



Impact of Dietary and Self-sufficiency Changes on Nitrogen Load in the Kasumigaura Watershed

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Received 30 December 2024 Accepted 21 April 2025 (*Corresponding Author)

Abstract Recently, dietary change has been increasingly recognized as a viable strategy to reduce nitrogen pollution. This is because raising animal-based proteins results in significantly higher nitrogen loads compared to raising (cultivating) their plant-based alternatives. In Japan, there has been a rise in animal-based food consumption in recent decades, which could have detrimental effects on water quality. However, dietary changes are rarely considered in watershed environmental conservation. Given Japan's low food self-sufficiency of 38%, shifting diets could improve both domestic and international water quality. Therefore, the aim of this study was to evaluate whether dietary changes among the Japanese population could result in nitrogen load reduction and water quality improvement in the Kasumigaura watershed. Firstly, nitrogen load from each point source and non-point source was quantified by examining various nitrogen flows, using land-use data to capture the contributions from different sources. This analysis also incorporated food production-related anthropogenic nitrogen from crops and livestock. The estimated nitrogen load in 2020 was around 4,403 tons/year, and it was a reasonable value compared with previous research. Then, the impact of dietary and self-sufficiency changes on the nitrogen load was estimated. The results suggest that the reduction of animal proteins has significantly lowered the nitrogen load in the watershed, therefore offering a promising approach to improving water quality.

Keywords nitrogen pollution, water quality, dietary change, eutrophication, Kasumigaura watershed

INTRODUCTION

Nitrogen pollution has detrimental effects on water quality. When excess nitrogen enters bodies of water, it leads to excessive algae bloom, resulting in degraded water quality and loss of aquatic biodiversity. Current food production practices were recently recognized as the largest contributors to water's nitrogen pollution, particularly related to the use of synthetic fertilizers and animals' release of fecal waste (Shindo et al., 2009). Despite nitrogen's negative effects on the environment, its use in agriculture remains essential for feeding the global population, as it supports higher crop yields. While sustainable agricultural practices, such as precision fertilization or indoor farming, offer promising solutions, their implementation can be costly or difficult to implement. Therefore, one of the recently proposed solutions to nitrogen pollution has been a change in one's dietary habits. This is related to the fact that raising/cultivating certain food groups results in higher nitrogen release into the environment, such as animal-based proteins, compared to plant-based proteins. This results from feed requirements and fecal waste production (Leach et al., 2012). Such impact is measured through a unit called a nitrogen footprint (NF). This measure shows the dietary-related yearly nitrogen emissions per capita. Food production-associated nitrogen emissions are calculated through the multiplication of an individual's yearly protein intake by a virtual nitrogen factor (VNF). This factor varies largely according to each food group. The higher the VNF value, the greater the

emissions associated with the food production of that specific food group. With a shift of dietary intake to less nitrogen-intensive food, it can possibly reduce nitrogen load, which could help eutrophicated areas that are found across the globe. Xian et al. (2021) demonstrated that an increase in livestock product barriers significantly contributes to water environment degradation in China. In the case of Japan, multiple studies have explored the link between eating habits and nitrogen pollution (Oita et al., 2017; Oita et al., 2020; Shibata et al., 2014; Shindo et al., 2009). Shindo et al. (2009) conducted an initial study to identify that one of the causes of higher nitrogen flows, which is a movement of nitrogen through the environment, was higher consumption of livestock products by the Japanese population. This contributed to Japanese waters quality decrease. Their intake increased dramatically in the last decades, with daily animal-based protein intake rising from 30% of overall daily protein intake to 53% [19.5g/day in 1961 to 37.3g/day in 2011; (FAO, 2015)]. Subsequently, Oita et al. (2020) explored the impact of this Japanese dietary switch in more detail. The authors found that between 1961 and 2013, the NF of Japan increased by nearly twofold, due to increased preference for livestock diets. A study by Oita et al. (2017) highlights the importance of dietary changes in lowering nitrogen emissions. This study compared NF of the current Japanese diet with NF of various dietary scenarios. The authors analyzed the average Japanese citizens' diet using data from Japan's food balance sheet, representative of the whole of Japan (MAFF, 2020a). The results showed that most NF-reducing dietary patterns were those that replaced livestock protein with legumes, fish, and seafood. It reduced nitrogen emissions by 45% while maintaining the same level of protein intake as the current diet. Understanding dietary impacts requires considering both national and localized scales. However, due to food production and trade data being available at a country level, studies have focused on the national scale. But, it is also important to consider the impacts of dietary changes on a smaller scale, such as at the watershed level, as nitrogen pollution tends to be a localized problem. Despite this, dietary changes are not researched or considered in watershed environmental conservation strategies. This study is designed to point out the importance of considering dietary impact on this scale. For example, the Kasumigaura watershed in Japan experiences algae blooms caused by nitrogen pollution. The lakes of the watershed are only 4 meters deep, which makes them susceptible to eutrophication caused by various sources. Despite improvement from the past due to control measures of point and non-point sources, the nitrogen in the watershed still remains above environmental standards. This was mostly attributed to non-point agricultural influence, such as fertilizer application or inefficient manure disposal management.

OBJECTIVE

The aim of this study was to evaluate whether dietary changes among the consumers of food products from the Kasumigaura watershed could result in nitrogen load reduction and water quality improvement in the Kasumigaura watershed. The research seeks to answer the following questions:

- (1) What is the current nitrogen load of the watershed in 2020?
- (2) What is the impact of dietary change on the nitrogen load?

METHODOLOGY

Study Area

The Kasumigaura watershed was chosen as the target area. It covers a third of Ibaraki Prefecture with an area of approximately 2,157 km². The average annual temperature of the area is 14 degrees Celsius, and rainfall is approximately 1300 mm annually (Matsushita et al., 2006). Current land-use patterns of the watershed are paddy field (24%), upland crop (21%), forest (20%), urban area (17%), water (12%), golf course and other (6%), through land-use analysis (Fig.1). Land-use analysis used data by Ministry of Land, Infrastructure, Transport and Tourism (2024) from 2016, assuming that the land-use area has not significantly changed compared with the current state. With agricultural land being the dominant landscape, the watershed is one of the largest food producers in the country, largely supplying its citizens and other prefectures. In addition, due to this proximity to Tokyo, it experienced

a severe population decline and industry establishments since the 1960s, with population increasing from approximately 700,000 citizens in the 1960s to almost 1,000,000 residents in the early 2000s (Statistics Bureau of Japan, 2020). However, the population movement has stabilized, and now the population decreased to 937,300 in 2020 (Ibaraki Government, 2022).

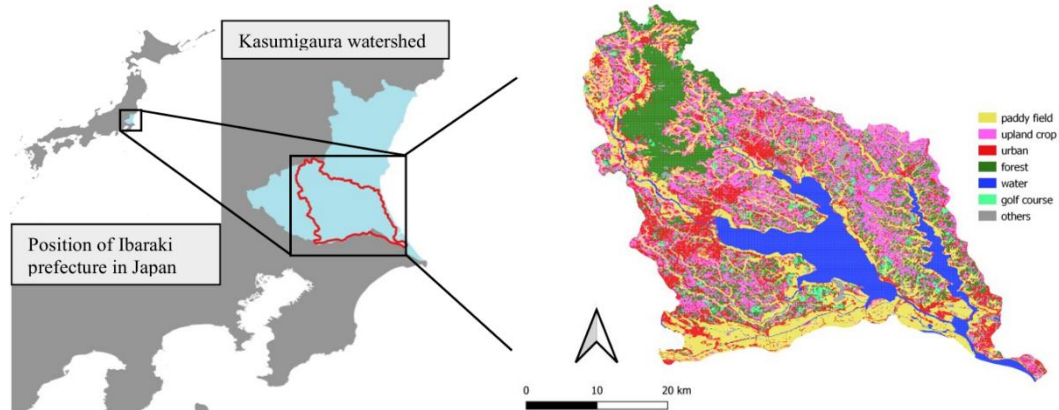


Fig. 1 Location of Kasumigaura watershed and its land-use (MLIT, 2024)

Current Nitrogen Load Quantification

This study focused on the year 2020 because it is the most recent year for which comprehensive nitrogen loading unit data were available. Comparable datasets for previous years were either unavailable or incomplete, making 2020 the most suitable reference point for analysis. Various nitrogen flows were analyzed to understand the extent of food production impact. In the case of point sources (domestic wastewater, industry and factory, and general workplace), their exact value was taken from an official report by the Ibaraki Government (2022). For non-point sources such as urban areas, forests, water, and others, their value was calculated based on their nitrogen loading unit/ha provided by the Ibaraki Government (2022), then multiplied by their area defined by land-use analysis. The method of Makoto et al. (2005) was used to calculate the nitrogen load of upland crops and paddy fields. Basic data for these calculations, such as crop type and area, were obtained from MAFF (2020a). The nitrogen loading unit for upland crops was averaged from top crops in Ibaraki Prefecture and applied to the watershed's upland crop area determined by land-use analysis. For paddy fields, the entire area was directly identified through land-use analysis. Livestock numbers of the watershed were estimated by dividing the total livestock population of Ibaraki Prefecture based on the watershed's proportion of Ibaraki's total area, and this value was multiplied by their emission unit (Ibaraki Government, 2022; MAFF, 2020a).

Impact of Dietary Changes on Current Nitrogen Load

It is important to establish the self-sufficiency of the watershed's food products, to identify the extent of the impact of its consumers' dietary changes. It is assumed that all the watershed's food production consumers have an average Japanese citizen's dietary intake, due to the prefectural data limitation. The food groups were created based on their similar nitrogen load impacts (Shibata et al., 2014). Self-sufficiency estimation was divided into 3 groups: livestock, livestock feed crops, and crops for human consumption (crops). Figure 2 further explains the process for each group's calculation. In case of livestock, total protein supplied by the watershed was based on livestock numbers and their edible weight (MAFF, 2020a). Edible weight was calculated according to each livestock product (MAFF 2020a, 2020b; 2020c). In case of crops, total protein supplied by the watershed was based on their edible weight through the yield of each crop type (MAFF 2020a). In contrast to livestock and crops intended for human consumption, the self-sufficiency of livestock feed was estimated using dry matter (DM) as a measure. The amount of DM feed required to produce one kilogram of

animal products varies by livestock type and was calculated using feed conversion ratios (MAFF, 2020b; 2020c). To assess the impact of eating habits on food production-related load, 2 alternative scenarios were analyzed. Analyses only focus on the nitrogen load to the watershed, not all virtual nitrogen, such as in similar studies (Oita, 2017; Oita, 2020). The purpose is to measure yearly water quality impact more directly. Moreover, the usual calculation considers more processes, such as crop processing or household waste. However, this study considers only synthetic fertilizer use and manure, as they are the largest contributors.

Scenario 1: Livestock protein is fully replaced by legume protein grown within the watershed. This scenario aims to analyze the most nitrogen-reducing eating pattern (Shindo, 2014; Oita, 2017). Scenario 2: The watershed is fully self-sufficient in producing animal feed, with no change in food production or diet. This scenario seeks to demonstrate that although animal feed production is not a direct dietary change, it is linked to dietary choices, as it is driven by demand for animal products.

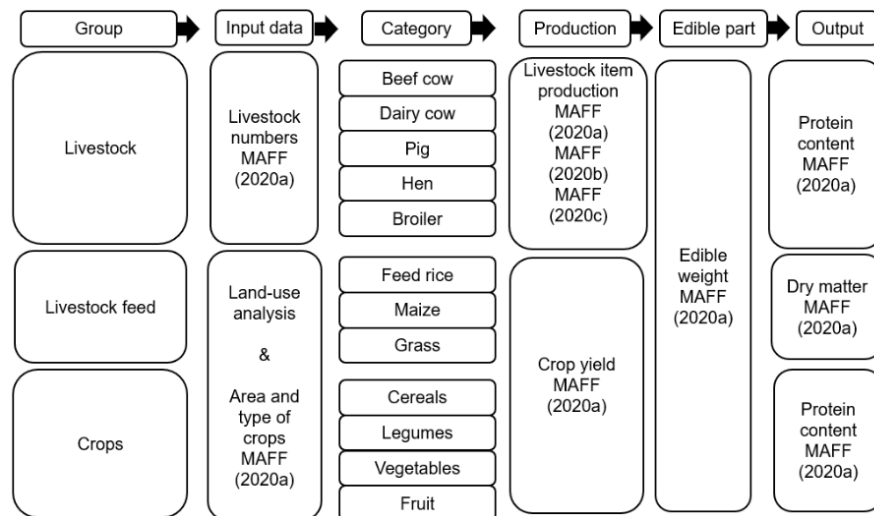


Fig. 2 Methodology of self-sufficiency calculation flowchart

RESULTS AND DISCUSSION

Current Nitrogen Load Quantification

Estimation of nitrogen load (Fig.3) correlated with previous research, 4,343.5 tons/year reported by the Ibaraki Government (2022) in 2020. The discrepancies in the results could be due to the omission of mineralization or biological fixation. Results show that food production had the largest impact on the load (total 1,668 tons/year).

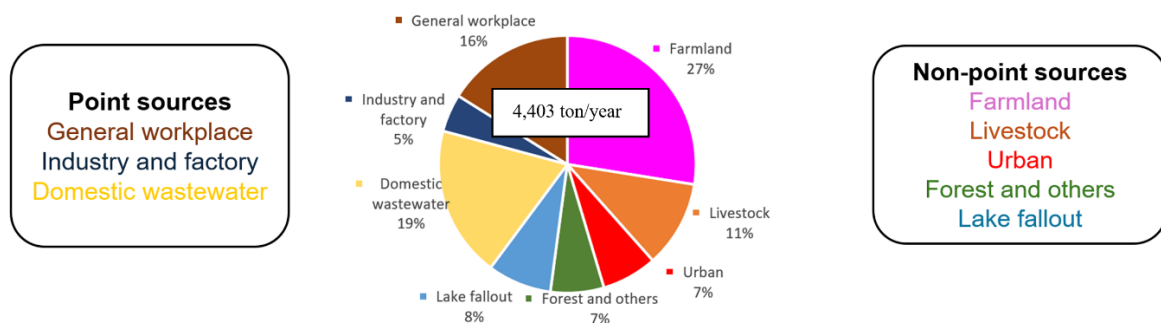


Fig. 3 Estimated nitrogen load per year 2020

While internal sources like sediment resuspension also release nitrogen, our findings suggest that current agricultural inputs have a greater impact (Havens et al., 2001). This underscores the importance of targeting food production in policy-making. Farmland consisted of 514.4 tons/year from paddy fields (12%) and 671.1 tons/year from upland crops (15%). An additional 482.2 tons/year was attributed to livestock (11%). Usually, it is assumed that manure is applied onto farmland as fertilizer. However, its distribution rate is low due to barriers such as the labor force, making it still a large nitrogen load source (Ibaraki Government, 2022). Fish and seafood were not considered as their loading is low in the watershed (Ibaraki Government, 2022).

Impact of Dietary Changes on the Current Nitrogen Load

Table 1 shows the protein supply and self-sufficiency of various food groups for the watershed's population of 973,300 citizens. The study only focuses on the nitrogen impact of the population that consumes food products from the watershed. It is vital to distinguish between the self-sufficiency production of various food groups, as these can vary (MAFF, 2021). Protein supply in the watershed is self-sufficient in cereals, vegetables, fruits, beef, and eggs, as they can supply all the watershed's population (Table 1). Their additional supply is possible to export to other parts of Japan or abroad. Despite intensive livestock production, the watershed cannot supply its citizens with a sufficient amount of animal products apart from beef and eggs, suggesting that other livestock products are imported from other prefectures or abroad, correlating with other studies (Oita et al., 2020; Shibata et al., 2014). This dependency on imports for animal products may increase in the future, particularly with a growing preference for animal-based diets, which could drive up livestock production and further exacerbate this external reliance. This could be potentially beneficial to watersheds, but not favorable to their food security. On the other hand, the domestic supply may also increase, as the government aims to increase food self-sufficiency to 45% by 2030 (MAFF, 2021). This might worsen nitrogen pollution in the watershed. In addition, it was found that the watershed is not self-sufficient in animal feed. Results showed that the watershed produces 63,271 tons/year of feed (DM), which only makes up 14.3% of the required feed (441,327 tons/year of DM) for the watershed's livestock, according to the watershed's feed production (MAFF, 2020a). This indicated that most of the virtual nitrogen footprint related to livestock production is generated externally, likely in another country, as domestic animal feed self-sufficiency is low, around 25% (MAFF, 2021). This could be viewed positively for the watershed's water quality; however, it is still contributing negatively to global nitrogen pollution.

Table 1 Protein supply and self-sufficiency (973, 300 people) among food groups

Food group	Yearly protein supply of the watershed (kg)	Yearly protein intake per citizen (kg)	Number of people supplied by the watershed (persons)	Self-sufficiency (%)
Cereals	16,324,000	6.57	2,484,627	265
Legumes	1,116,000	3.61	309,141	33
Vegetables	10,549,000	1.42	7,428,873	793
Fruits	707,000	0.33	2,142,424	229
Beef meat	1,079,000	1.10	980,910	105
Pork meat	741,000	2.34	316,667	34
Chicken meat	184,000	2.77	66,426	7
Eggs	6,789,000	2.08	3,263,942	348
Milk and its product	1,574,000	2.99	526,421	56

Moreover, analyses of two scenarios revealed that dietary changes impact on the nitrogen load. Figure 4 illustrates the results of scenario analyses compared with food production-related nitrogen load.

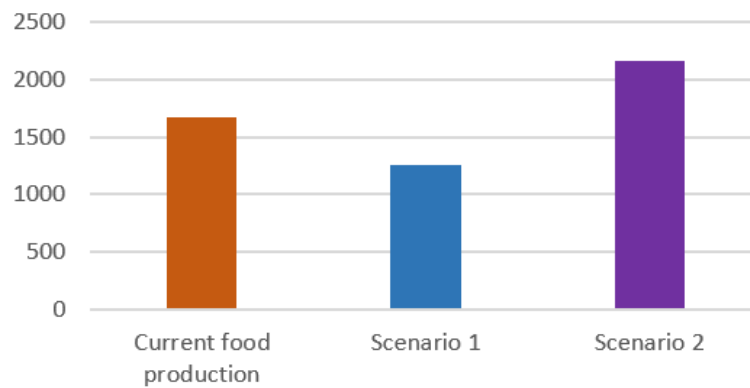


Fig. 4 Scenario analyses of nitrogen load changes (ton/year) from food production

Scenario 1 depicts a decrease of nitrogen load by 416 tons/year, which is a significant impact with a decrease of 46%, despite most of the feed being imported, as most of the livestock-related nitrogen footprint usually comes from feed crop fertilizer. This decrease is due to the elimination of nitrogen load from manure and all the feed crops, which would mean that all the animals would be removed from the watershed. Moreover, it could be argued that the biological fixation of legumes will add additional nitrogen into the soil, which was not considered. However, we based our analysis on the fact that legumes tend to have the smallest nitrogen among the food groups, implying that previous studies also did not consider biological fixation in nitrogen load calculations. Furthermore, scenario 2 analysis revealed an increase in nitrogen load in the case of feed self-sufficiency, correlating with previous research (Alexander et al., 2016). In such a case, nitrogen load rose to 2,160 tons/year, which is more than 492 tons/year compared to the current nitrogen load. However, the distribution of manure into farmland could mitigate this increase by lowering the load associated with livestock by 482,2 tons. Therefore, a scenario with manure distribution should be further researched. Contrasting scenarios, scenario 2 has an increase of nitrogen load of 908 tons/year compared to scenario 1. These results align with previous research from other countries and Japan, which all demonstrated potential water quality improvement with legume as an alternative protein (Poore and Nemecek, 2018; Xian et al., 2021). It is essential to consider other dietary scenarios, as a fully plant-based pattern might not be realistic, as it would mean that all the animals would have to be removed from the watershed. That is why further research should consider a partial dietary shift, such as 30% or 50%. Similarly, future investigations should also focus on partial feed self-sufficiency shift (such as 30% or 50%), as a full shift is not realistic. Moreover, combinations of various scenarios and dietary patterns should be taken into account.

CONCLUSION

This study represents a pilot investigation of the predicted impacts of proposed dietary changes on nitrogen loads on the Kasumigaura watershed scale. The load in total was 4,403 tons/year of nitrogen in the year 2020, with a large amount of 1,668 tons/year caused by food production. Scenario 1 decreased the load by 416 tons/year by replacing livestock products with legumes, while feed self-sufficiency in scenario 2 increased the load by 492 tons/year. The study showed that dietary changes had a significant impact and greatly reduced the nitrogen load. A key finding is that by replacing livestock in the watershed with legumes, nitrogen load can be largely reduced. It advances current knowledge and nitrogen pollution strategies to recognize the importance of plant-based, focused dietary changes. To promote such eating shifts in Japan, policy implementation should focus on alternative protein sources through education, incentives, and accessibility improvements, while addressing cultural and socioeconomic barriers. Combined with practical strategies like simple cooking methods and food movements, such strategies could reduce nitrogen loads and environmental impacts. In this study, an overall nitrogen footprint could not be included due to data

limitations, such as a lack of food manufacturing-related data in the watershed. Therefore, further research is needed to fully understand the role of fecal waste management, biological fixation, mineralization, various food groups' self-sufficiencies, and other kinds of dietary changes.

ACKNOWLEDGEMENTS

This work was supported by MEXT/JSPS Fund for the Promotion of Joint International Research (KAKENHI), Grant Number 23K27017, and the MEXT Scholarship.

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