food and social aspects between the different countries affecting obesity and calorie consumption (e.g. [Roberto *et al*. 2015]), which all are not accounted for in this analysis and may contribute to data scatter. Given these uncertainties, this analysis presents a first attempt to correlate obesity/overweight with changes in total kcal consumption and plant protein consumption.

It is interesting to note that the same 3000 kcal of dietary energy supply, as a national average, has been identified as a level that safeguards countries against hunger and thus is recommended as a lower level to attain the Millennium Development Goals [Rockström *et al*. 2005]. This level has been chosen despite the fact that only a part of the population ever achieve such dietary energy requirements [FAO 2004]. Rockström *et al*. [2005] arrive at an average energy requirement allowing for growth and light physical activity of 1,720-1,970kcal per person and day. It seems that beyond a dietary energy supply of 3,000 kcal, food availability has very little connection to individual intakes, while at lower levels both obesity and hunger are influenced.

In contrast, the nitrogen fertilizer use per person in a country increases with the increase in kcal, even beyond 3,000 kcal, while at the same time the nitrogen use efficiency (as obtained from [Sutton *et al*. 2013]) decreases. Mineral fertilizer use for countries of high food supply (above 3000 kcal p.p.) is roughly three times as high as for less developed countries, implying that the major part of mineral fertilizers is used to feed obesity rather than to eradicate hunger. For decreasing malnourishment it would therefore be better by improved distribution of available food products.



(A)



(B)

Figure 3 Adult obese and overweight share of national population versus the national average kcal supply (A) and the share of plant protein in diet (B).

This is the first time that statistics about overweight, obesity, fertilizer and food consumption patterns have been combined. Although there is uncertainty and confounding factors, we demonstrate that over-consumption of kcal--especially of food components other than staple foods--has a clear correlation with obesity and overweight and fertilizer consumption. Therefore, both human health and environmental pollution (nitrogen in this case) can be clearly related to food consumption.

Over-consumption, as derived from data presented here, specifically refers to food components other than staple foods, but also to food wastage. This implies that, for large parts of fertilizer used, increasing environmental damage via Nr addition from agricultural production would not decrease malnourishment (which only can be covered by improved distribution of available food products) but increase obesity.

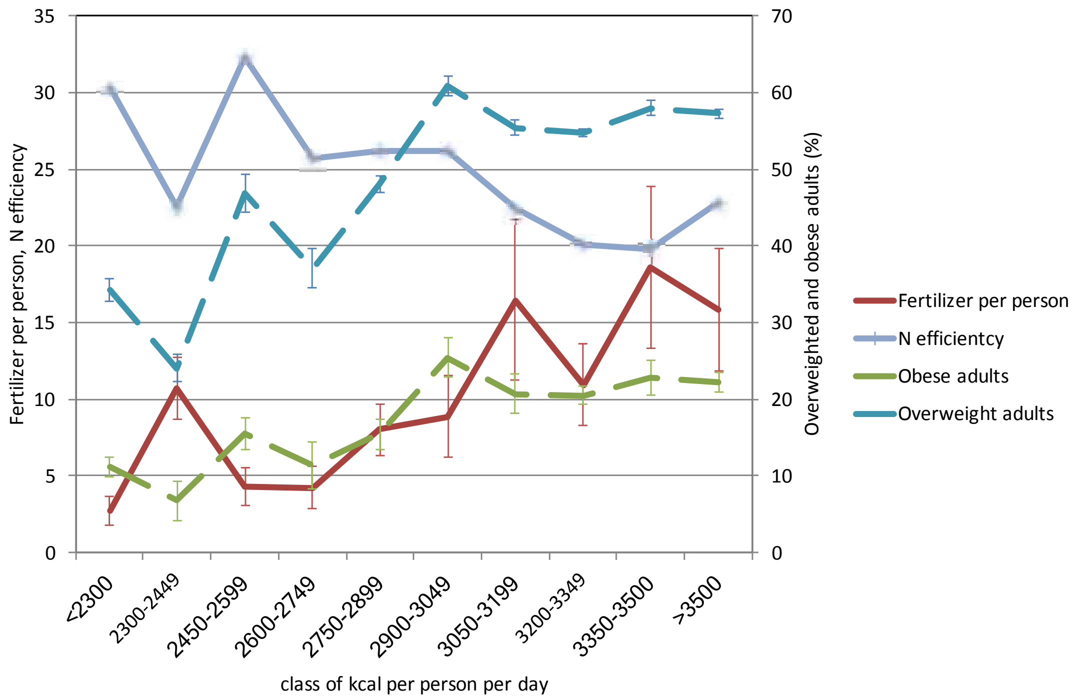


Figure 4 The mineral N fertilizer applied in kg per person in a country, the NUE, and the average percentage of overweight and obese people per class of average kcal per person in a country. The error bars represent the standard deviation.

Reducing over-consumption by way of a more N-efficient diet would contribute to improved health and reduce health costs and to a reduction in further disruption of the N-cycle and the associated societal costs.

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