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REPORT

Socioeconomic Driving Factors of Nitrogen Load from Food Consumption and Preventive Measures

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Abstract To diagnose environmental nitrogen (N) load from food consumption and to suggest preventive measures, this study identified relationships between nitrogen load from food consumption and driving factors by examining six representative countries and regions for the period 1970–2009 as an example. The logarithmic mean Divisia index technique was used to disassemble nitrogen load growth into four driving factors: population, economic activity, food intensity of the economy, and nitrogen content of food. In all study areas, increased economic activity was the main factor driving nitrogen load increase. The positive effect of population growth was relatively small but not negligible and changes in food intensity had a decreasing effect on nitrogen load. Changes in nitrogen content of food varied between areas. Broad strategies to reduce and mitigate nitrogen loading and decouple nitrogen load from economic growth in both developed and developing countries are suggested.

Keywords Decomposition analysis · Food consumption · Nitrogen load · Economic activity · Food intensity of the economy · Nitrogen content of food

INTRODUCTION

Until the development of Haber–Bosch process in the early twentieth century, the supply of nitrogen (N) to plants, and ultimately to animals and humans, was limited to natural sources. However, driven by human activities, such as agriculture, energy use, and changes in land use, the amount of reactive nitrogen (Nr; all species of N except N_2) has more than doubled since the 1940s (Galloway et al. 2004, 2008). Many studies on nitrogen loading have shown that excess nitrogen from human activities has threatened air and water quality, disrupted the health of terrestrial and aquatic ecosystems, and has generally been detrimental to global ecosystems (Rockström et al. 2009). Many studies have clarified that human food consumption has a major impact on the environmental nitrogen load (Smil 1999, 2002; Shindo et al. 2003; Liu et al. 2008, 2009, 2013; Leach et al. 2012).

To reduce and control the nitrogen load from human food consumption, analysis and quantification of socioeconomic driving factors become necessary as the demand profile changes with economic growth and globalization. However, few studies have focused on socioeconomic driving factors. This study intended to clarify the historical nitrogen load changes from food consumption, as well as to reveal the relationships among changes in nitrogen load from food consumption and the associated determinants: (1) population, (2) economic activity (per capita GDP), (3) food intensity of the economy (food consumption per GDP), and (4) nitrogen content of food (nitrogen consumption per food consumption), using decomposition analysis and existing statistical data from six representative areas for the period 1970–2009. Our goal was to detect environmental nitrogen load that can threaten regional sustainability and end with to seek out adaptable solutions to reduce nitrogen load.

MATERIALS AND METHODS

Areas of Study

The study area included four countries—China, Japan, Mongolia, and the USA—and two regions—Southeast Asia (SEA) and Europe. According to the database launched by the Statistics Division of the United Nation's Food and Agricultural Organization (FAOSTAT), SEA includes 11 countries, such as Indonesia, the Philippines, and Vietnam, and Europe includes 46 countries along the watershed divides of the Ural and the Caucasus Mountains, the Caspian and the Black Seas, and the Ural River. As representatives of developed areas, Japan, the USA, and Europe are well known for high economic activity and income levels. China and SEA were analyzed as representatives of developing areas. Mongolia was chosen as a comparative case due to its unique traditional dietary habits.

Methodology and Data

The equation $I = PAT$ [i.e., human impact (I) on the environment equals the product of population (P), affluence (A), and technology (T)] was developed in the 1970s by Ehrlich and Holdren (Kwon 2005) and can aid in understanding how growing population, affluence, and technology contribute to human environmental impact. The Kaya Identity (Eq. 1) suggested by the Intergovernmental Panel on Climate Change is closely related to the $I = PAT$ equation and does an excellent job of helping us understand driving factors (population, economic activity, energy intensity, and carbon intensity) and potential solutions for CO_2 emissions (IPCC 2000).

$$\mathrm{CO_2\ emission} = \mathrm{Population} \times \frac{\mathrm{GDP}}{\mathrm{Person}} \times \frac{\mathrm{Energy}}{\mathrm{GDP}} \times \frac{\mathrm{CO_2}}{\mathrm{Energy}} \tag{1}$$

where GDP is Gross Domestic Product.

Considering that nitrogen loading from human activities has the same characteristics as energy consumption and CO_2 emission, we propose an alternative formulation of the $I = PAT$ equation and Kaya Identity to investigate potential factors that contribute to the increase in nitrogen load from food consumption. For healthy adults under standard metabolic conditions, the amount of nitrogen consumed is equal to that excreted (FAO/WHO/UNU 1985). Except for relatively few cases where advanced sewage treatment with nutrient removal technology or waste recycling systems have been implemented, most of the nitrogen in human waste and food waste is emitted to the environment (water bodies, atmosphere, etc.) as nitrogen load. Then the potential nitrogen load from human waste that is derived from food consumption (TN) can be estimated as follows:

$$\mathrm{TN} = \mathrm{Population} \times \frac{\mathrm{GDP}}{\mathrm{Person}} \times \frac{\mathrm{Food\_Consumption}}{\mathrm{GDP}} \times \frac{\mathrm{Nitrogen\_Consumption}}{\mathrm{Food\_Consumption}}. \tag{2}$$

Equation (2) can also be expressed as follows:

$$\mathrm{TN}_{it} = P_{it} \times E_{it} \times F_{jit} \times C_{jit}, \tag{3}$$

where TN_{it}, total nitrogen consumption/load (ton) from food consumption for study area i in year t; P_{it}, total population (person); E_{it}, per capita GDP (US dollar/person), which is frequently used as a factor that measures economic activity, per capita production, disposable income, standard of living, among others; F_{it}, food intensity of the economy (food consumption per GDP, ton/US dollar); C_{it}, nitrogen content of food (nitrogen consumption per food consumption, ton/ton).

In decomposition analysis, index decomposition analysis has been widely used to break down an aggregate indicator and quantitatively measure the relative contributions of a set of predefined factors leading to change in the aggregate indicator (Huntington 1989; Ang 1995a, b; Ang and Zhang 2000; Wang et al. 2011). According to Ang and Zhang (2000), the most widely applied index decomposition methodologies in recent decades are based on the Laspeyres and Divisia indexes. The large residual term found in most applications was an issue with conventional Laspeyres and Divisia index methods, leaving a significant part of the examined changes unexplained. Fortunately, a refined Divisia index method, the logarithmic mean Divisia index (LMDI) approach, which has the desirable characteristics of perfect decomposition and consistency in aggregation, was introduced by Ang and Liu (2001). Ang (2004) noted that the LMDI has several useful features: it is consistent in aggregation under certain conditions; it uses the logarithmic mean of two endpoint values as a weight function and leaves no residual term after the decomposition.

On the basis of the detailed explanation and practical guide to the LMDI method provided by Ang (2005), this study decomposed the total change in nitrogen load ($\Delta\mathrm{TN}_{tl}$) from year $t1$ to year $t0$ using an additive decomposition model as follows:

$$\begin{aligned}\Delta\mathrm{TN}_{tl} &= \mathrm{TN}_{t1} - \mathrm{TN}_{t0} \\ &= \Delta\mathrm{TN}_P + \Delta\mathrm{TN}_E + \Delta\mathrm{TN}_F + \Delta\mathrm{TN}_C.\end{aligned} \tag{4}$$

The factors on the right-hand side of Eq. (4) represent the change in a country's total population ($\Delta\mathrm{TN}_P$), economic activity ($\Delta\mathrm{TN}_E$), food intensity of the economy ($\Delta\mathrm{TN}_F$), and the nitrogen content of food ($\Delta\mathrm{TN}_C$). These factors can be expressed as Eqs. (5)–(8), respectively ($\mathrm{TN}_{t1} \neq \mathrm{TN}_{t0}$):

$$\Delta\mathrm{TN}_P = \frac{\mathrm{TN}_{t1} - \mathrm{TN}_{t0}}{\ln \mathrm{TN}_{t1} - \ln \mathrm{TN}_{t0}} \ln \frac{P_{t1}}{P_{t0}}, \tag{5}$$

$$\Delta\mathrm{TN}_E = \frac{\mathrm{TN}_{t1} - \mathrm{TN}_{t0}}{\ln \mathrm{TN}_{t1} - \ln \mathrm{TN}_{t0}} \ln \frac{E_{t1}}{E_{t0}}, \tag{6}$$

$$\Delta\mathrm{TN}_F = \frac{\mathrm{TN}_{t1} - \mathrm{TN}_{t0}}{\ln \mathrm{TN}_{t1} - \ln \mathrm{TN}_{t0}} \ln \frac{F_{t1}}{F_{t0}}, \tag{7}$$

$$\Delta TN_C = \frac{TN_{t1} - TN_{t0}}{\ln TN_{t1} - \ln TN_{t0}} \ln \frac{C_{t1}}{C_{t0}}. \quad (8)$$

For details of the additive decomposition model, refer Ang and Liu (2001), Ang et al. (1998), and Boyd et al. (1988).

Data used in this study were acquired from the following sources. Data for consumption quantity and protein supply quantity of food by type (cereals, pulses, starchy roots, oilcrops, sugarcrops, treenuts, vegetables, fruits, poultry, pork, beef, eggs, milk, aquatic products, seafood, alcoholic beverages, and others) in the study areas during 1961–2009 and population data during 1961–2012 were downloaded from FAOSTAT (http://faostat.fao.org/). The GDP data for the study areas during 1970–2010 are available from the World Economic Outlook Databases (http://www.imf.org/external/pubs/ft/weo/disclaim.htm).

It is noteworthy that the food and protein supply data describe the total amount of food and protein available for consumption, including food waste, rather than the amount of food and protein actually consumed. Food waste was included because it contributes to environmental nitrogen loading. In addition, since nitrogen accounts for 16 % of protein by mass, nitrogen consumption could be estimated by multiplying protein consumption by 0.16.

RESULTS AND DISCUSSION OF DECOMPOSITION ANALYSIS

Total Potential Nitrogen Load from Food Consumption

The nitrogen load from food consumption has changed significantly during the past 50 years (Fig. 1). Prior to 1990, European countries showed the highest nitrogen load; however, this began to decrease at the beginning of the 1990s, stabilizing and increasing slightly by the end of the decade. The total potential nitrogen load in China reached 7.48 million tons in 2009, which was a 4.8-fold increase over that in 1961 and has surpassed that of European countries since 1992. Similar to China, SEA has also shown a significant 4.3-fold increase. Although the absolute value of nitrogen load from food consumption in Mongolia is low, the growth rate was striking, exhibiting a 2.6-fold increase during 1961–2009. Unlike developing Asian countries, Japan has maintained consistent nitrogen load levels since the 1970s. The nitrogen load in the USA increased stably throughout the study period.

Trends of Potential Driving Factors

The nitrogen load from food consumption by human beings is directly connected to the per capita protein consumption and total population.

According to the data from the FAOSTAT database, per capita protein supply in developing countries has increased rapidly during the past few decades. In China, the per capita daily protein supply increased from 39 g in 1970 to 94 g in 2009, which is an increase of 2.4 times. For SEA, the per capita daily protein supply increased from 39 g in 1961 to 65 g in 2009, which is an increase of 1.7 times. As an exception, Mongolia showed the largest reduction and huge fluctuations, with no overall growth between 1961 and 2009. Among the developed areas, Europe and Japan reached peak per capita protein supply of 104 g in 1988 and 98 g in 1995, respectively. In the USA, the protein supply increased from 95 g in 1961 to 116 g in 2005, and then decreased to 113 g in 2009.

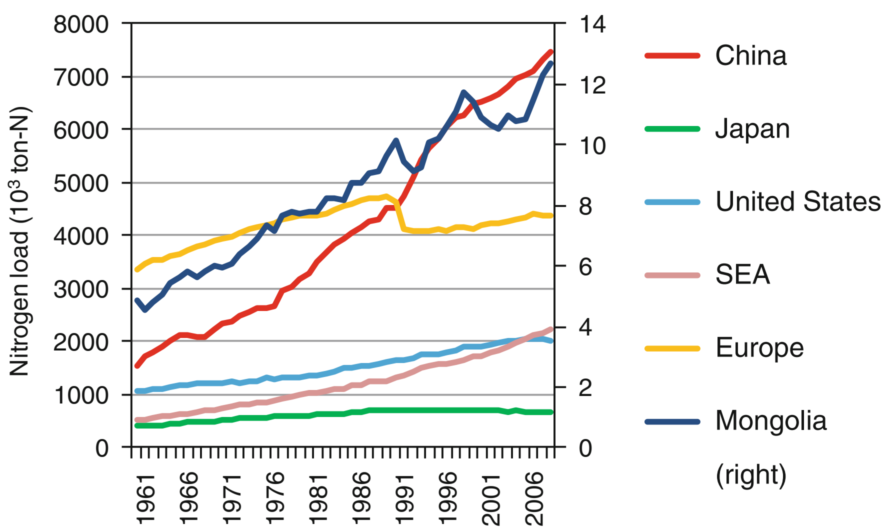

Fig. 1 Fifty-year trends in nitrogen load originating from food consumption in the different study regions (The *right vertical axis* is for Mongolia and *left vertical axis* is for others.)

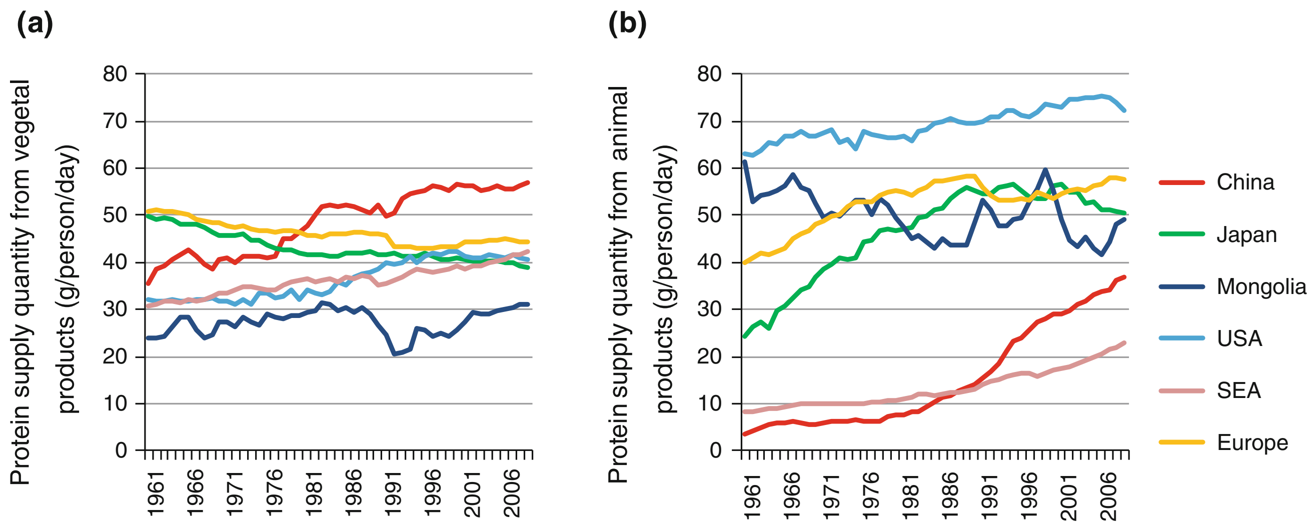

Fig. 2 Fifty-year trends of per capita daily protein supply from vegetal and animal products in the different study regions

Protein supply from food can be roughly divided into two types: vegetal and animal products. The protein supply from vegetal products increased the most in China, with significant growth beginning in 1978 (Fig. 2a). This increase was due to the dramatic increase in vegetables and vegetal products other than cereals. The protein supply from cereals reached a peak of 40 g/person/day in 1984 and decreased to 35 g/person/day in 2007. During 1961–1995, protein supply from vegetal products in Japan and Europe showed a decreasing trend, while that of the USA and SEA showed an increasing trend; however, since 1995, the trend stabilized for both the USA and SEA to approximately 40 g/person/day. Among the study areas, the rate of consumption of protein from animal products is significantly higher in the USA (72 g/person/day in 2009), followed by Europe, Japan, and Mongolia (Fig. 2b). In Japan and Europe, protein supply increased marginally from 1960 to 1990 and maintained stable levels (around 55 g/person/day) in the 1990s. Since 2000, protein supply decreased slightly in Japan and increased slightly in Europe. China showed the most remarkable increasing trend (over 10 times between 1961 and 2009), particularly since the 1980s. SEA showed a quick increasing trend since 1990s. However, the protein supply in China and SEA was still lower than that of the developed countries and Mongolia in 2009. In more developed regions, the share of animal protein supply remained unchanged (approximately 60 %) in the past 20 years. In contrast, in developing regions, the share of animal protein has increased rapidly. In China, it increased dramatically from 9 % in 1961 to 39 % in 2009. In SEA, it increased from 21 % in 1961 to 35 % in 2009. A different pattern is evident in Mongolia; given the unique traditional dietary habits, meat is a major component of the total protein supply. Although the trend has fluctuated, in general, the share of vegetal foods increased slightly in Mongolia, while that of animal foods decreased slightly during 1961–2009.

The population of developing countries shows high growth rates, while growth rates in developed countries have been slow or stable (Fig. 3a). Between 1961 and 2012, the average population growth rates per annum are 4.6 % in Mongolia, 4.2 % in SEA, 2.6 % in China, 1.6 % in the USA, 0.9 % in Japan, and 0.4 % in Europe.

In the USA, per capita GDP increased steadily during the study period and showed the highest value among study areas (Fig. 3b). Per capita GDP in Japan increased dramatically during 1974–1984; however, growth rates fluctuated between 1985 and 1999. European GDP increased significantly after 1990. Compared with the developed countries, GDP in China, SEA, and Mongolia was definitely lower. However, the growth rate was dramatic, particularly in the last 20 years of the study period.

Food intensity in the developing countries showed a significant decreasing trend in the study period (Fig. 3c). The main reason could be that GDP increased faster than food consumption. As for the trend of the nitrogen content, Mongolia and China showed a decreasing trend (Fig. 3d). There were no significant changes in Japan, SEA, the USA, or Europe. Japan and SEA maintained a relatively high level, and the USA and Europe maintained a relatively low level.

Relationships Among Changes in Nitrogen Load and the Associated Determinants

The result of decomposition analysis is shown in Table 1. Between 1970 and 2009, increases in total nitrogen load varied considerably. The greatest increases were in China (5232 tons), followed by SEA (1505 tons). The supply increased slowly in developed countries, increasing by 824,

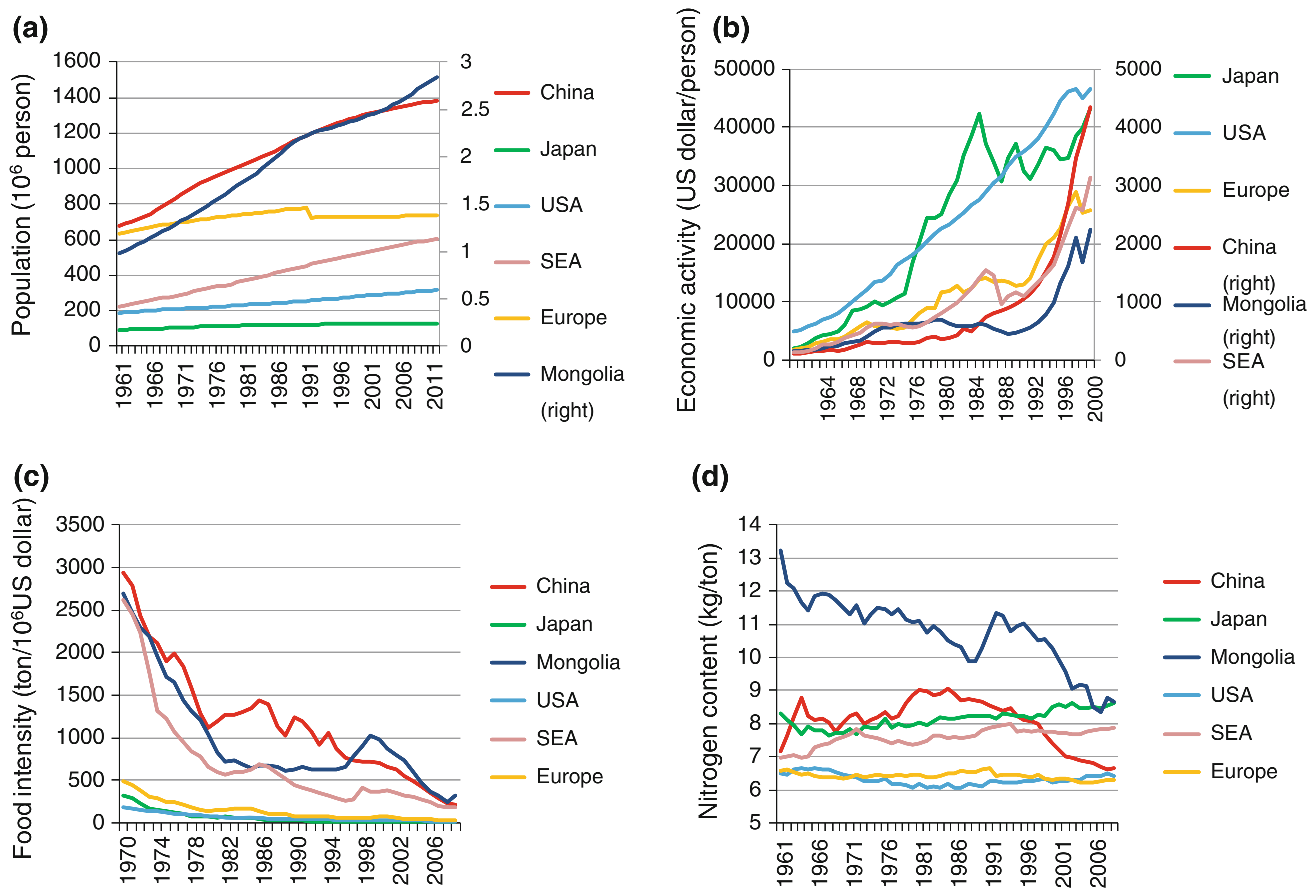

Fig. 3 Fifty-year trends of four driving factors used in the decomposition analysis driving factors (In (**a**), *right vertical axis* is for Mongolia; *left vertical axis* is for other study areas. In (**b**), *right vertical axis* is for China, Mongolia, and SEA; *left vertical axis* is for other study areas.)

Table 1 Decomposition of human nitrogen load from food consumption for study areas, 1970–2009 (unit: ton)

	China	Japan	Mongolia	USA	SEA	Europe
Change in nitrogen load (ΔTN_{tl})	5 232	161	7	824	1505	485
Change in population (ΔTN_P)	2 001	119	6	621	899	262
Change in economic activity (ΔTN_E)	18 442	1832	22	3319	3704	11 392
Change in food intensity (ΔTN_F)	−13 750	−1859	−18	−3136	−3157	−11 132
Change in nitrogen content (ΔTN_C)	−1 461	69	−3	20	59	−36

485, and 161 tons in the USA, Europe, and Japan, respectively. Mongolia showed an increase of only 7 tons.

The decomposition results reveal that economic activity is the most significant contributor to the increase in nitrogen load from food consumption, which is the most evident in China, followed by Europe, SEA, the USA, and Japan. The population index, which was positive for all study areas, provided a relatively small but noteworthy contribution. The impact of food intensity of the economy had the greatest negative impact, contributing to a reduction in the overall supply of protein. From 1970 to 2009, changes in the food intensity index reduced nitrogen load by 13 750 tons in China, 11 132 tons in Europe, 3157 tons in SEA, 3136 tons in the USA, and 1859 tons in Japan. Note that the effect of nitrogen content of food differed by area; yielding a negative effect in China, Europe, and Mongolia, and a positive effect in Japan, SEA, and the USA.

To expand our understanding of the changes that occurred, we examined the changes by region in 5-year subperiods from 1970 to 2009 (Fig. 4). The results varied widely among the regions, reflecting different historical economic development strategies. Nevertheless, some common patterns could be identified.

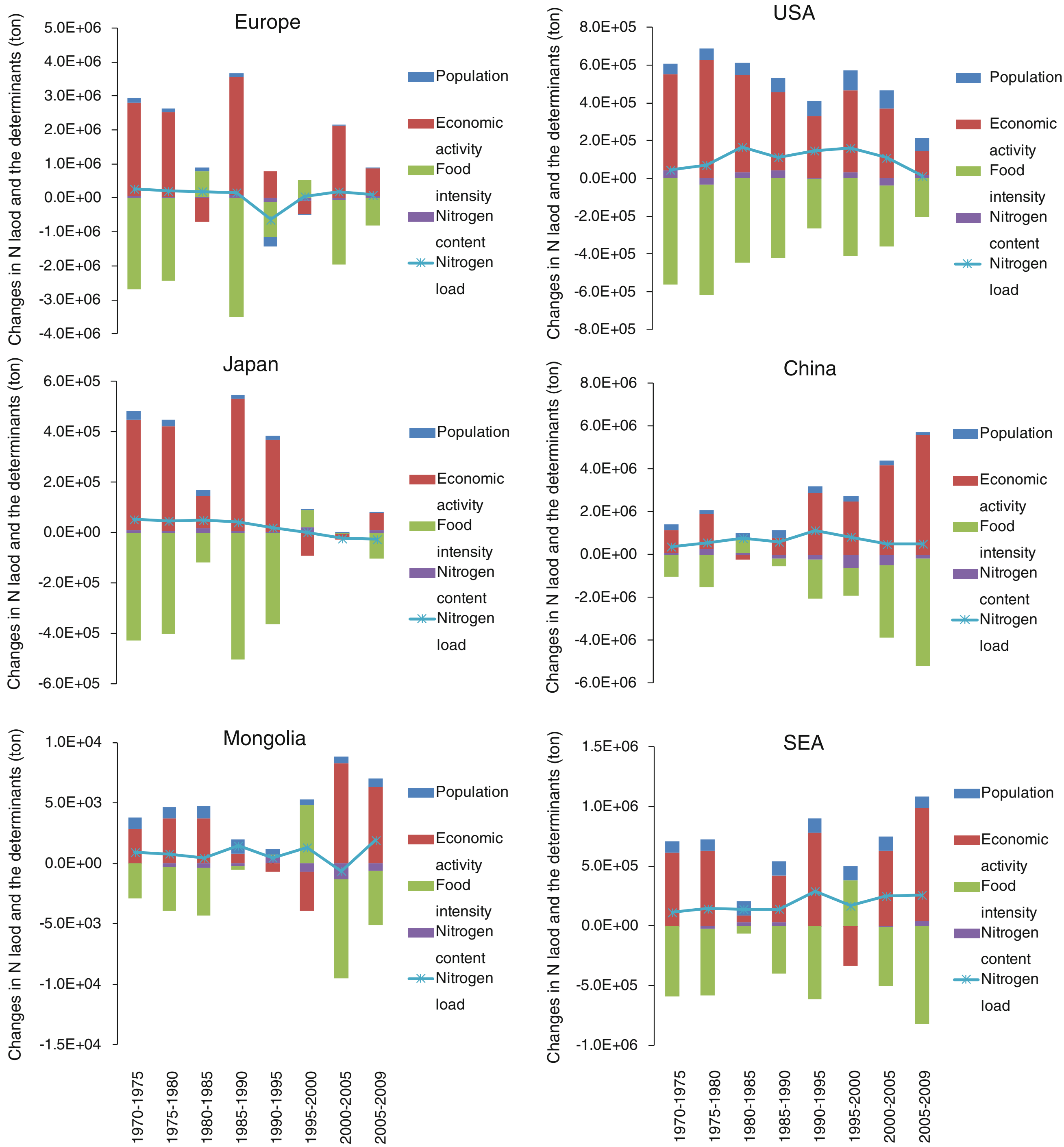

Fig. 4 Decomposition results for different study regions in 5-year subperiods from 1970 to 2009

The nitrogen load increased during most of the study period. However, it has been decreasing in Japan since 2000 and decreased from 1990 to 1995 in Europe. In China, the increase reached a peak in 1990–1995, and then subsequently slowed. In the USA, the increase was relatively high during 1980–2000, but has slowed since 2000. On the other hand, increases have been on the rise in Mongolia since 2005 and in SEA since 2000.

The growth of economic activity is clearly the most important factor affecting nitrogen load increase in most subperiods. Population growth was also a positive but relatively small contributor, except for Europe during 1990–2000. Changes in food intensity of the economy, however, appear to have offset some of the increase induced by economic activity in all subperiods. The effect of nitrogen content of food is relatively small and differed by subperiod. In these two areas, the main driving factors for the upsurge in nitrogen load were increases in economic activity and population growth, which are likely to continue increasing in the future.

Preventive Measurement to Reduce Nitrogen Load

According to Rockström et al. (2009), the safe boundary for nitrogen input to the biosphere has been surpassed. A safe boundary would be 3.5×10^{10} kg/year of nitrogen; however, to date, human activity has released 12.1×10^{10} kg/year of nitrogen into the environment, which is more than three times the safe threshold. That is, to live within the safe threshold, we would need to cut the total nitrogen load to 30 % of the current load annually.

Our results indicate conclusively that increases in economic activity and population growth are the dominant factors affecting nitrogen load for all countries. Economic activity is the most significant factor, and a simple correlation suggests that nitrogen load could be reduced by limiting economic activity. However, at present, no country would sacrifice economic development to reduce nitrogen load. This is particularly true for developing countries. As for population growth, according to official United Nations population estimates (medium variant, 2012 Revision), there are three identifiable growth patterns in the study areas. The first is a decreasing pattern, as is projected for Japan (126 million in 2012 is projected to be 109 million in 2050). The second pattern is a population increase followed by a decrease, which is expected for China (1385 million in 2012 is projected to peak at 1428 million in 2026, and then drop to 1326 million in 2050) and Europe (740 million population in 2012 is projected to peak at 744 million in 2022, and then drop to 719 million in 2050). The third pattern is a population increase, which is expected for the USA (316 million in 2012 is projected to reach to 403 million in 2050), SEA (607 million in 2012 is projected to reach 759 million in 2050), and Mongolia (2 million in 2012 is projected to reach 4 million in 2050). A way to curb population growth is to extend the time between generations by having children later in life, which would slow the development of an entire population. It is accepted that no nation will be willing to sacrifice economic and population growth to achieve reduced nitrogen load. Thus, to achieve economic development without a proportional increase in food and nitrogen consumption, i.e., decoupling food and nitrogen consumption from economic development, is purported to be the most important way to maintain regional nitrogen balance and deliver true long-term sustainability.

According to the Japan Eating Intake Standard (edition 2010, HP of Ministry of Health, Labor and Welfare), the average protein requirement is 40–60 g/day. However, the nitrogen supply per capita in all study areas in 2009 is above standard, particularly in the USA, which shows nearly twice the standard. Furthermore, animal protein consumption in developed countries is quite high even though it introduces significant loss and waste. In addition, animal protein consumption has been increasing significantly in developing counties (except for Mongolia). High-intensity animal protein intake will increase not only the nitrogen load from human excreta but also the load by feed production and livestock excreta (Bouwman and Booij 1998; Woli et al. 2002; Liu et al. 2012). Current trends may be characterized as "too much of a good thing." To mitigate nitrogen loading and decouple nitrogen load from economic growth, shifting consumption patterns from excessively high nitrogen-intensive diets to more suitable nitrogen-balanced diets may be necessary. For example, considering that the current low price of food, feed, and meat production in developed countries is supported by government grants-in-aid, and many inexpensive meats and feeds are imported, the price of food does not sufficiently cover its environmental costs. Price control policies can encourage a shift in buying and consuming patterns from high to low nitrogen-intensive foods. Furthermore, efforts to reduce food wastes may be useful for decoupling nitrogen load from economic growth.

High nitrogen-intensive consumption was once limited to developed countries; however, with rapid economic and income growth, urbanization, and globalization in the late twentieth century, Asian countries in economic and demographic transition are already showing dramatic increases in food consumption. In addition, changes in food consumption patterns (increased overall meat, milk, vegetable, and fruit consumption per person; reduced overall cereal, root, and tuber consumption) are evident even though food consumption per person, including animal protein, is still lower than that in developed countries. However, in Asia, resources are too limited to sustain a huge population with high nitrogen consumption. In particular, the most populous country, China, has maintained the highest economic growth, population growth, and nitrogen consumption/load growth during the past few decades. This growth will continue to increase in the coming decades. However, these increasing growth rates have decreased somewhat in recent years. On the other hand, economic and population growth in SEA will continue to maintain high growth rates in the coming years, which will contribute to even greater nitrogen load. Whatever kind of diet style that China and SEA would choose, it would give a big influence on global nitrogen load. Therefore, maintaining balance between economic and population growth and environmental load has become critical in achieving a sustainable society. Political strategies to maintain regular balanced diets have considerable potential to reduce contributions to the global nitrogen load. In addition, a proper nitrogen cycling system based on traditional Asian methodologies, especially in the countryside, such as recycling human excrement as an alternative to chemical fertilizers, is considered a “kill two birds with one stone” approach to local nitrogen load management (Liu et al. 2012).

Nitrogen loading problems have shifted from local problems, such as eutrophication of local rivers and lakes, to global environmental problems, such as increases in NO_x greenhouse gases and global warming, because nitrogen is cycled globally by water and atmospheric circulation, as well as by international trade. This means that reducing and mitigating nitrogen load is a global responsibility and cannot be perceived as an independent national responsibility. By strengthening the understanding of the need to optimize strategies and communicating this message to all stakeholders (individual consumers, policymakers, and governments) through effective education and information campaigns should encourage stakeholders to improve environmental awareness and encourage environmentally friendly eating habits globally.

A sample of six developed and developing areas may be too small to generalize patterns of change in human protein consumption. Nevertheless, the results may shed some light on the relationship between social impact factors and human nitrogen consumption as well as the consequent nitrogen load associated with human food consumption. This study provides important information that could be used to develop effective policies to reduce nitrogen load.

CONCLUSIONS

The results indicate that improvement in economic activity was the most significant factor in increasing nitrogen load in all areas throughout the study period, followed by the increase in population growth rates. Decreases in nitrogen load originated primarily from food intensity, but these effects are insufficient to offset the entire increase in nitrogen load. The global nitrogen load is increasing and that ways to reduce it should be investigated both globally and locally. Governments should encourage sustainably managed population, economic and food growth and develop policies that target nitrogen load reduction to facilitate a sustainable global environment.

Apart from food consumption, many other areas contribute to the nitrogen load, e.g., crop production, domestic animal feeding, industrial sectors, and domestic nonfecal wastewater. For a complete picture of the nitrogen load these areas require additional investigation.

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