Topsoil N-budget model in orchard farming to evaluate groundwater nitrate contamination

Yureana Wijayanti, Kadarwati Budihardjo, Yasushi Sakamoto, Oki Setyandito

Department of Agriculture, Faculty of Agriculture, Institute of Agriculture Stiper (INSTIPER), Yogyakarta, Indonesia
Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Yamanashi 400-8511, Japan
Department of Civil Engineering, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia 11480

Corresponding Author: ywijayanti@instiperjogja.ac.id

Abstract. A small scale field research was conducted in an orchard farming area in Kofu, Japan, where nitrate contamination was found in groundwater. The purpose of assessing the leaching of nitrate in this study is to understand the transformation and transport process of N-source in topsoil that leads to nitrate contamination of groundwater. In order to calculate N-budget in the soil, the model was utilized to predict the nitrogen leaching. In this research, the N-budget model was modified to evaluate influence of precipitation and application pattern of fertilizer and manure compost. The result shows that at the time before the addition of manure compost and fertilizer, about 75% of fertilizer leach from topsoil. Every month, the average remaining nitrate in soil from fertilizer and manure compost are 22% and 50%, respectively. The accumulation of this monthly manure compost nitrate, which stored in soil, should be carefully monitored. It could become the potential source of nitrate leaching to groundwater in the future.

Keywords. N-Budget Model, Fertilizer, Nitrate Available for Leaching

1. Introduction
Nitrogen accumulation from fertilizer application and increasing of soil organic matter, in agriculture field can cause nitrate leaching to groundwater [1,2]. Other factors that also influence agriculture nitrate are, manure management, crop cultivation practices [3,4], soil texture [2], and precipitation surpluses [5,6], and an escalation of organic fertilizer [7]. It is a common practice in agriculture soil to apply chemical fertilizer and manure compost to enhance the crop production [8]. Composted manure is a very good source of organic matter and also nutrient source for crop production [9,10].

Nitrogen budget is correlated with annual mean nitrate concentration in groundwater. Wick et al., [11] shown the correlation between the gross nitrogen budget and nitrate groundwater (mg/l) in Austria. The nitrogen (N) budget has been recognized as an indicator in agriculture-environment. It indicates the N losses from agricultural areas that is not save for the environment [6]. According to
statistics, Nitrogen budget could predict nitrate contamination occurrence significantly (in 10,000 t) [11]. The concentration of nitrate in groundwater is controlled by prevent the leaching of large amount of nitrate from soil. Once the ground water has been contaminated, it takes a long period of process to recover. Also, it required a very expensive and sophisticated technology. Sometimes the recovery result still cannot be as it was before the contamination [12]. Studies were conducted in order to determine nitrate leaching to groundwater by integrated some models of transformation in soil [13]. Subsoil and vadose zone factors are important in determining the likelihood of NO$_3$-N being transported to groundwater [14]. The method using soil column experiment has been conducted in order to assess N leaching in soil [15]. Other method is using a model of nitrogen transformation and transport with field data calibration [15]. Simulation of concentration of nitrate, temperature, water content, and chloride in soil were performed. Garnier [16] concluded that two factors had great influence on leaching of nitrate, they are: 1) initial (nitrate concentration) and boundary conditions (potential evapotranspiration) in the soil first layer ; 2) hydraulic conductivity. However, this research not yet studied nitrogen that stored in the soil and does not leach. This can be the source of nitrogen leaching in the future. Hence, it should be predicted and incorporated in the model. Therefore, the first objective of this research is to evaluate N-budget in nitrogen transformation and transport model. This model was applied to simulate nitrogen available for leaching (NAL) which represent stored nitrogen in soil, and simulate nitrogen leaching (NL) to groundwater. The result was compared to field data of nitrate in soil solution.

The main method for analyzing and predicting the potential of NO$_3$ leaching is a field-or plot-scale Mass Balance analysis combined with a simple uniform steady-state flow model. The equation of N mass budget to calculate leaching of annual NO$_3$-N is [17]:

$$N_{leaching} = N_{input} - N_{uptake} - N_{transformation} - \Delta N$$

Where $N_{input}$ is the total N input to the root zone, $N_{uptake}$ is the N used for plant uptake, $N_{transformation}$ is the N loss through various N transformations (immobilization, denitrification etc.), and $\Delta N$ is the change in the total amount of N stored in the soil.

In this study, the algorithm is utilized to calculate N budget in the soil. This algorithm is applied in the model to predict the groundwater nitrate concentration [18]. Almasri et al. [18] developed the integrated three-zone (on ground-soil-groundwater) method to model the integrated processes that regulate nitrate appearances in groundwater. The strength points of this model are: 1) The calculation and evaluation of each zone can be done separately; 2) Calculation performed in monthly-bases. However, in this study we could not compare simulated nitrate leaching concentration in the soil with field data (in a form of soil water or soil solution) because this model was predicting groundwater nitrate concentration. Simulated soil water can only be assessed after calculation using fate and transport in groundwater-model. Therefore, this study will modify the model so that it could assess simulated N budget in the soil. After that, we compared nitrate leaching from this N budget model with field data from soil water in study area. The calculation has applied the equations used in the soil dynamic-zone within the model framework [18]. The soil dynamics of N process in the model influenced by nitrogen input to soil, transformation of nitrogen in soil, and soil water that leached to groundwater. The output of this model is concentration of nitrate leaching to groundwater and nitrate stored in soil.

Groundwater in the sampling site, a small orchard farming area of Kofu, Yamanashi, Japan, has been identified as contaminated by nitrate from chemical fertilizer, soil organic matter and manure and/or septic waste. Existence of nitrate is caused by both mixing process and denitrification, based on the result of both isotope and also ion values [19]. Also, it was found that the main source of nitrate is
different between winter and summer. It elucidates that extreme hot and cold temperature between two seasons affected the microbial processes of nitrification and denitrification [20]. Hence, the study was conducted to assess the seasonal change of nitrate leaching in soil. Although, leaching of nitrate in soil is a complex process, soil N-budget model can be utilized to understand the processes that might occur. For this study, the purpose of assessing the leaching of nitrate is to understand the transformation and transport of N-source in topsoil that leads to N contamination of groundwater.

2. Methodology

a. Study area

Our study area is a small peach and grape agriculture area (14.2 km²) in the eastern of Kofu City, Yamanashi Prefecture, Japan. Average annual temperature is 15° Centigrade. Air temperature in summer and winter is 26.8° (highest) and 2.2° (lowest), respectively [21]. The average annual precipitation is 1160 mm recorded over 75-year period from 1936 - 2010. Rainy period precipitation occurs from June to October. Soil type at this area is silt loam. Fertilizer is applied with manure compost in October when there are no growing activities and with an amount of fertilizer (N-P-K) of 60 up to 72 kg N/ha/year [22].

b. Data and Investigation

Sampling of topsoil was performed in seven locations. These sampling locations are at the higher land and lower land of study area, with and elevation of 390 m (GW9) and 280-300 m elevation (GW13, GW11, GW10, GW5, GW4, GW2), respectively (see Figure 1). These samples were taken monthly, start in October 2011 and end in December 2012.

![Figure 1](image1.png)  
**Figure 1** Sampling locations of the study area

Soil samples were taken at 10 and 20 cm depth. The mixture of both soils was placed in a container and transfer to the laboratory for further analysis.

The solution of topsoil was created using the soil saturation extracts method [23]. The first step was air dry of soil samples by let it dry in open space. After that, the dry soil was sieved using a 2-mm opening strainer. Each of fertilizer and compost manure were sieved using a 0.5-mm opening sieve. Then, a soil-water mixture was generated. It was started by adding 10 grams of soil with 40 ml of Milli-Q water and shaking it for 1 hour. Afterwards, this mixture was rotated for 10 minutes at 3000
rotate per minutes (rpm) by using a centrifuge machine. Filtration process by using a membrane filter (0.45 μm, Advantec) of this supernatant was performed. Ions value in the supernatant is corresponded to the condition when precipitation water is in contact with soil, by performing this method. However, there is a downside of this method, NH₄⁺, NO₂⁻ and NO₃⁻ (weak anions) could only be dissolved in small number of concentration thus it will be difficult to be detect its presence. In order to overcome this problem, this study utilized ion chromatograph (DIONEX ICS-1100). This device could quantify NH₄⁺, NO₂⁻ and NO₃⁻, and other substance with concentration within the low range from 0.03 to 0.04 mg/litre. This procedure applied also for composted manure and fertilizer.

c. Modeling N-budget in topsoil

The annual N balance or N budget was obtained to estimate the nitrate available for leaching (NAL). The topsoil nitrogen budget was calculated using modification of Soil Dynamic sub framework for N-budget model framework developed by Almasri et al [18]. N-budget framework is shown in Figure 3. The parameter values for the calculations are listed in Table 1, the nitrogen input are from chemical fertilizer and manure. The output is the principal reactions and transport that take place upon N dynamics in topsoil, include nitrification, immobilization, volatilization, denitrification, plant intake, and percolate from the root zone.

Figure 3 The framework for N-budget calculation

\[
NAL = NAL_0 + NO_3^{So} + NO_3^{Si} \quad (1)
\]

Where:

NAL₀ : nitrate available for leaching at the beginning of each month
NO₃⁰ : summations of all the monthly sources of nitrate; include nitrate that enters the soil from the ground surface (fertilizer and manure); Superscript So is origin
NO₃⁴ : summations of all the month sinks of nitrate; include nitrate losses in volatilization, denitrification and plant uptake; Superscript Si is infiltrate

The monthly flux of nitrate leaching (kg/month), NL, is computed using exponential relationship as presented by Shaffer et al. [24] and Pierce et al. [25] in equation (2) and (3), by using the parameters in Table 1.
Where:

\[ K \]: leaching coefficient; 1.2 inferred from Pierce et al., [24]

\[ \text{WAL} \]: the water available for leaching (m³) from rainfall

\[ \omega \]: the volume of voids of the soil (m³)

\[ w = 1 - \frac{\text{BD}}{\text{PD}} = 1 - \frac{\text{BD}}{2.6 \times \text{BD}} = 1 - \frac{1}{2.6} \approx 0.731 \]

(3)

Where:

\[ \text{BD} \]: Bulk Density of soil (kg/m³) is the weight per unit volume of the solid portion of soil

\[ \text{PD} \]: Particle Density of soil (kg/m³) is the oven dry weight of a unit volume of soil inclusive of pore spaces.

| Parameter                              | Value | Units   | Method/reference                  |
|----------------------------------------|-------|---------|-----------------------------------|
| \( \text{NO}_3^- \text{So} \): N-input from: Fertilizer Manure | 70    | Kg N/ha | Field data                        |
| \( \text{NO}_3^- \text{Si} \): N-loss from: Plant uptake Volatilization, denitrification | 0.01  | kg N/ha | Literature/Do T, N., [27]         |
|                                           | 20% per year to amount of applied chemical fertilizer | kg N/ha | Literature/Do T, N., [27]         |
|                                           | 2% per year to amount of applied manure compost | kg N/ha | Literature/Do T, N., [27]         |
| Leaching coefficient (K)                    | 1.2   |         | Literature/Pierce et al., [26]    |
| Water available for leaching (WAL)          | Monthly rainfall height, from October 2011 to December 2012 | mm | Literature/Japan Meteorological Agency (JMA) data of Kofu Sta. No.47638 (Lat 35°40.0’N, Long 138°33.2’E) |
| Bulk Density (BD)                            | 0.001 | kg/m³   | Field data                        |
| Particle Density (PD)                       | 2.6 x BD = 0.0026 | kg/m³  | Field data                        |

3. Results and Discussion

a. Nitrate Leaching Evaluation

The N-budget model result of nitrate available for leaching (NAL) and nitrate leaching (NL) calculation using equation (1) and (2), respectively, is shown in Figure 4. N-budget model shows that at the time before the addition of manure compost and fertilizer (September 2012), about 75% of fertilizer and manure compost leach from topsoil. This result is similar to field study by Mengis et al [29] that about 80% of the applied fertilizer left the soils with the leachate. The nitrogen load in the
soil is decreasing from October 2011 to September 2012. However the nitrate that leach to groundwater vary from each month (Fig 5) due to the influence of precipitation. Therefore, in order to evaluate the influence of precipitation to the nitrate concentration in groundwater, the precipitation graph was superimposed with the calculation result of N leach to groundwater (Fig 4). It shows that the nitrate leach to groundwater had the similar trend to precipitation occurrence. This is in agreement with the research reported by Paz and Ramos [27] using the groundwater loading effects of agricultural management systems (GLEAMS) model coupled to a GIS.

However, in October, November and December 2012, nitrate leach is slightly increasing while precipitation depth is decreasing. This high concentration of nitrogen leach is probably due high precipitation in September followed by fertilizer application in October. Hence, in October and November 2012, small quantity of soil water (remaining from September rainfall) is in contact with high concentration of nitrogen input has resulted denser concentration leached.

![Figure 4](image)

**Figure 4.** Nitrate leaching to ground water (NL) in kg N/ha versus the precipitation depth in mm

b. Nitrate Available for Leaching Evaluation

In order to analyze the nitrogen input that remains in soil, NAL and NL is evaluated. The difference between NAL and NL is considered as nitrogen remaining in topsoil after leaching. The average remaining nitrogen from fertilizer and manure compost are 22% and 50%, respectively. Figure 5 shows the increasing of nitrogen load remains in soil after its application in October 2011 (shown by black arrow) and the decreasing of nitrogen load remains in soil after 3 months. The average monthly nitrogen decreasing for fertilizer and manure compost are 3.6 kgN/ha and 0.8 kgN/ha, respectively. This difference might due to slow decomposition rate of manure compost compare to chemical fertilizer (Fig 6).

![Figure 5](image)

**Figure 5.** N-budget calculation result of NAL and NL
Figure 6. Nitrogen available for leaching (NAL) trend line in topsoil, the manure compost and chemical fertilizer were applied in October and Nitrogen load from fertilizer and manure accumulation in topsoil.

Figure 7. Comparison between N-budget model and field data

Figure 7 shows comparison between N-budget from model and field data. Ratio of nitrate to chloride is utilized because there is strong correlation between nitrate and chloride in the previous at study site. As the chloride increases, the nitrate is also increase [19]. Ratio of nitrate leaching (NL) to nitrate available for leaching (NAL) represents fraction of nitrate in soil from N-budget model. N-budget model shows similar trend in between October-December 2011 and that in 2012. Also, the trend between October-December 2012 in model and field observation is similar.

4. Conclusion
N-budget analysis was performed to study how much nitrate concentrations in topsoil and transported or leached to groundwater. The result of nitrate leaching (NL), considered as the nitrate that leaving topsoil, shows that the nitrate leach to groundwater had the similar trend to precipitation occurrence. However, in October, November and December 2012, nitrate leach is slightly increasing while precipitation depth is decreasing. It is due to more concentrated soil water in soil after fertilizer application at the beginning of October.
The simple N-budget model could show only general estimation of potential nitrate leaching to groundwater. However, the monthly budget approach allows the incorporation of seasonal and monthly effects on nitrate leaching that include changes in precipitation, and fertilizer and manure compost application. The gap between model and field observation might due to: 1) nitrogen available for leaching (NAL) in soil which was applied with chemical fertilizer and compost manure behave differently due to chemical process in soil; 2) this simple “hand” calculation of nitrate leaching utilizing the leaching coefficient of 1.2 based on other study conducted by Pierce et al [24], that might have big influence in the calculation outcome. Therefore, in the next phase, the modification of NAL and NL calculation in the model should be performed.

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