Trends and Analyses of Farmland Nitrogen Load and Use Efficiency

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ABSTRACT

This study examined the nitrogen-use efficiency and nitrogen surplus of a recently developed region with a well documented history. Consequently, we were able to produce a N-flow model for farmland. The farmland was balanced as follows: N input to farmland = chemical fertilizer N + N through deposition and irrigation in farmland + biological N, fixation in farmland + N in human manure + N in livestock manure. The farmland surplus = N input to farmland – N production in farmland – de-nitrification in farmland – NH3 volatilization from manure – N2O emissions from farmland/ humans/ livestock. We analyzed the regional N flow changes. Results suggest that 1959 was a turning point, with neither a N input change, nor a N surplus. The increased efficiency in N use was the major cause of that change. The N load factor is useful as an indicator for characterizing the change, the maximum N load factor was 4.2 and the minimum was 0.9; 4.2 was also considered to be the turning point of change in N.

Key words: environmental nitrogen load, nitrogen-use efficiency, nitrogen load factor.

Introduction

Continually, rapidly growing populations have increased their quantitative and qualitative demands for food products. To meet that demand, fertilizers with high content of nitrogen (N) have come to be used on a large-scale for agricultural production. Typically, the N application exceeds the crops’ N needs. Agricultural land cannot retain such high excess levels of N and consequently discharges N, which in turn burdens the environment (Bock, 1984; Nelson, 1985; Roy et al., 2002). Consequently, such excess N input begets N surpluses, engendering either accumulation or leaching (Zebarth et al., 1998; Hatano et al., 2002). For those reasons, N input, N crop production and N surplus are good indicators of secular changes in N flows in a region. To assess the impact of human activity on N flows changes, we chose a recently developed region with a well documented history. This paper presents a review of the literature related to characterizing N-flow changes in the region, with emphasis on the region’s N use efficiency and N surplus.

Materials and methods

Study site:

Mikasa is located in central Hokkaido, 52 km east of Sapporo (N43°14’, E141°50’). Based on the History of Mikasa City (Mikasa City Office, 1971) the region was first developed with the discovery of coal in 1885. The first data documented 22 ha of farmland managed by six farms in 1885. Its total area is now 302.6 km², and farmland is 1211 ha, of which paddy rice, onion, wheat, vegetable and grass cultivation respectively accounts 590, 212, 145, 63, and 210 ha. In all, 294 dairy cows and 15700 chickens were raised in this area in 2002.

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**N Flow Mode for Farmland:**

Figure 1 shows the farmland N flow model used for this study. The input items of the system were biological N fixation and atmospheric deposition in farmland, chemical fertilizer, and manure. The system’s outputs were the crop production, ammonia volatilization, and de-nitrification in farmland. Farmland surplus N was defined as the difference between inputs and outputs.

![Diagram of N flow model for estimating N budget in farmland.](image)

**Fig. 1:** N flow model for estimating N budget in farmland.

**Calculation Methods:**

Data describing the human population, livestock population, agricultural area, crop production, and sewerage diffusion ratio in Mikasa during 1912–2002 were collected from public statistical information (Mikasa City Office, 1934–2002; Mikasa City Office, 1971, 1994). These amounts were calculated by multiplying food, feed and excrement units by the number of livestock.

The farmland balance was determined as follows:

\[ \text{Farmland surplus } N = \text{Farmland inputs} - \text{Farmland production} - \text{De-nitrification in farmland} - \text{NH}_3 \text{ volatilization from manure} - \text{N}_2 \text{O emission from farmland} / \text{human/ livestock}. \]

Also,

\[ \text{Farmland surplus } N = \text{N input to farmland} - \text{N production in farmland-de-nitrification in farmland} - \text{NH}_3 \text{ volatilization from manure} - \text{N}_2 \text{O emission from farmland}. \]

For the N amounts of livestock and human excrement, the excrement was composted to create manure. The N\textsubscript{2}O emission under this management was 0.02 kg N\textsubscript{2}O-N kg \textsuperscript{-1} excreted in the International Panel on Climate Change, 1996 (IPCC, 1996). The ammonia loss was assumed as 36% of the manure ammonia, according to Brentrup et al. (2000). Data for the human population, livestock population, agricultural area, crop production, and sewerage diffusion ratio in the Mikasa City during 1912–2002 were collected from public statistical information (Mikasa City Office, 1934–2002; Mikasa City Office, 1971, 1994).

The applied amount of fertilizer was calculated from the total chemical fertilizer use in Hokkaido (Fertilizer Survey Department for Industry Enforcement, Hokkaido, 1910–1918, 1920–1923, 1927, 1929–1931, 1935–1940; Ministry of Public Management, Statistics Bureau, 1950, 1968; Ministry of Agriculture, Forestry and Fisheries (MAFF) 1962–1978; Hokkaido Department for Agro-policy, 1986–1997) divided by the total cropland area (MAFF, 1973, 1984–2002). In cases for which no data were available for the applied amount of fertilizer, the recommended amount by the government (Hokkaido Agricultural Experimental Station, 1943; Fertilizer Distribution Office Sapporo, 1950; Hokkaido Department for Agro-policy, 2002) were used.

All manure that was not treated at sewage treatment plants or otherwise disposed of was considered to be applied to farmland. For human manure, disposal N signifies the processed N in sewage treatment plants. The present application rates of dairy cattle, beef cattle, and pigs were, respectively, 93, 94, and 74% (Hokkaido Statistics and Information Office, MAFF, 1993); that of poultry was 0%, according to questionnaires administered to selected poultry farms (Kaku et al., 1993). Because horses and sheep are mainly raised by grazing, all excrement was presumed to be applied to cropland, including that directly deposited on grassland (Nagumo and Hatano, 2000). Data describing the application rate of manure are almost unavailable: the only exception is 1949, when all manure was applied to cropland and grassland (Hokkaido, 1950). Therefore, we created a regression analysis of data of 1950–2002, assuming an interpolated application rate of manure changing linearly during those years.
The levels of biological N fixation were determined as 30 kg ha\(^{-1}\) y\(^{-1}\) for paddy fields, 5 kg ha\(^{-1}\) y\(^{-1}\) for onion fields and 20 kg N ha\(^{-1}\) y\(^{-1}\) for pastures (Matsumoto, 1997).

Atmospheric N deposition was calculated from the amount of precipitation in 1912–2002 (History of New Mikasa City References, 1994; Statistics Reports in Mikasa City, 1989–2001), with a concentration of 1.1 mg N L\(^{-1}\) (Noguchi et al., 1988). The N input through irrigation water for paddy rice was calculated as 7.5 kg N ha\(^{-1}\) (Sekiya, 1987). For estimating crop N, the amount of crop products was multiplied by the N content of each crop (Matsumoto, 1997). The e-nitrification loss was estimated as 18% of the applied chemical fertilizer (Pain et al., 1989); the direct and indirect N\(_2\)O emissions constitute 2.1% of the total N input to farmland (IPCC, 1996). The NH\(_3\) volatilization from chemical fertilizers was presumed to be 8% (Bouwman et al., 1997).

**Results and discussion**

Figure 2 shows estimations of the total N input output (production) and N surplus in farmland.

**N Input to farmland:**

![Fig. 2: Historical change on the N budget in farmland of Mikasa City.](image)

Compared to the unit area, the highest amount was 301 kg N ha\(^{-1}\) y\(^{-1}\) in 1959. Because of the rapid decline in human manure application, the N input fell from 301 kg N ha\(^{-1}\) y\(^{-1}\) by the end of the 1950s to 126 kg N ha\(^{-1}\) y\(^{-1}\) in 1975. In the 1990s, it increased again with higher application rate of chemical fertilizer, and remained at 150 kg N ha\(^{-1}\) y\(^{-1}\).

**N Production of Farmland:**

The total N production of farmland in this area was 51 kg N ha\(^{-1}\) y\(^{-1}\) in 1912; it decreased to the smallest value of 28 kg N ha\(^{-1}\) y\(^{-1}\) in 1945. After 1945, it increased steadily, and showed the highest value, 94 kg N ha\(^{-1}\) y\(^{-1}\), in 1989. The values subsequently decreased, reaching 68 kg N ha\(^{-1}\) y\(^{-1}\) in 2002.

**N Surplus of Farmland:**

The farmland surplus N had two remarkable peaks, the first was observed in the middle of 1950, with 140–173 kg N ha\(^{-1}\) y\(^{-1}\); the second one appeared in 1987, with 82 kg N ha\(^{-1}\) y\(^{-1}\). Between these two peaks, the value dropped to 32 kg N ha\(^{-1}\) y\(^{-1}\). It was 49 kg N ha\(^{-1}\) y\(^{-1}\) in 2002, and became greater than 50 kg N ha\(^{-1}\) during 1935–1971 and during 1981–1997.

**Discussion:**

Regarding the N input per unit area, the highest amount was 301 kg N ha\(^{-1}\) y\(^{-1}\) in 1959. Because of the rapid decline in human manure application, the N input dropped from 301 kg N ha\(^{-1}\) y\(^{-1}\) by the end of the 1950s to 126 kg N ha\(^{-1}\) y\(^{-1}\) in 1975. In the 1990s, it increased again with a higher application rate of chemical fertilizer. Figure 2 shows that 1959 was the turning point: before 1959, N input continually increased; after 1959, N input decreased In terms of N input at the farmland, the period of 1912–2002 is divisible into two periods. The first, during 1912–1959, was the N input increase period; the N input decrease period was that during 1960–2002.
The total N production of farmland in this area was 51 kg N ha⁻¹ y⁻¹ in 1912. It decreased to its lowest value of 28 kg N ha⁻¹ y⁻¹ in 1945. After 1945, it increased steadily, showing its highest value of 94 kg N ha⁻¹ y⁻¹ in 1989. The values decreased thereafter, reaching 68 kg N ha⁻¹ y⁻¹ in 2002.

N use efficiency = N production / N input was used to evaluate the N production efficiency of the farmland. Figure 3a shows that N production was not proportional to the amount of N input to farmland. During 1912–1959, N input continued to increase ($R^2 = 0.8978$ and $p < 0.001$), but the N-use efficiency continually decreased ($R^2 = 0.9221$ and $p < 0.001$). Irrespective of the continued increase in N input, improper input of manure produced greater NH₃ volatilization and NO₃-N leaching (Chambers et al., 2000; Mattila and Jokitalo, 2003) resulting in low production (Sikora and Enkiri, 2001; Zebarth et al., 1996). The lack of high-yielding cultivars and mechanized cultivation might have also lowered production (Smethurst, 1986). On the other hand, during 1960–2002, a gradual increase was apparent in N production, even as N input decreased. That increase was attributable to increased N-use efficiency (Fig. 3b) ($R^2 = 0.8082$ and $p < 0.001$). Therefore, the data show that N production is divisible into two periods: 1912–1959 was the N input dependence period; and N-use efficiency dependence period was 1960–2002.

The farmland surplus N had two remarkable peaks, the first was observed in the mid-1950s, with 140–173 kg N ha⁻¹ y⁻¹; the second one appeared at 1987, with 82 kg N ha⁻¹ y⁻¹. Between these two peaks, the value dropped down to 32 kg N ha⁻¹ y⁻¹. The value was 49 kg N ha⁻¹ y⁻¹ in 2002; it was greater than 50 kg N ha⁻¹ during 1935–1971 and during 1981–1997.

The change in N cycling due the human activity imparted a huge impact on the regional environment. The largest contribution to the N cycling came from agriculture (Bleken and Bakken, 1997). Agriculture is the main component of N production and N surplus was the indices of environmental risk (Mishima et al., 1999). Consequently, we can try to define the “N load factor” = N surplus / N production as an indicator to unify the analyses and evaluate N production and its associated environmental impact.

Figure 4 shows that 1959 was also a turning point, when higher yielding cultivars moved the data from dependence on N input to dependence on N use efficiency. The amount of surplus N is related closely to the amount of N input to farmland. Figure 4 shows the change in the N load factor. The N load factor was greatest in 1959. It had been thought that the N load factor had continued to increase with N input. The N load factor had decreased after 1959. It was considered that the change in the amount of N surplus per kg N ha⁻¹ production, the maximum N load factor of Mikasa was 4.2 in 1959, i.e. 1 kg N ha⁻¹ production had been attributable to a 4.2 kg N ha⁻¹ N surplus.

The N surplus of 50 kg N ha⁻¹ y⁻¹ created a great N loss from the root zone (i.e. loss that was greater than that required to obtain optimal crop production based on agronomic considerations), whereas N surplus values of less than 50 kg N ha⁻¹ y⁻¹ might have resulted in excessive N loss from the root zone only in some cases.

Fig. 3: Historical change between N use efficiency and N input a, 1912 to 1959; 1960 to 2002.

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(Zeharh et al., 1999). After 1998, the N surplus, which was less than 50 kg N ha\(^{-1}\) y\(^{-1}\), implied the N load factor of about 0.91 (Fig. 4); consequently, we can estimate that N production will be less than 55 kg N ha\(^{-1}\) y\(^{-1}\).

**Fig. 4:** Historical change on N load factor in farmland.

**Conclusion:**

We analyzed the N flow changes in this region. Results suggested that 1959 was a turning point: with neither a N input change nor a N surplus change. The reason for that change was improved N-use efficiency. The N load factor is useful as an indicator for characterizing the change: the maximum N load factor was 4.2 and the minimum was 0.9; 4.2 can be considered as the turning point in the N change.

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**References**


