Numerical simulation of nitrogen groundwater pollution for proper management of cow manure

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Abstract

About 20 million tons of cow manure is generated in Hokkaido, Japan, each year. Approximately 94% of this manure is reported to be recycled. However, the actual amounts of cow manure generated and of manure applied to pastures as compost or soil improver are not entirely clear, and so the reported rates of cow manure recycling are unlikely to represent the realities of current cow manure management. It is possible that excessive amounts of manure are being applied to pastures, leading to nitrate-nitrogen leaching and groundwater pollution. Therefore, it is necessary to assess the mass balance of nitrogen in the system to determine appropriate management strategies for cow manure. In this study, the nitrogen mass balance was calculated for cow manure during all stages of the process, from its generation to its application as a compost or soil improver. The nitrogen mass balance was determined through site investigations. Assuming a typical model of dairy farming, the actual amount of nitrogen applied in pastures was calculated in terms of nitrogen use efficiency, depending on vegetation type. The potential for groundwater pollution was evaluated by numerical simulations based on the nitrogen mass balance. The results showed that when large amounts of manure are applied to pastures, excess nitrogen will be present in the system, which may be susceptible to leaching and lead to groundwater pollution. Methods for cow manure management are discussed based on the results of the numerical simulations.
Keywords: cow manure, nitrogen mass balance, nitrate, groundwater pollution.

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1 Introduction

Cow manure accounts for about half of the industrial waste generated in Hokkaido, Japan, amounting to nearly 20 million t/year (FY 2007) [1]. If untreated, manure can be a potential source of pollution, as it contains high concentrations of nutrients, including nitrogen, phosphorus and carbon. Alternatively, manure can be treated and used as high-quality fertilizer and/or energy under appropriate management regimes. Plants can efficiently use the nutrients in cow manure in the production of biomass.

Cow manure is typically used as a compost or soil improver, to return nitrogen and carbon to pastures and soils. In 2007, approximately 94% of cow manure in Hokkaido was reported to be recycled (FY 2007) [1]. Although reports of such high rates of cow manure recycling are encouraging, there are concerns that, because of uneven distribution of supply and demand for nutrients, excessive amounts of manure are being applied locally, creating significant risk of groundwater pollution. In general, farmers are applying enormous amounts of manure, rather than composted manure; this suggests that there are problems with the composted, recycled product.

Current data collection methods do not consider the range of original unit of cow manure generation, the ratio of manure to bedding material, or the change in the weight of cow manure during the composting process, nor do they distinguish the amount of cow manure applied to pastures from the amount of cow manure used effectively as compost. The currently available data on recycling of cow manure do not reflect the reality of the situation or lend themselves to the calculation of a nutrient mass balance.

Therefore, the objectives of this study are:

1) To clarify the nitrogen mass balance from cow manure generation to compost application based on site investigations;
2) To evaluate the potential for groundwater pollution based on numerical simulations of nitrogen use efficiency; and
3) To propose cow manure management strategies for prevention of groundwater pollution.

2 Site investigations

2.1 Aims of the site investigations

Two different dairy farms were studied: Farm S and Farm I. To calculate the nitrogen mass balance from cow manure generation through to compost application, the following values were measured:

1) The amounts of cow manure generation and ratios of discharged bedding material to cow manure;
2) The weight reduction occurring during the composting process; and
3) The nutrient and water content in the compost.

2.2 Description of dairy farms

Farm S has 39 cows, including 34 milking cows and 2 breeding cows. All cows are pastured for about 165 days a year from May 15 to October 31, and all cow manure is applied directly to the pasture during this time. Cows are kept in the cowshed for the remainder of the year (200 days from November 1 to May 14), and the manure generated in this period is kept in storage. The cow manure is periodically turned, matured and applied to the farmer's pastures 2 years later.

Farm I has a total of 80 cows, including 60 milking cows. Cows are kept in a cowshed throughout the year. The manure generated is stored but never turned. The stored manure is applied to dent corn fields 6 months later.

2.3 Results of the site investigations

Table 1 presents the data obtained from the site investigations.

Table 1: Site investigation results.

		Farm S	Farm I
Amount of manure generated (t)	Production unit method	1.7	2.8
	Measured value	1.8	3.0
% weight increase from bedding material		7.8	7.1
Composting	Turninng (Y/N) over	Y	N
	Storage period	2 years	6 months
% weight decrease during composting process		52.0	39.0
Composted manure analysis component (dry matter basis)	Water content (%)	79.5	74.7
	Nitrogen content (%)	2.3	1.9
	C/N ratio	13.0	1.8
	Ammonium nitrogen (%)	<0.01	0.1
	Nitrate nitrogen (%)	0.1	0.1

The measured amount of manure generated on Farm S was 1.8 t/day. Using an alternative method, the "production unit" method for cow manure, the amount of manure generated was found to be 1.67 t/day. The difference between these methods arises because bedding material (7.8%) was included in the measured amount of manure. Based on this amount, the total amount of cow manure generated during a 200-day period was estimated to be 360 t.

After 2 years of composting, the estimated amount of stored/composted cow manure was 174 t, indicating a 52% decrease in weight during the composting process.

The measured amount of manure generated on Farm I was about 3.0 t/day or, using the production unit method, 2.8 t/day. This farm showed a similar percentage increase in the measured amount of manure due to bedding material as found for S farm (7.8% increase).

Data on weight reduction after composting could not be gathered from this farm as the farmer had applied the compost to the field just before our site investigation. Compost from this farm was still sampled for nutrient and water content analysis.

3 Estimation of nitrogen emission to groundwater based on nitrogen mass balance

3.1 Settings for average daily farming models

The nitrogen mass balance from cow manure was estimated based on the site investigation results, assuming average daily farming models in Hokkaido. To develop the average daily farming models, the following parameters were considered and set as follows:

1) Production unit of cow manure: 45.5 kg/cow/day
2) Number of cows per area of pasture (here referred to as "cows/area"):
 2 cows/ha
3) Compost quality (storage period, occurrence and frequency of turning)
 6 months without turning or 2 years with turning
4) Frequency of compost application: biannual
5) Pasture vegetation type:
 Grass field with legume content of over 30% (vegetation 1); required nitrogen in spring is 2.5 kg-N/10a and in autumn 1.5 kg-N/10a [2].

3.2 Results of pasture nitrogen mass balance

The amounts of compost required (based on calculated N application rates in 6-month- or 2-year-old composted cow manure) and actually applied are presented in Figure 1.

The recycle ratio, R (%), is defined as follows:

$$R\,(\%) = \frac{\text{(the amount of compost used based on N requirements)}}{\text{(the amount of compost applied per annum)}} \times 100$$

Using this equation, R is estimated to be 38.5% (6-month-old compost) or 49.2% (2-year-old compost). If the weight decrease during the composting process is also taken into account (from Table 1), the recycle ratio R is estimated to be 23.5% for 6-month-old compost and 23.6% for 2-year-old compost. This indicates that the amounts of cow manure being applied greatly exceed the nitrogen requirements on these pasture fields.

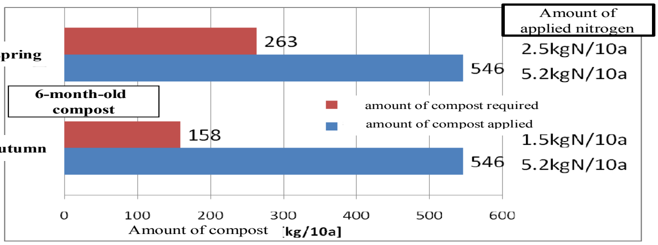
3.3 Sensitivity analysis

3.3.1 Range of the generation original unit

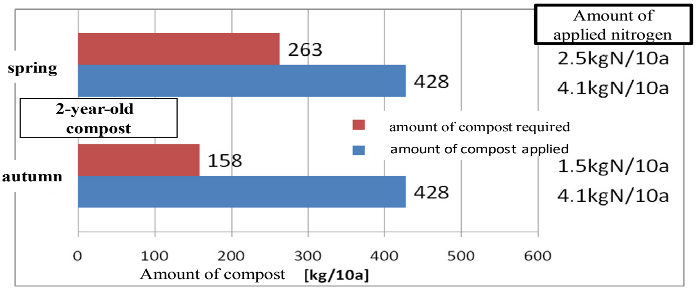
"Production unit" refers to the amount of manure generated per cow per day. In this section, the amount of manure generated is discussed in terms of 3 production units: 45.5 kg/cow/day, 30 kg/cow/day and 50 kg/cow/day.

3.3.2 Number of cows per area of pasture

Nitrogen use efficiency is dependent on the ratio of manure generated to the area of pasture on which it is applied, given that the frequency of application and compost quality are constant. Essentially, this then relates to the stocking rate of



(a)



(b)

Figure 1: (a) Amounts of compost required and applied based on compost nitrogen content (6-month-old-compost). (b) Amounts of compost required and applied based on compost nitrogen content (2-year-old-compost).

cattle on the pasture. In this chapter, 3 stocking rates (number of cows per pasture area) are set: 2 cows/ha (average value in Hokkaido), 3 cows/ha (average value in all of Japan), and 1 cow/ha.

3.3.3 Compost quality and production parameters

Compost quality is determined by the period of storage, and the occurrence and frequency of turning. In this chapter, 2 patterns of compost quality are set: compost storage for 2 years with turning, and compost storage for 6 months with no slashing back.

3.3.4 Compost application

It is assumed that all compost produced by a farmer is applied to that farmer's own pastures.

3.3.5 Pasture vegetation type

Pasture vegetation type and the percentage legume in the pasture are important factors in determining a field's nitrogen requirements. The nitrogen requirements of different vegetation types (differing in percentage legume) and dent corn are shown in Table 2.

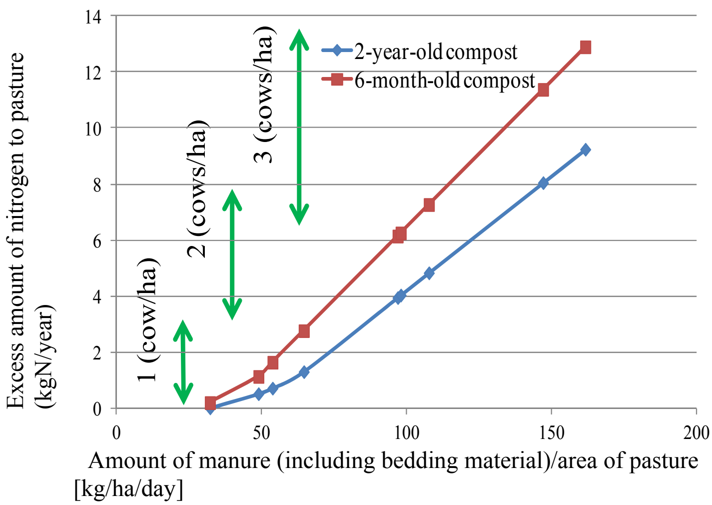
3.3.6 Sensitivity analysis of nitrogen emission to groundwater

The amounts of excess nitrogen for the pasture are shown in Figure 2, based on the condition that the same amount of 6-month-old compost or 2-year-old compost is applied to the pasture twice a year, in spring and autumn.

Table 2: Nitrogen requirements for different vegetation types [2].

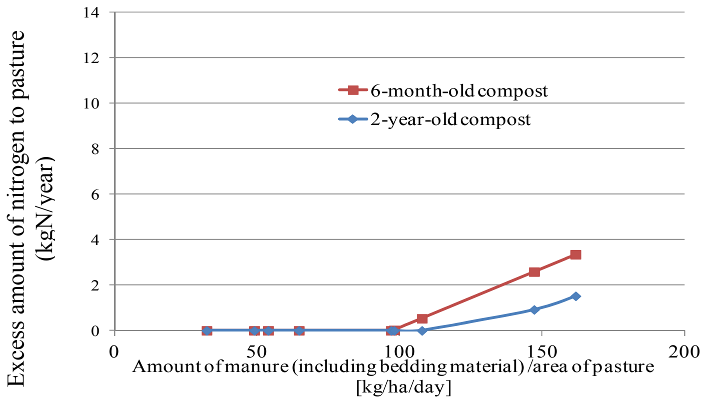
		Legume percentage (%)	Nitrogen requirements (kg/10a)	
			Spring	Autumn
Pasture	Vegetation 1	Over 30	2.5	1.5
	Vegetation 2	15～30	4.0	2.0
	Vegetation 3	5～15	6.0	3.6
	Vegetation 4	<5%	8.5	5.1
Dent corn		-	16 per annum	

The amount of excess nitrogen depends on not only the stocking rate but also the production unit of cow manure. It is therefore important for proper management of manure that we are able to accurately quantify the amount of manure generated, including bedding litter, on each farm. It is also apparent that the amount of nitrogen in compost is regulated by the frequency of turning and length of maturation time. If compost is to be applied to pastures twice a year, in spring and autumn, the nitrogen requirements of the pasture must be taken into account, and any compost excess to the pastures' nutrient requirements should be stored or applied elsewhere. The amount of excess nitrogen also depends on the vegetation types. It is important to manage the pasture to reduce legume percentage.



(a)

Figure 2: (a) Excess nitrogen in manure compost as determined by manure production rate (vegetation 1). (b) Excess nitrogen in manure compost as determined by manure production rate (vegetation 4). (c) Excess nitrogen in manure compost as determined by manure production rate (dent corn).



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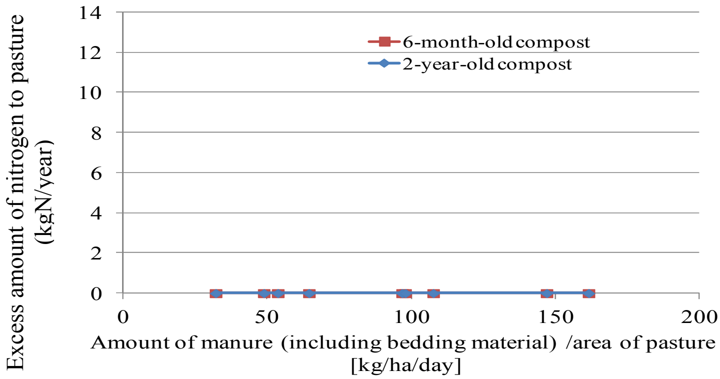

(c)

Figure 2: Continued.

4 Evaluation of potential for groundwater pollution using a numerical simulation model

4.1 Estimation method

The COUP (Coupled Heat and Mass Transfer Model for Soil–Plant–Atmosphere Systems) model [3], developed in Sweden, is used in the field of groundwater pollution. This model considers regional characteristics (soil type, air temperature, rainfall and so on) and compost quality (the amount of nitrogen, C/N ratio) to determine the potential for nitrate transport into the unsaturated zone. Nitrate flux data over time in the aquifer were obtained and input to the groundwater models, 1) GMS (Groundwater Modeling System) for simulation; 2) MODFLOW for groundwater flow; and 3) MT3DMS for solute migration, to estimate the concentration distribution of nitrate-N in the aquifer, taking into account the input of nitrate-N to pastures and leaching potential [4].

4.2 Conditions used for calculations

The potential for groundwater pollution was estimated under 4 scenarios, assuming that the original unit of cow manure generation was 45.5 kg/cow/day, the number of livestock/area was 2 cows/ha, and 6-month- or 2-year-old compost was applied to pastures for both vegetation types 1 and 4.

4.3 Estimation of nitrogen emission to groundwater using the COUP model

4.3.1 Outline of COUP model and parameter setting

The COUP model can estimate the amount of nitrogen leaching from soil, while simultaneously considering water and heat transfer through use of the vertical 1-dimensional mash model.

Water percolates into soil after rainfall and the model considers absorption from each soil layer to plants, transpiration from plants, and infiltration into groundwater. Heat transfer is influenced by the soil surface temperature, which is derived from the air temperature, and so the program also models heat transfer through soil layers and radiation from the soil back into the atmosphere (Figure 3).

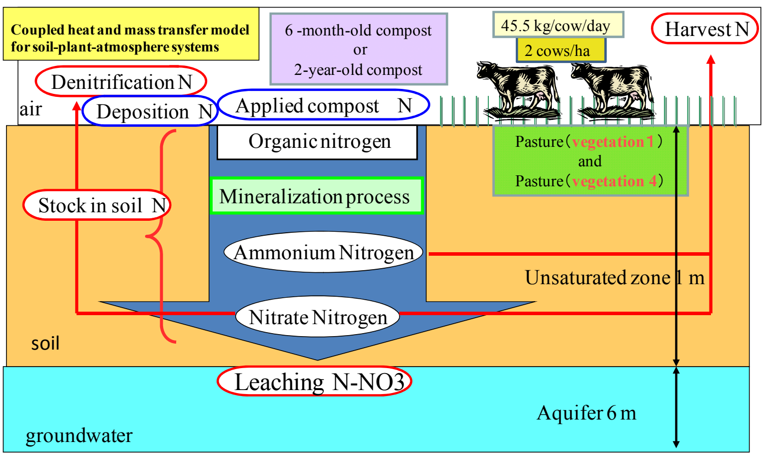

Figure 3: Schematic outline of the COUP model.

4.3.2 COUP model results

The COUP model predicted nitrogen leaching per unit area. Under all scenarios tested, nitrogen leaching patterns became almost constant after 10 years. Figure 4 shows the change in the amount of nitrogen leaching with time for the first year after constant conditions are obtained, for the 4 scenarios tested. As can be observed, nitrogen leaching is high after snowmelt and compost application in every scenario. Nitrogen leaching is reduced during the pasture-growing period (May to October). The amount of nitrogen leached was, from highest to lowest: 6-month compost–vegetation 1 > 2-year compost–vegetation 1 > 6-month compost–vegetation 4 > 2-year compost–vegetation 4. This indicates that the vegetation type may have a greater effect on nitrogen leaching than the compost quality under the scenarios tested.

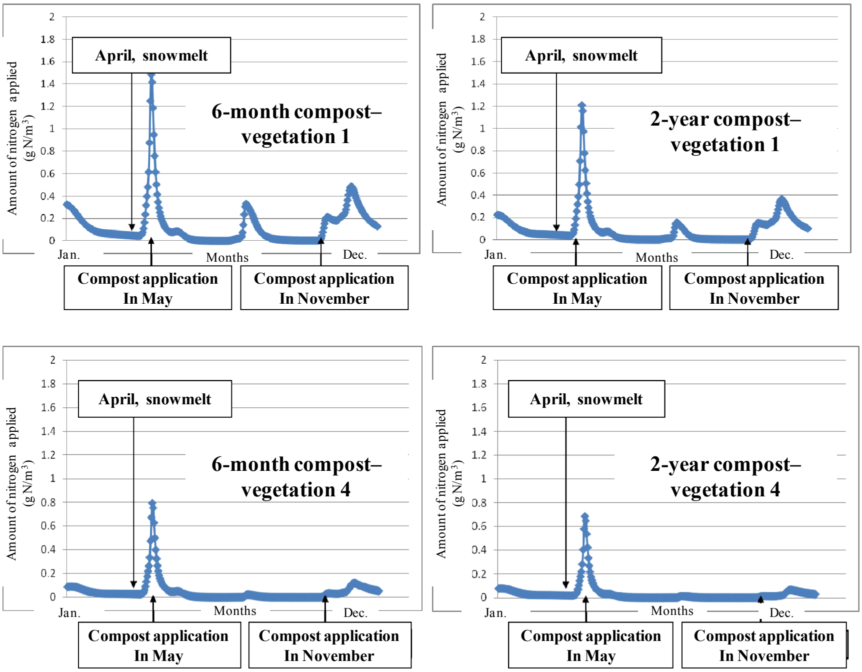

Figure 4: Results of nitrogen leaching to groundwater.

4.4 Three-dimensional groundwater numerical simulation

4.4.1 Outline of numerical simulation model

Output from the COUP model (nitrate-N flux into groundwater) was input into the 3-dimensional groundwater model to calculate the concentration distribution of nitrate-N in the aquifer. The investigation date was used to inform the outbreak term of nitrate-N from pasture.

The calculation area is 2000 m × 1500 m and the aquifer depth is 6 m. The grid size was set to 10 m × 10 m × 2 m, and the field is divided into 90,000 grids (= 200 × 150 × 3). The pasture area is 400 m × 500 m. Figure 5 presents a conceptual diagram of the model in this study.

4.4.2 Three-dimensional modeling results and discussion

Figure 6 shows the change in modeled groundwater nitrate-N concentrations at point A (aquifer depth 0~2 m) over 1 year for each scenario tested (the recycle ratio R for each case is also presented). The maximum allowable nitrate-N concentration in groundwater is 10 mg nitrate-N/L, which is environmental quality standard in groundwater in Japan. The modeled nitrate-N concentrations

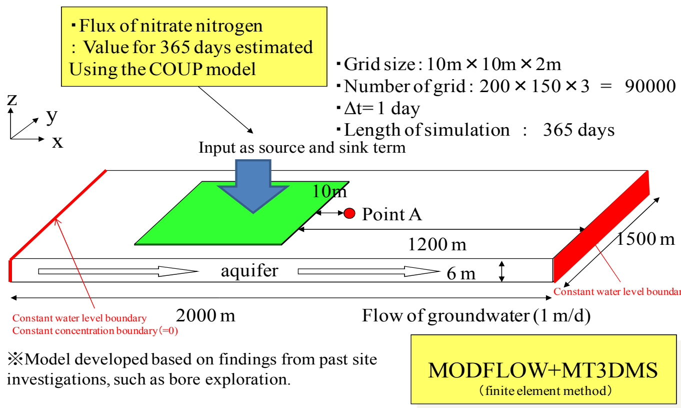

Figure 5: Conceptual illustration of 3-dimensional groundwater simulations.

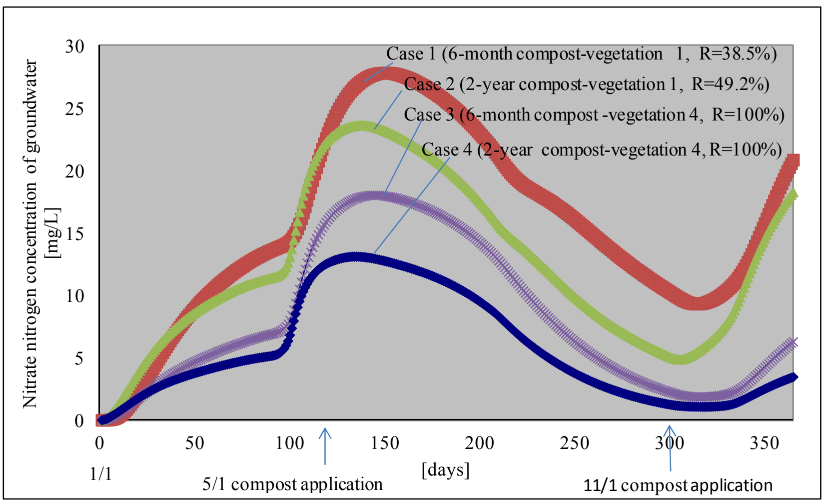

Figure 6: 3-D groundwater simulation results.

for the "6-month compost–vegetation 1" scenario were 3 times higher than the allowable maximum concentration; by contrast, the "2-year compost–vegetation 4" scenario approached but did not exceed the guideline value. The use of mature compost (both 2-year scenarios) appears to lower the potential for nitrate leaching into groundwater.

4.5 Recommendations for cow manure management

4.5.1 Improvement of format for reporting manure generation and recycling

Accurate quantification of the amounts of manure generated, the area to which the manure is applied and compost quality (i.e., N content) are critical parameters to ensure accurate modeling of the potential for nitrate-N groundwater pollution.

4.5.2 Recommendations for cow manure composting and application

Important factors for appropriate application of cow manure compost to reduce nitrogen emission to groundwater are as follows:

1) Cow stocking rate management and the area of pasture available for compost application;
2) Management of manure composting to ensure adequate aeration and maturation time;
3) Accurate quantification of the N content of manure compost and appropriate application based on N requirements of pasture or crops (excess compost should be stored appropriately for future application when required); and
4) Application of manure to other crop types with higher N needs than pasture (such as dent corn).

5 Conclusions

The main points of this study are as follows.

1) The nitrogen mass balance was calculated for the process of cattle manure production and composting through thorough site investigations.
2) The currently reported recycling rates of cattle manure do not reflect what is really happening on farms. This is problematic in terms of excess nitrogen application to pastures and potential for nitrate-N groundwater pollution.
3) It is recommended that farmers adjust their cow manure management to grasp the actual amount of manure applied to pasture and nitrogen content in the manure to reduce nitrogen emission to groundwater.

Acknowledgement

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