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Substance Flow Analysis of Nitrogen in Food Production and Consumption System of Thailand

Master of Science Thesis in the Industrial Ecology Master Programme

TANAKORN SUESATPANIT

Department of Space, Earth and Environment, Physical Resource Theory
Division of Physical Resource Theory
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2017

MASTER'S THESIS No. 2017:18

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Cover: Floating market https://pantip.com/topic/36653745
Printed by Chalmers Reproservice
Göteborg, Sweden 2017

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Abstract

Nitrogen fertilizer is a vital production factor for agriculture of which many countries worldwide including Thailand rely almost entirely on import. In Thailand, soy meal, a protein-rich feed constituting a large share of livestock feed demand is also imported. With Thailand's great ambition to become the World's Kitchen, a question arises in how to realize the sustainability of this ambitious target. As a principle of circular economy and sustainable agriculture, efficient use of resource should be maximized. With improved understanding of the current nutrient flows in the food system as a starting point, opportunities to close the nutrient loop can be found. Scoping on food production and consumption system of Thailand in 2014, this thesis aims to identify the origin of re-utilizable nitrogen budgets, quantify the size and evaluate the current recycling of these resources. Identification of material in which nitrogen is stored is also done wherever possible.

Using Substance Flow Analysis (SFA), a nitrogen flow diagram is constructed based on official reports and scientific literatures. The system entails seven subsystems; CROP, FEED, ANIMAL, FOOD, HUMAN CONSUMPTION, FOOD WASTE, PUBLIC WWTP (Waste Water Treatment Plant). As a result, six key re-utilizable nitrogen budgets are identified including 1) on-field residue, 2) feed unexplained, 3) manure retrieved, 4) food industrial waste, 5) food waste retrieved and 6) sewage sludge. Out of 812 ktN (±23%) re-utilizable nitrogen in total, on-field residue accounts for the largest share of 36% followed by feed unexplained 25%, animal manure 19%, food industrial waste 14%, sludge 5% and food waste 1%. This implies that 530 ktN (±28%) of organic fertilizer could potentially be returned to agricultural soil annually or approximately 22% of total input. Furthermore, an unaccounted amount of 416 ktN (±76%) is found to be a potential stock on agricultural land annually. Zooming into the constituents of these budgets, rice straw contains 172 ktN (±41%) or 60% of N in on-field residue. The manure retrieved is from chicken 37%, pig 29% and beef cow 14%, similar to their order of prevalence. Due to unknown consumption of each kind of feed, the identification of material holding N is not possible.

This thesis is the first nationwide study of nitrogen flow in food production and consumption system that gives an overview in opportunity areas. Further research remains necessary to gain insights in actual capacity, utilization options and practical limitations.

Keywords; Agriculture, Food production, Nitrogen, Nutrient recycle, Substance Flow Analysis

Acknowledgement

I would like to express my gratitude to Prof. Christel Cederberg my supervisor and examiner for her invariable support and invaluable feedback throughout this project.

Thanks to Erasmus Mundus Master's Programme in Industrial Ecology, especially people behind; Ralf Aschemann, Ulrika Lundqvist, Ester Van Der Voet and Ulrike Krawagna for all academic activities, warm parties and life advices.

Thanks to my dear friends in the same and previous generations of MIND for making my two years in Europe a life changing experience.

Thanks to John Laurence Esguerra for who always be there in the time in need.

Finally, thanks to my mom, J' Yung, for showing me the way of life no one else could.

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List of Abbreviations

DW	Dry weight
FW	Fresh weight
IFA	International Fertilizer Association
N	NItrogen
NH3	Ammonia
N2	Nitrogen gas
N2O	Nitrous oxide
NO	Nitrogen monoxide
NOx	Nitrogen oxides
OAE	Office of Agricultural Economic
TFA	Thai Feed Mill Association
WWTP	Wastewaster treatment plant

Units

ha	Hectare
L	Litre
yr	Year
d	Day
g	Gram
kg	Kilogram
t	Tonne
kt	1,000 Tonnes
ktN	1,000 Tonnes Nitrogen

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1. Introduction

Thailand is a country where much of its resources is devoted to agriculture and food production. In global trade, it presents among the top exporters of rice, cassava, sugar and tropical fruits (FAOSTAT, 2016) and exports a large portion of domestic chicken production (OAE, 2015). Thailand has an ambition to be the World's Kitchen yet one of the most important production factors, synthetic Nitrogen fertilizer, relies greatly on import. Similarly, animal production, most importantly chicken and pig, is dependent on an import of soymeal. In physical resource perspective, the efficiency in resource use is an important question for Thailand to sustainably become a World's Kitchen.

Nitrogen (N) is a highly transformable element. It exists in many forms, yet its abundancy does not always imply its accessibility (Galloway et al., 2004). Reactive N enters food production system via biological fixation, atmospheric deposition and fertilizer as well as finished food or feed. Reactive N are lost through various pathways and resides in materials at some point in time. Understanding the flows and stocks are necessary in closing the loop and maximizing the resource efficiency.

Throughout the chain of food production, N in products is only a sum of production processes in which numerous inputs and losses are associated along the way. To illustrate this, cultivation of crops requires fertilizer. Some of which is absorbed to nourish the biomass which is returned to the soils later if it is not part of the harvested products. Feed is consumed by animal to be converted into body mass or product mass which unavoidably generates a great amount of manure. Some biomass residue might be reconnected to feed. A certain amount of manure might be returned as fertilizer. How much these are occurring has so far not yet been systematically assessed in national level in Thailand.

In post-consumption, food waste is another aspect that receives a growing interest (Gustavsson et al., 2011). While food waste prevention is unquestionably a first priority to implement, how much potential the generated food waste holds and to what extent we have currently been reutilizing is no less thought-provoking to answer.

Part of nutrient loss from the society is arrived at wastewater treatment plant, analogously a final gatekeeper of resource of the society. This loss includes all forms water emission ranging from run-off, leaching, household discharge, to human excreta seeped from septic tank (Boontanon and Buathong, 2013). It may or may not originate from food production and consumption system. Regardless, certainly after the process of water refinement, some of the removed nitrogen ends up in the form of sludge, one last nitrogen retrieval of the society.

Evaluating these budgets of resource and comparing could offer us a comprehensive picture of where in the food chain nitrogen losses occur most and what are being retrieved to what extent relative to one another. Apparently, this will be an invaluable input for strategy planning in resource re-utilization by providing prioritization and characteristic of the materials.

Field measurement of nitrogen throughout the whole system could be unimaginably arduous and warrants no reliable representation in such a dynamic system. It is perhaps not even efficient to do so in time, effort and money aspect. An alternative way to assess these flows is Substance Flow Analysis (SFA), a methodology employed in industrial ecology to track stocks and flows of substance based on a principle of mass balance.

Stemmed from Material Flow Analysis (MFA), SFA has been employed to assess the nutrient flow in food production system in various countries e.g. Netherland, China, Japan and Austria (Olsthoorn and Fong, 1998; Hou et al., 2013; Shindo et al., 2009; Pierer et al., 2014). In Thailand, SFA studies of nitrogen have been focusing on pollutive natural emission while the resource perspective remains untapped. Furthermore, the scopes were confined in basin or multi-provinces level (Schaffner, 2007; Leelapanang 2010, Matsumoto et al., 2010). This thesis will be the first SFA attempt to assess the in re-utilizable N budgets of materials in food production and consumption at national level of Thailand.

1.1 Research objective

This study aims to identify the source, quantify the magnitude and evaluate the current recycling of re-utilizable N budgets in food production and consumption system of Thailand in 2014 through the construction of flow diagram of nitrogen.

1.2 Research questions

Based on current scenario of Thai food production and consumption system 2014;

- At which steps in food production and consumption system are re-utilizable N budgets created?
- How large are re-utilizable N budgets?
- How much N is potentially being returned to agriculture?
- What factors in food production and consumption are these budgets sensitive to?
- What materials are re-utilizable N budgets constituted of?

2. Background

2.1 Thailand and food production

Background of Thailand

Thailand has a population of 65,124,716 inhabitants in 2014 (0.4% growth rate) with an area of 513,115 km^2. Locating slightly above equator makes it a tropical country in Southeast Asia (OSRS, 2015; UNdata, 2016; Meteorological Department, 2015). Average temperature ranges from 23-30 degree centigrade with annual rainfall of 1,200-1,600 mm (Meteorological Department, 2015). Meteorologically, Thailand has 3 seasons, rainy (mid-May to mid-October), winter (mid-October to mid-February), and summer (mid-February to mid-May). Divided into 5 regions northern, central, northeastern, eastern, and southern, each region has different geographical and climate characteristics (Figure 2- 1). Northern part features mountainous topography covered with forest and is relatively colder than the rest. This is where the biggest river of Thailand, Chaophraya River, is originated. Northeastern is the largest part featuring highland plateau with the lowest rainfall. Drought, therefore, tends to be the problem which is also contributed by its sandy soil with low organic content. Eastern part is the smallest region consisting of small hills in the north and the Gulf of Thailand on the south. Central part is prevalently a low land where several basins are located receiving nutrient rich sediment from the river. These rivers flow into the gulf of Thailand. Availability of water throughout the year and fertile soil makes it highly suitable for agriculture. Southern region is a peninsular paralleled by Andaman sea, a part of Indian ocean, and the gulf of Thailand, a part of South China Sea. Influenced by tropical monsoon climate, southern region receives the highest amount of rainfall across Thailand (Meteorological Department, 2015).

(UN, 2007)

Figure 2-1 The map of Thailand

Food production in Thailand

Agricultural sector employs 41.9% of Thai population (United Nations, 2015) and contributes 40.6 Billion US$ or 10.1 % of Thai GDP in 2014 (World Bank, 2015). From the international trade perspective, in 2014 Thailand ranks among the top exporters for various agricultural products. To name a few (with global share indicated in bracket); the 1st for cassava (77.7%), the 1st for Pineapple

(53.8%), the 1st for natural rubber (37.2%), the 2nd for rice (25.3%), the 5th for sugar (12.5%), the 5th for shrimp (7.5%) and the 4st for chicken (5.2%) (OAE, 2016b).

According to Agricultural Statistics of Thailand, up to 46.5% of land is devoted for agriculture in 2014 (OAE, 2016). Within this, 47% is Rice paddy field, 23% Orchard and perennial crops, 21% Upland crops, 1% Vegetables and ornamental plants and the rest 8% covers other agricultural land use which includes animal farms, ponds and pastures (Figure 2-2a).

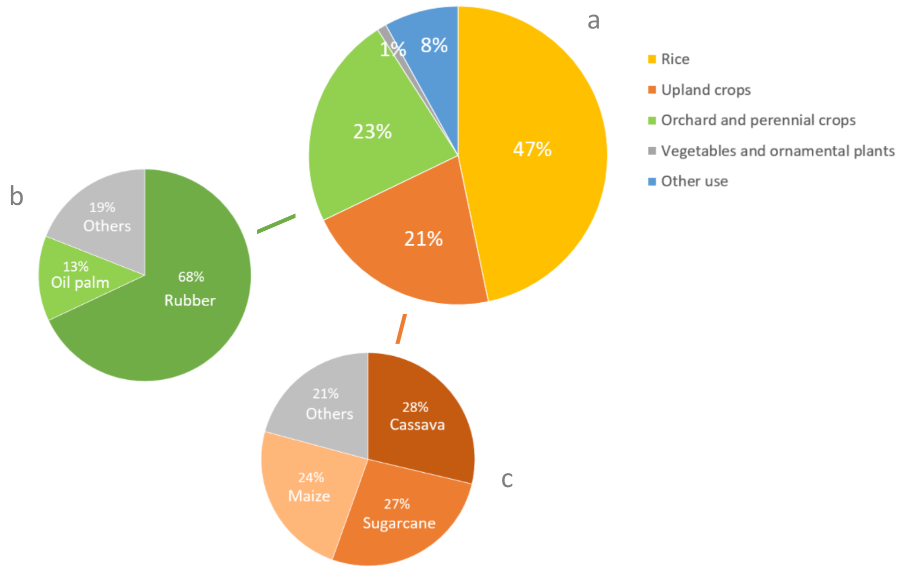
Among orchard and perennial crops, 68% is covered with para rubber cultivation which is not related to food system. The second biggest (13%) is used to grow oil palm which has a mixed use of food and biofuel. 19% is used almost entirely for diverse fruit orchards, for instance, coconut, longan, durian, mangosteen, lychee, longkong, rambutan and lime (Figure 2-2b). Looking into the upland crop area, 28%, 27% and 24% are the cultivation of cassava, sugarcane and maize respectively, leaving 20% for other crops (OAE, 2016) Figure 2-2c.

Livestock production in Thailand is dominated by chicken and pig (OAE, 2014) Figure 2-3. Small percentages of beef cow, duck and buffalo meat combined are less than 10%. Every species of livestock except for cattle is mostly farmed in central part of Thailand, followed by northeastern and northern part. Cattle are raised in the northeastern part in highest number. The southern part is a home for the smallest population of all species (OAE, 2016) Figure 2-3.

On the input side of food production, 95% of synthetic fertilizer used is imported (Tanpaibool, 2016). According to OAE (2017), Thailand imports 5.4 million tons of synthetic fertilizer in 2014. Supplier countries are Saudi Arabia, Qarta, Malaysia, China, Kuwait. Domestic production of N fertilizer is rather low, approximately 0.58 million tons of ammonia and ammonium sulfate annually (Tanpaibool, 2016). It is worth noting that although the import of fertilizer is declining over last 5 years, this is not because of the improvement in nutrient efficiency but the fall of agricultural product prices and prohibitive climatic condition (Tanpaibool, 2016).

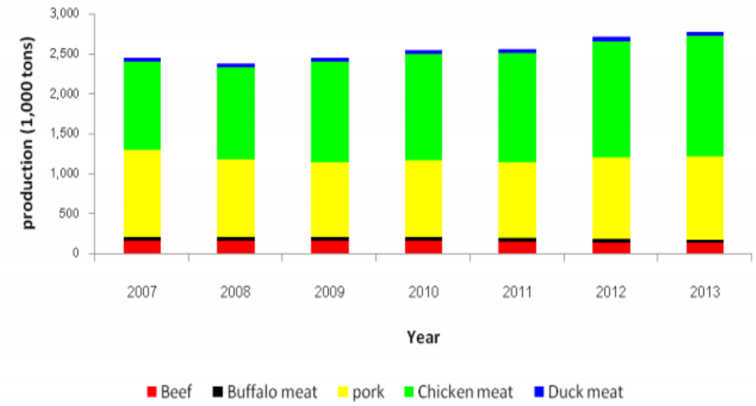
Among animal feeds, soy meal is the most important plant-based source of protein which is most abundant worldwide. In Thailand, about 70% soy meal is imported totaling 2.8 Mton in 2014. On 30% from domestic production, still, 98% of virgin soy grain is imported for cooking oil and other intermediate industries which generate soy meal as a byproduct (OAE, 2014; “Import Policy and Measure,” 2013). Putting this in context, soy meal accounts for roughly 24% weight of feed mill demand yet holds 63% of all feed mill’s nitrogen content (TFA, 2014).

The growing population and political ambition to be the World’s Kitchen emphasized the significance of food production in the years to come (Berendes, 2012; Sirivalo, 2012, Mudlek, 2017). If the world population hits 9.1 billion by 2050, FAO (Alexandratos and Bruinsma, 2012) estimates that the world food production must be raised by 70%, especially in developing countries may need to double. This figured has been revised to be even higher as 9.8 billion (UNDESA, 2017). On top of this, the pressure on agriculture might be an underestimate because this does not take into account a competition from biofuel crops. Increasing the efficiency in nutrient use will alleviate the need for imported resource and its side environmental impacts from nitrogen.



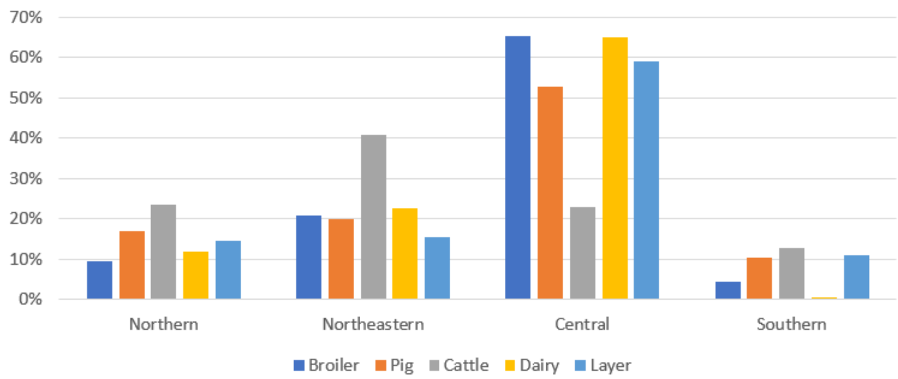
(OAE, 2016)

Figure 2-2 Distribution of crops (%) on agricultural land in Thailand 2014



(OAE, 2014)

Figure 2-3 Beef, buffalo meat, pork, chicken eat and duck meat production in Thailand



(OAE, 2016)

Figure 2-4 Distribution of livestock (%) in different regions of Thailand 2014

2.2 Material Flow Analysis

Definition and terminology

Material Flow Analysis (MFA) is a systematic assessment of flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2005, pp. 3). It concerns sources, pathways, intermediate sinks and final sinks that materials flow through a period of time. Based on mass balance principle, inputs, outputs and stocks of a process can be determined. Substance Flow Analysis (SFA) is terminologically a subset of MFA which will be discussed in the following.

What exactly does 'material' here means? Brunner and Rechberger (2005) discussed in their Practical Handbook of Material Flow Analysis that material is a term that can represent both substance and good. Brunner (2002) defines goods as "economic entities of matter with a positive or negative economic value. Goods are made up of one or several substances" The synonyms of goods that are commonly used are product, merchandise and commodity. A substance, on the other hand, is any (chemical) element or compound composed of uniform units (Atkins and Beran,1992, pp. 5). All substances are characterized by a unique and identical constitution and are thus homogeneous. Therefore, in MFA elements and compounds are similarly addressed as substance.

Materials can be undergone through 'processes,' which are the transformation, transport or storage of materials. Processes can be viewed in different levels i.e. human body, households, factory, industrial sector or society. Process could also be completely natural such as the carbon fixation of plants into biomass. Stock is a retention of material within a system and has a physical mass unit. It is a part of process in which mass is stored (Brunner and Rechberger, 2005, pp. 37).

Processes are linked by flows and fluxes. Flow is defined as a "mass flow rate" which has a unit of mass per time while flux is a flow per cross section. Note that cross section could mean different things such as an area, a person, a region. Flows and fluxes that cross the system boundary are called import (inward) and export (outward). Flows and fluxes that go into the process are called input and output for those that comes out (Brunner and Rechberger, 2005, pp. 39).

System is an assemblage of processes, flows and stocks within a defined system boundary. System boundary is delimited in terms of space and time. Space can be a geographical area or virtual delineation such as households, companies, waste treatment systems. System boundary should be determined based on the objectives, data availability, balancing period or residence time of materials (Brunner and Rechberger, 2005, pp. 4).

Application of MFA

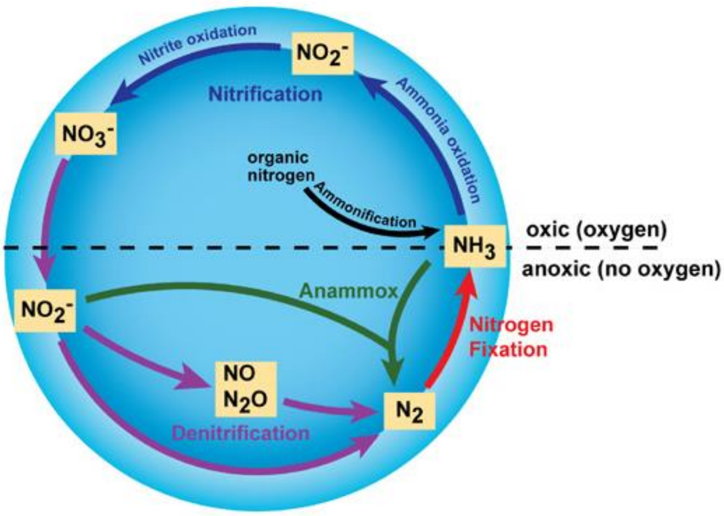
MFA has been a valuable tool in various fields of management. In environmental management and engineering, MFA has been used to identify the flow of hazardous substances, build pollution control strategies and design nutrient management plans. MFA could highlight sources and pathways of materials which therefore aids prioritization of problems or flags specific issue for further investigation. Consequently, inefficient use of time and resource can be avoided. MFA also serves transparency in Environmental Impact Assessment (EIA) in which alternative scenarios can be analyzed, illustrated and communicated among different audiences (Schachermayer et al., 1995).

MFA is a first step in life cycle assessment (LCA) known as life cycle inventory where inputs and outputs to every process in the defined system are accounted. Although the focus is slightly different in a sense that MFA concerns the stocks and flows of materials while LCA seeks for the environmental implications in the use of materials, the basic of mass balance principle is similarly applied (Venkatesh et al, 2009).

In resource and waste management, it is apparent that MFA can contribute in tracking and evaluation of material stocks in nature and anthroposphere. The growing world population warrants the increasing demand for materials in the society. Natural resources are extracted to build infrastructures for long-term function or quick utilization period at various rate (Gerst and Graedel, 2008; Kuo et al., 2007). Managing these flows and anticipating the release of materials and substances from the stock could be benefited by MFA. Furthermore, MFA can save the effort to determine the composition of municipal waste where data collection is arduous and costly yet yielding an arguable result's representativeness (Nakamura et al., 2007). As a result, a proper waste treatment plan can be designed to match the type of waste generated. Beyond this, it could serve as a guide to design out waste or encourage the incorporation of recyclable materials in products.

2.3 Nitrogen cycle

Nitrogen is a vital element for organisms just like other macronutrients such as carbon, hydrogen and oxygen. It is an irreducible element presenting in a variety of major and minor biomolecules i.e. proteins, DNAs, RNA, chlorophyll and secondary metabolites. Nitrogen is massively abundant in nature. Eighty percent of the air is nitrogen. However, it is in nitrogen gas form (N_2) which is inaccessible for organisms due to the strong triple bond linking between the two nitrogen atoms. Only after N_2 has been transformed into reactive forms (such as NH_3, NO, N_2O, NO_2^-, NO_3^-), is it available for biological utilization. Diverse groups of microorganisms play different crucial roles in processes that convert inert N_2 into reactive nitrogen and vice versa. These processes include nitrogen fixation, nitrification, denitrification, anammox, and ammonification (Figure 2-5). Only denitrification and anammox eliminate the availability of reactive nitrogen while the rest contributes the increase or mere transformation among reactive forms of nitrogen (Bernhard, 2010; Galloway et al., 2004).



(Bernhard, 2010)

Figure 2-5 Nitrogen Cycle in Nature

1. Nitrogen fixation

$$N_2 + 8\ H^+ + 8\ e^- \longrightarrow 2\ NH_3 + H_2$$

Nitrogen fixation converts N in to NH_3 which is a biologically accessible form of nitrogen. Since the nitrogen's triple bond has to be broken, it is an energy demanding process that only a certain group of bacteria are capable of, so called, nitrogen fixing bacteria. Some of them are free-living while others are symbiotic organisms, for example, *Rhizobium* bacteria inhabiting the root of leguminous plants. Biological fixation can occur both in nature and human cultivated crops and forages such as peas, clover and soybeans. Besides this, non-biological nitrogen fixation can also occur through lightning and combustion of fossil fuels. These reactive nitrogen compounds in the atmosphere will then be washed down with the rain, namely, wet deposition or simply deposited onto the land and sea known as dry deposition (Bernhard, 2010; Galloway et al., 2004). Anthropogenic nitrogen fixation is done through a process called Haber-Bosch developed by two Nobel Laureates German scientists Fritz Haber and Carl Bosch in the early 1900s. Under extremely high pressure (200-400 atm) and moderate temperature (400-650 °C), ammonia is formed from nitrogen in the air and hydrogen (Encyclopædia Britannica, 2017). This synthetic N fertilizer production process played a revolutionary role in agricultural productivity (Galloway et al., 2004).

2. Nitrification

1) $NH_3 + O_2 + 2\ e^- \longrightarrow NH_2OH + H_2O$

2) $NH_2OH + H_2O \longrightarrow NO_2^- + 5\ H^+ + 4\ e^-$

(a) Ammonia oxidation

$$NO_2^- + \tfrac{1}{2}O_2 \longrightarrow NO_3^-$$

(b) Nitrite oxidation

Nitrification is a process that converts ammonia into nitrate which is a more oxygen-rich form of nitrogen. This happens in two steps. The first step (a) is called ammonia oxidation, carried out by ammonia-oxidizing microbes in soils. Ammonia is converted into nitrite (NO_2^-) in this step. The second step where nitrite is further converted into nitrate (b) is called nitrite oxidation and is carried out by a different group of organisms known as nitrite-oxidizing bacteria. Both reactions release small amount of energy in which some group of microorganisms can rely on for living in the same way that energy in sunlight would do for plants (Bernhard, 2010).

3. Anammox

$$NH_4^+ + NO_2^- \longrightarrow N_2 + 2\ H_2O$$

Annamox is a process involving with loss of reactive nitrogen. It converts ammonia and nitrite into nitrogen gas (Bernhard, 2010). This process occurs in various aquatic systems such as wastewater treatment, low-oxygen zones in freshwater and marine environment. A report suggests that it could be responsible for a significant loss of reactive nitrogen in some areas of the ocean (Kuypers et al. 2005).

4. Denitrification

$$1)\ NO_3^- \longrightarrow NO_2^- \longrightarrow NO + N_2O \longrightarrow N_2$$

$$2)\ 2\ NO_3^- + 10\ e^- + 12\ H^+ \longrightarrow N_2 + 6\ H_2O$$

Denitrification is a process that converts an oxidized form of nitrogen into a reduced form (less oxygen atoms or completely removed). The final outcome of this process is nitrogen gas. During the process, however, intermediate forms of nitrogen such as NO and N_2O can be generated. Denitrification is a process that occurs in anaerobic condition such as soil, sediment and oxygen-free zones in water body. Microorganisms involved in this process are called denitrifying bacteria which generally are the member in genera *Paracoccus*, *Bacillus* and *Pseudomonas*. Denitrification in farmland can be a main problem for plant nutrient availability. On the other hand, it could benefit by reducing the nutrient load in wastewater thus alleviate the problem of eutrophication (Bernhard, 2010).

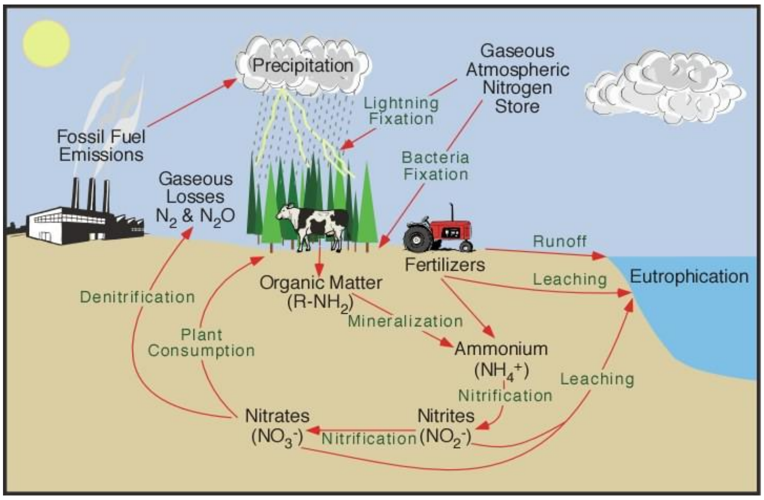
5. Ammonification

Waste excretion and dead body masses from organisms contain nitrogen in organic forms i.e. protein, amino acids, DNA. Decomposition processes carried out by fungi and bacteria can convert such organic material into ammonia through ammonification process making it available again for plants and other organisms (Bernhard, 2010).

Galloway et al. (2004) discussed that humanity has contributed to the alteration of global availability of reactive nitrogen in various ways, as illustrated in Figure 2-6. Cultivation of rice, sugarcane, forages and other leguminous crops since the past, albeit replacing natural biological nitrogen fixation, has fixed atmospheric nitrogen in to soil to the rate unprecedented by natural process. To elaborate this, paddy field provides anoxic condition that promote greater nitrogen fixation in cyanobacteria. Associative microorganism in leguminous forages (alfafa and clover) and sugarcane could fix nitrogen at a higher rate than naturally occurred (Smil, 1999).

The impact leapt to an even higher level after the invention of Haber-Bosch process in which ammonia is generated, sourced from N_2 out of the air. Such revolutionary technology ramp up agricultural productivity and increased losses of reactive nitrogen to water and air. It was predicted that in 2030 the nitrogen fixation by human will exceed the natural processes (Vitousek 1997). The general estimation of nitrogen loss through runoff and therefore riverine flow could be as high as 25% of the applied nitrogen fertilizer in the U.S. (Boyer et al., 2002). While in waterbody, denitrification of reactive nitrogen could also occur concurrently.

At the same time, a growing demand in energy derived from combustion of fossil fuels also released reactive nitrogen into atmosphere in the form of NOx. Burning of biomass to open the land and seasonal residue clearing also contributed in the same way. While some part NOx can return to the land by atmospheric deposition, N2O stays in the atmosphere for more than a century with and affect the planet´s heat balance as it is a greenhouse gas.



(Pidwirny, 2006)

Figure 2-6 Nitrogen pathway across human activities and nature

2.4 Substance Flow Analysis in Thailand

There are various SFA studies conducted in several River Basins in different regions of Thailand focusing on the flow of nitrogen (N) and in some cases phosphorus (P) as well. This section discussed the key research which are relevant for my study.

Schaffner (2007) conducted a study on material flow analysis to assess river water pollution and mitigation potential in Thachin River Basin of Central Thailand. Hydrology as well as the flow of N and P are considered with particular focus on pig farming and rice cultivation. The components included in this study are field crops, fruits & vegetables, aquaculture, rice, pig, poultry, water plants, industry and households. Among various components investigated, aquaculture turns out to be the most significant source of pollution contributing around 60% of nutrient load. Industry and rice farming could contribute the same magnitude of impact if the whole range of uncertainty is considered. Households accounts for a very small share even when all uncertainties are respected. Pig farming which was believed to be the major polluter of the basin surprisingly turns out to account for less than 15% of the nutrient.

In Bang Pakong Basin, eastern of Thailand, N and P flow analysis from pig farming was carried out by Kupkanchanakul and Kwonpongsagoon (2011). Here is where 20% of pigs in the country are raised. Slaughterhouse is included in the scope of this study. System components include 1) pig farming, 2) Pond/Anaerobic digester, 3) Heap of solid dung, 4) agriculture, 5) aquaculture, 6) river and canals. Annually, the system receives 15,000 tN and 3,300 tP as input. Water supply and animal feed are main inflow of the system. Outflow of five million tons of water is generated containing 3,250 and 1,030 tons of respective nutrients. Three different waste treatment mixes are considered according to different practices in three sizes of farms; Small <500 pigs, Medium 500-1,000 pigs, large >1,000 pigs. These sizes of farms raise 10%, 15% and 75% of total pigs respectively. However, the degree of pollution emitted is inversely correlated as there is more direct discharge in small farms. Besides this, overflow from wastewater treatment and runoff from dung heap are also key sources of pollution.

Two provinces, Ratchaburi and Samut Songkhram, locating on the river delta to the gulf of Thailand were studied for N flow by Pharino et al. (2016). This Maeklong River basin could potentially face eutrophication and the prevention strategies are needed to avoid the impact. Four major activities are included; agriculture (rice cultivation, livestock, and aquaculture), industry, households, waste management, and wastewater treatment. The result shows that 25,911 tN was released in to river in 2010 with livestock being the most significant sector contributing 55% of total load. Industry and households ranked the second followed by rice cultivation.

Chaophraya River Delta, a part of the biggest river of Thailand, was a subject of N flow analysis in food production and consumption by Leelapanang (2010). Wet and dry season are modelled separately. The major flows, from biggest to smallest, are feeding to aquaculture (107,363 tN), sedimentation of excess aquacultural feed (89,794 tN), agricultural output to industry (86,527 tN), anthropogenic fertilizer application (74,940 tN), and livestock feed (61,850 tN). All in all, the fate of nitrogen to air, water, and soil are 33,263 tN, 116,739 tN, and 128,998 tN, respectively.

Nitrogen and phosphorus flow in food production and consumption in Bangkok was investigated by Færge et al. (2001) with an aim to explore the reuse possibility in agriculture. Data from FAOSTAT as well as provincial record are employed for the study period in 1996. The result indicates that only 7% and 10% of N and P respectively were currently reused while the rest contributes to the escalated nutrient in Chaophraya river. Atmospheric emission is ignored for the lack of possibility to accurately quantify the magnitude. Bangkok's total discharge to Chaophraya River is estimated to be 24,206 tN and 1490 tP per annum. Scenario analysis of the masterplan in enlargement of wastewater treatment system and sewage indicates that even so, more than half of the nutrient would still be lost.

3. Materials and Methods

3.1 System Boundary

Kingdom of Thailand is defined as a geographical boundary with a period of one year in 2014 as a temporal limit. No stock from previous year is considered for the commodities. Owing to our focus on food production and consumption system, para rubber and oil palm are excluded from our scope because para rubber is non-food and there are significant alternative uses of oil palm outside of food area. Further details of system boundary could be found under their own specific topics in system component section.

3.2 Materials

This study utilizes secondary information compiled from sources specific to Thailand, as well as regional and global studies where there is a lack thereof. Thailand's statistics on agriculture, international trade and waste are obtained from press releases by Thai authority. Scientific facts such as nitrogen content and common practices such as fertilizer application are collected through reviews, databases and primary studies. All in all, a mixed source of information entailing research literatures, field measurements, lab tests, modellings, educated estimates and expert opinions are appreciated.

3.3 Methodology

A substance flow diagram of nitrogen in food production and consumption of Thailand in 2014 is constructed consisting of 7 subsystems. The relationships between subsystems are analyzed to create internal flows between subsystems and external flows with outside of system boundary. Six re-utilizable nitrogen budgets resulted from different subsystems are identified. Assuming that these are all turned in to organic fertilizer, the amount of N returned to agriculture is evaluated. Finally, a sensitivity analysis is performed to test the degree of influence of five suspected parameters on re-utilizable nitrogen budgets (Figure 3).

3.3.1 Flow Diagram Construction of Food production and consumption system

In this study, food production and consumption system of Thailand are divided into 7 subsystems;

1. CROP
2. ANIMAL
3. FOOD
4. FEED
5. HUMAN COSUMPTION
6. FOOD WASTE
7. PUBLIC WWTP

At a glance, CROP involves activities related to soil cultivation which generates plant-based products. ANIMAL involves livestock production excluding aquaculture and fishery. FOOD and FEED are two conceptual spaces where the agricultural produces removed from farmlands or farms are turned into marketable products. Imports and exports of food products are considered in these two components. HUMAN CONSUMPTION describes domestic consumption of Thai population which generates two subsequent streams of wastes; FOOD WASTE and human excreta. FOOD WASTE refers to a dissipative food waste generation from human society as opposed to point-generated industrial wastes in FOOD.

Finally, PUBLIC WWTP deals with the recovery of N in sewage system which associates with the excretion from human population (Figure 3).

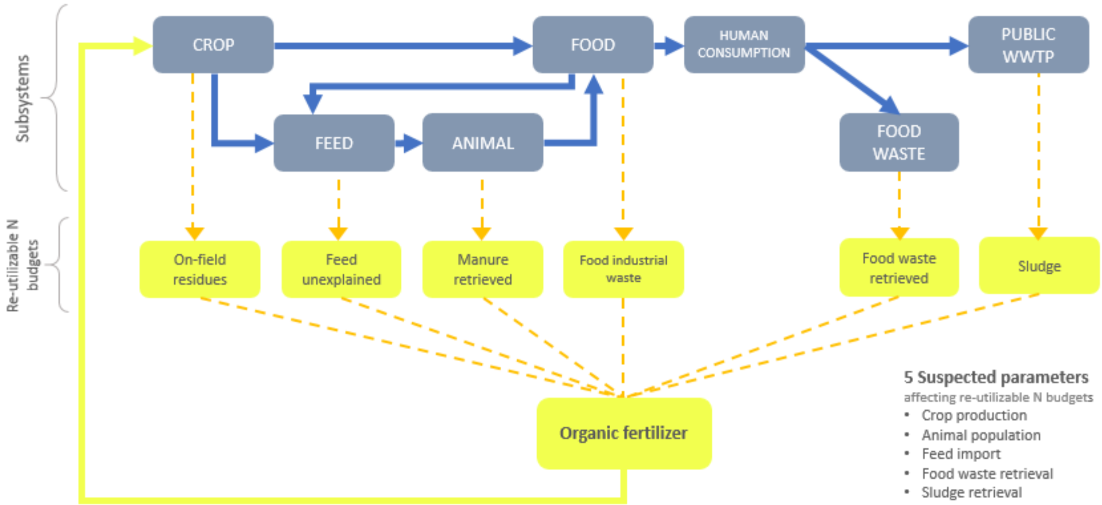


Figure 3 A simplified overview of food production and consumption system

Two approaches in model construction are used to facilitate the completion of flows and minimize the data gap; 1) Top-down; a high-level perspective which represents the flow of the whole country, oftentimes without the data broken down to specific constituents. 2) Bottom-up; a perspective which serves to indicate the source of nitrogen down to the type of materials or its specific pathway in the system. These two approaches are complimentary of each other, albeit not necessarily applicable in all subsystems. They are cross-referenced wherever possible. The details of parameters in top-down and bottom-up approach are elaborated in each subsystem.

1. CROP

About half of Thailand's agricultural area is allocated to rice paddy field. The next 40 percent are equally occupied by upland crops and perennial crops. Leading plants among upland crops are sugarcane, cassava and maize while in perennial crops, no more than 20 percent of land belongs to food production entailing diverse fruit orchards such as longan, durian, mangoesteen, tangerine. The majority of perennial plantation is covered by para rubber around 68% and oil palm 13% (Figure 2-2).

Subsystem CROP concerns cultivation of food crops on the area classified as agricultural land use. On this range of land, the input, output and unaccounted fraction can be structured in equation and diagram as follows;

$$N_{in\_crop} = N_{out\_crop} + N_{unaccounted}$$

$$N_{in\_crop} = N_{syn} + N_{fix} + N_{dep} + N_{irr} + N_{org}$$

$$N_{out\_crop} = N_{crop\_food} + N_{crop\_feed} + N_{crop\_air} + N_{crop\_water} + N_{crop\_onfld}$$

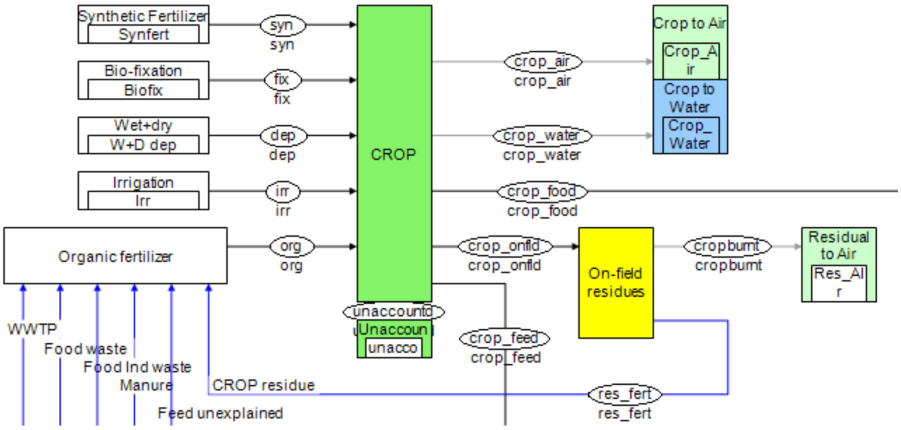


Figure 3-1 Subsystem CROP structure

INPUT

N_{in_crop} includes N inputs to the agricultural land which can be expressed in equation as follows;

$$N_{in\_crop} = N_{syn} + N_{fix} + N_{dep} + N_{irr} + N_{org}$$

Synthetic fertilizer application; N_{syn}

In top-down picture, the national fertilizer use in Thailand is derived from a statistic of synthetic fertilizer import by formula (OAE, 2017). The reported numbers are then calculated for N content and subsequently adjusted by domestic production and export volume (FAO, 2016). Furthermore, the use in non-food crop namely oil palm and para rubber are deducted (Heffer, 2013) resulting in 2014 domestic fertilizer use of 1.2 million tN/yr (Table 3-1). The equation that express this is as follows;

$$N_{syn} = Import\ [tN] + Domestic\ production\ [tN] - Export\ [tN]$$

Bottom-up model provides another perspective by demonstrating how the resource is allocated. Ideally, adding up the value of subcomponents of the bottom-up model should approximately be matching with the top-down model.

The crops included in the bottom-up approach are major crops reported in Office of Agriculture Economic (OAE) yearbook (OAE, 2016) which covers more than 85% of Thai agricultural land use (Table 3-2) and accounts for more than 80% of annual synthetic N fertilizer use.

The information on annual fertilizer use per crop is based on IFA report in 2010 (Heffe, 2013) (Table 3-3). Combined with data on cultivation area in 2010 reported by OAE yearbook (OAE,2011), the annual fertilization application rate per area [kgN/ha.yr] could be derived. This application rate assumed to be the same in 2014. Although the IFA report does not specify crop species in some crop categories, we can confidently say that sugar crops is sugarcane, and roots/tubers crop is cassava due to their huge domination in Thai agriculture. Besides this, by ‘other crops’, para rubber is the only remaining widespread crop that fits this category.

Table 3-1 Quantity of synthetic fertilizer import/export in Thailand

Chosen	List	Unit		Reference
	Fertilizer use in Thailand [tN/yr]	1,311,000		Heffe (2013)
	Oil palm fertilizer use [tN/yr]	41,000		Heffe (2013)
	Other crop fertilizer use [tN/yr] Assumingly, for para rubber mainly	127,000		Heffe (2013)
	Total synthetic fertilizer use for food production [tN/yr]	1,143,000		Based of Heffe (2013)
★	Production Quantity [tN]	90,000		FAO (2016)
	Import Quantity [tN]	1,480,496		FAO (2016)
★	Export Quantity [tN]	49,323		FAO (2016)
	Consumption [tN]	1,521,173		FAO (2016)
	Total synthetic fertilizer use for food production [tN/yr]	1,353,173		Based of FAO (2016) adjusted by Heffe (2013)
★	Import Quantity	1,293,462		OAE (2017)
★	Total synthetic fertilizer use for food production [tN/yr] excluding oil palm and para rubber	1,166,139	±5%	Based on OAE (2017) adjusted by FAO (2016); Heffe (2013)

While several major crop categories are nearly homogeneous in species and have their own report on fertilizer use, other categories such as fruits and vegetables are considerably diverse and lack of a specific fertilizer application data. The representative fruit, longan, and vegetable, garlic, are selected owing to their large share of land use which implies their large N application. It is noteworthy that their cultivation areas are not extremely larger than the next widespread species. These two representative species of fruit and vegetable serve to portray reference information on N flow in biomass. Connecting to the top-down model, these two species are extrapolated for the entire area of fruit and vegetable cultivation to fill the gap of N flow for fruits and vegetables. The equation that express this bottom up approach is as follows;

$$\sum N_{syn} = \sum \textit{Specific fertilizer application rate [kgN/ha.yr]} * \textit{Cultivation area [ha]}$$

Table 3-2 Cultivation area of crops in Thailand in 2014

List	Area [ha]
Rice	11,084,800
Maize	1,157,054
Oil palm	739,400
Sugarcane	1,353,025
Cassava	1,436,138
Fruits	595,375
Vegetables	36,738
Para rubber	49,237

(OAE, 2016)

Table 3-3 Synthetic fertilizer application rate by crop of Thailand in 2010

List	Amount of synthetic fertilizer application [kgN/ha.yr]
Rice	46
Maize	79
Oil palm	63
Sugarcane	129
Cassava	56
Fruits	178
Vegetables	266
Para rubber	40

Heffe (2013)

Human-induced biological nitrogen fixation; N_{fix}

This parameter could be derived from the bottom-up model taking into account the fixation rate per area in different crop species and the area of cultivation. Biological nitrogen fixation (BNF) is notable in rice and sugarcane while in the other crops it is negligible given that cultivation of leguminous crop is negligible in Thailand (Table 3-4). The equation that express this bottom up approach is as follows;

$$\sum N_{fix} = \sum \textit{Specific BNF rate [kgN/ha.yr]} * \textit{Cultivation area [ha]}$$

Table 3-4 Biological fixation rate in by different crops

Biological fixation	min	mid	max	Sources
Rice bio N fixation [kg/ha.crop]	2.9	5.0	10.0	Expert opinion in Schaffner (2007)
Maize bio N fixation [kg/ha.crop]	0.0	0.0	8.0	Schaffner (2007)
Sugarcane bio N fixation [kg/ha.crop]	0.0	10.0	10.0	Ando et al. (2002); Best guess by Schaffner (2007)
Other crops	0.0	0.0	0.0	Schaffner (2007)
Cropping cycle	**min**	**mid**	**max**	**Sources**
Rice cropping frequency [crop/yr]	1.7	2.2	2.7	Dobermann and Fairhurst (2000); Molle et al. (2001); Expert opinion in Scahffner (2007)
Maize cropping frequency [crop/yr]	1.0	1.5	2.0	Expert opinion in Schaffner (2007)
Sugarcane cropping frequency [crop/yr]	1.0	1.0	1.0	Schaffner (2007)

Organic fertilizer; N_{org}

The flow of organic fertilizer serves as an end-point of composted re-utilizable N budget in Thailand. It consists of materials from 6 different origins in food production and consumption system. More detail can be find in Organic fertilizer section (Page 44). Due to the lack of reliable documentation, organic fertilizer is assumed to be applied at the same rate for all crops.

Atmospheric deposition; N_{dep}

The atmospheric deposition is assumed to be the same across Thailand. The selected figure of N deposition is of based on southeast Asian region. A few different figures were used in previous substance flow analysis studies in Thailand but an alternative source which appears to be more robust and most up-to-date was employed (Table 3-5). The equation can be expressed as follows;

$$N_{dep} = Wet{+}dry\ deposition\ rate\ [kgN/ha.yr] * Agricultural\ area\ [ha]$$

Table 3-5 Atmospheric wet and dry deposition rate

Chosen	List [kgN/ha.yr]	min	mid	max	Sources
★	Atmospheric wet+dry N deposition	6.7	9.6	12.4	Dentener et al. (2006)
	Atmospheric wet+dry N deposition	4.8	5.0	5.3	Faerge et al. (2001) as used by Schaffner (2007)
	Atmospheric wet+dry N deposition		15.8		EANET (2008) as used by Leelapanang (2010)
★	Agricultural area in 2014 [ha]		21,987,945		OAE (2015)

OUTPUT

Output form CROP (N_{out_crop}) give rise to two commodity flows which are the objectives of cultivation; to become food for human and feed for animal. The rest are either left on land (N_{crop_onfld}) as crop residue or loss through air (N_{crop_air}) or water (N_{crop_water}). This can be expressed in the following equation;

$$N_{out\_crop} = N_{crop\_food} + N_{crop\_feed} + N_{crop\_air} + N_{crop\_water} + N_{crop\_onfld}$$

Agricultural product for food; N_{crop_food}

The model could only be fulfilled from the bottom-up approach. For simplicity, what is considered in this parameter is a collection of to-be food products in the form as harvested from the field before any processing – as reported in OAE yearbook (OAE, 2016). E.g. pre-milled rice and maize on cob. This is done so as to differentiate the untaken residual left on field and the point-generation of industrial waste from food processing.

The quantity of N carried by agricultural product for food can be expressed by the equation as follows;

$$\sum N_{crop\_food} = \sum Production\ [t] * N\ factor\ [tN/t] + (HI * parts\ removed\ from\ field,\ if\ any\ [t] * N\ factor\ [tN/t])$$

Note that HI stands for Harvest Index, a factor which indicates the ratio of mass of different parts compared to a reference part. All related factors can be found in Table 3-6 and 3-7.

Table 3-6 Nitrogen content in plant parts

Crops	Production[1] [t]	HI[2]	%DW (±10%)	%N (±25%)
Rice[4]				
Paddy	41,161,121	1.00	86.0%	1.7%
Husk		0.23		0.4%
Bran		0.11		7.5%
Broken rice		0.16		1.3%
Full grain rice		0.50		1.3%
Straw		1.00		0.7%
Cassava[5]				
root	30,022,052	1.00	36.0%	0.3%
stem		0.25		1.5%
stocks		0.09		1.1%
leaves		0.09		4.3%
Maize[5]				
Grain	4,729,527	1.00	85.5%	1.5%
Cob		0.18		0.5%
Stem		0.34		0.3%
Leaves		0.37		0.9%
Hull		0.18		0.4%
Sugarcane[5]				
Stem	103,697,005	1.00	33.0%	0.2%
Dry leaves		0.09		0.2%
Top		0.03		1.2%
Crops	Production [t]	HI[3]	%DW (±10%)	%N (±25%)
Longan[6]				
Longan	994,904	1.00		
Meat		0.33	33.3%	0.2%
Peel		0.17	16.5%	0.5%
Branch		0.17	16.5%	0.5%
Seed		0.33	33.3%	0.8%
Garlic[6]				
Garlic	72,109	1.00		
Meat		0.70	70.0%	1.0%
Peel		0.05	5.0%	0.4%
Top		0.25	25.0%	0.4%

[1] OAE(2016)
[2] Harvest index based on dry weight of main product
[3] Harvest index based on fresh weight of main product
[4] Sommart et al. (2014); Champagne et al. (1985)
[5] Sommart et al. (2014); Luanmanee and Paisancharoen (2011)
[6] ESN (2012), USDA (2015)

Table 3-7 Transfer factors of plant parts to different fates

Crops	FOOD	FEED	On-field residues
Rice			
Paddy rice	100%		
Straw		25%	75%
Cassava			
root	100%		
stem			100%
stocks			100%
leaves		25%	75%
Maize			
Grain		100%	
Cob		100%	
Stem		25%	75%
Leaves		25%	75%
Hull		100%	
Sugarcane			
Stem	100%		
Dry leaves			100%
Top		10%	90%
Longan			
Meat	100%		
Peel	100%		
Branch	100%		
Seed	100%		
Garlic			
Garlic meat	100%		
Garlic peel	100%		
Garlic top			100%

Sommart et al. (2014) and Own reasonable guess

Agricultural product for feed; N_{crop_feed}

Similar to agricultural product for food which arises from bottom-up, this flow is calculated and connected to add to the pool of feed based on transfer coefficients used by Division of Livestock Development to estimate the feed availability in Thailand (Sommart et al., 2014) Table 3-6 and 3-7. Included here are destined feed and potential direct feed materials from farmland. This can be expressed as the following equation;

$$\sum N_{crop\_feed} = \sum \text{Feed production, if any } [t] * N \text{ factor } [tN/t] + (HI * \text{parts removed from field } [t] * N \text{ factor } [tN/t])$$

Air emission; N_{crop_air}

There are 4 major forms of gaseous N loss; ammonia (NH3) nitrogen gas (N2), nitrous oxide (N2O) and nitrogen monoxide (NO) which a function of applied fertilizer (Table 3-8). On NH3 and N2O, a general formula which does not differentiates between types of crops but specific to agriculture in Southeast Asian region is chosen (Bouwmann et al. 2002; Bouwmann et al. 2002b). The rate of emission is differed by type of fertilizer used in which we take urea as our representative synthetic fertilizer and employ a global rate for manure organic fertilizer. On N2, Smil (1999) discussed that N2 emission rate ranges between 10-15% of N input of total N applied on a global average.

Table 3-8 Air emission factor of synthetic and organic fertilizer by percentage of total N applied

Gas	Synthetic fertilizer		Organic fertilizer	
	% Emission	±	% Emission	±
NH3	18.00%	10.00%	22.50%	6.50%
N2	12.50%	2.50%	12.50%	2.50%
N2O	1.25%	0.75%	1.25%	0.75%
NO	0.63%	0.38%	0.63%	0.38%

Smil (1999)

Water emission; N_{crop_water}

Soil N can be lost through leaching and runoff. Smil (1999) discussed that the loss occurs to soil N in the form of nitrate (NO_3^-) much more than soil ammonia and for the land receiving fertilizer less than 150 kgN/ha annually, a leaching rate of 10% N fertilizer could be expected. Moreover, the loss tends to be higher for the land treated with manure fertilizer (Table 3-9).

$$N_{crop\_water} = (N_{syn}\,[kgN/ha.yr] * \text{Leaching rate } [\%]) + (N_{org}\,[kgN/ha.yr] * \text{Leaching rate } [\%])$$

Table 3-9 Water emission factor of synthetic and organic fertilizer by percentage of total N applied

Type	NO3 loss by leaching	
	% Emission	±
Synthetic fertilizer	10%	5%
Organic fertilizer	15%	5%

Based on Smil (1999)

On-field residues; N_{crop_onfld}

N in residual left on field refers to N fraction uptake in biomass but is not harvested neither for food nor feed, a balanced term. Assumingly, this part is left to decompose in farmland. The fates of N in on-field residual are to be burnt or to stay on the land. On-field residual is one of re-utilizable N budgets of our interest. The equation that captures the flow of on-field residual is expressed as follows;

$$N_{crop\_onfld} = N_{cropburnt} + N_{res\_fert}$$

The flow can be calculated from the bottom-up approach by the following equation;

$$\sum N_{crop\_onfld} = \sum \text{N uptake by plant } [tN] - (\text{N in food output } [tN] + \text{N in feed output } [tN] + \text{N loss from burning } [tN])$$

N in N_{crop_onfld} of each crop is then converted to average N per mass unit before subtracted by the loss from field burning according to FAOSTAT (2014) in Table 3-10. By doing so, N_{res_fert}, the part that is theoretically returned to soil, can be derived. Subsequently, the remaining residue is regarded as organic fertilizer and assumed to have respective N loss potentials.

Table 3-10 Biomass residue burned in Thailand 2014

List	Biomass burned [tDW]
Rice	5,958,977
Maize	1,131,728
Sugarcane	879,467

FAOSTAT (2016)

UNACCOUNTED NITROGEN

$$N_{unaccounted} = N_{in\_crop} - N_{out\_crop}$$

Unaccounted N ($N_{unaccounted}$) is a balanced term in the highest level of CROP subsystem. It takes into account all the input flows subtracted by all the output. The positive or negative value of this term could reflect an accumulation or lost, respectively, of N stock on agricultural land.

2. FEED

FEED is a conceptual space where destined feeds and byproduct feeds are collected, traded and transferred to ANIMAL. It is a final junction of all feed before being directed to animal production at the farms.

Four flows of Inputs to FEED comprise of 1) CROP products and byproducts, 2) FOOD by-products, 3) imported feed and 4) other feed – fishmeal (Figure 3-2). The summation of these four flows minus export and feed industrial waste becomes domestic feed available. There is no stock in feed because the difference between feed consumed by animals and the available feed is characterized as feed unexplained in this model. The equation that express FEED subsystem is;

$$N_{in\_feed} = N_{out\_feed} + N_{feed\_unexp}$$

$$N_{in\_feed} = N_{crop\_feed} + N_{food\_feed} + N_{imp\_feed} + N_{other\_feed}$$

$$N_{out\_feed} = N_{feed\_ani} + N_{feed\_exp} + N_{feed\_indw} + N_{feed\_unexp}$$

In constructing the flows of FEED component, two main data sources were based on; annual feed demand estimation by Thai Feed Meal Association (TFA, 2014) and a model on feed availability evaluation by Division of Livestock Development (DLD) as mentioned by Sommart et al. (2014). These two sources discuss the same information about quantity of feed albeit from different viewpoints; what might be needed and what exists in Thailand respectively. TFA's is based on the population size of animals while DLD's is based solely on agricultural production. The asymmetry in clarity of data in input and output allows the calculation to be done only in a high level. The gap between input and output is contained in feed unexplained– a re-utilizable N budget of interest in FEED subsystem.

It is noteworthy that forage and grass are not considered in my model due to a high uncertainty and scarcity of reliable source of information. The uncertainty includes, for instance, the unknown status of land used, the number of livestock feeding on, the amount of feed grazed on-site or removed to feed at stables. Furthermore, inclusion of uncertain amount of forage/grass into the feed pool at an unknown on-site grazing factor would complicate the subsequent consideration in organic fertilizer production from feed unexplained.

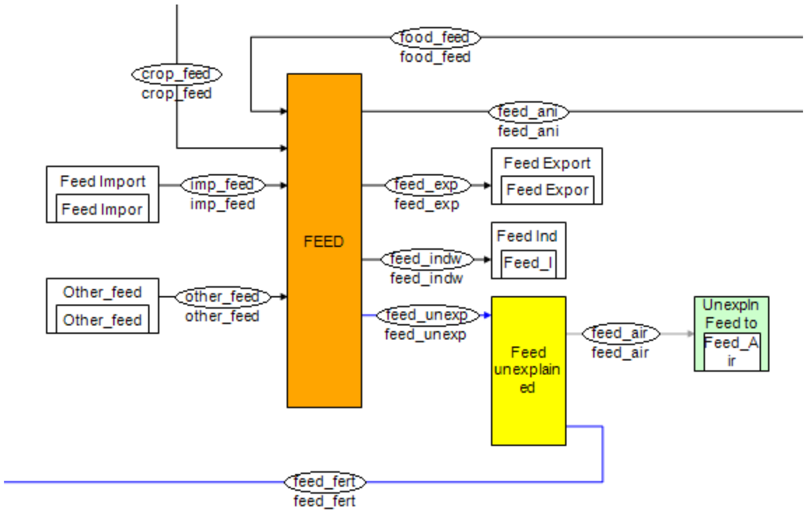


Figure 3-2 Subsystem FEED structure

INPUT

Inputs of FEED (N_{in_feed}) are 1) CROP's destined feed and byproduct, 2) FOOD's byproduct 3) imported feed and 4) other feed.

$$N_{in\_feed} = N_{crop\_feed} + N_{food\_feed} + N_{imp\_feed} + N_{other\_feed}$$

Agricultural product for feed; N_{crop_feed}

See Agricultural product for feed in CROP's output

Food byproduct as feed; N_{food_feed}

See Food byproduct as feed in FOOD's output

Other feed; N_{other_feed}

Other feed includes feed that does not come from both CROP and FOOD. In this study, it refers to fishmeal, a protein rich product from fishery. The amount of fishmeal demand reported by TFA (2014) was used to calculate the fish feed demand per head (Table 3-11). This demand is then multiplied by the actual figure of animal production in 2014 reported by OAE (2016) and calculated for N content (Table 3-12).

Table 3-11 Feed demand and animal population estimation in 2014 by TFA

Livestock	Population [Million]	Feed consumption [t]	Fishmeal [t]	%used	Soymeal [t]	%used	Corn [t]	%used	Broken rice [t]	%used
Broiler	1,350	5,494,500	164,835	3%	1,648,350	30%	3,406,590	62%	-	0%
Parent stock	15	772,632	23,179	3%	193,158	25%	463,579	60%	-	0%
Puller layer	49	927,622	27,829	3%	231,906	25%	556,573	60%	-	0%
Layer duck	51	2,040,000	102,000	5%	510,000	25%	1,122,000	55%	-	0%
Parent layer	1	28,800	864	3%	7,200	25%	17,280	60%	-	0%
Pig	16	4,720,000	141,600	3%	944,000	20%	1,180,000	25%	944,000	20%
Parent pig	1	883,500	44,175	5%	176,700	20%	-	0%	397,575	45%
Duck	32	264,600	15,876	6%	52,920	20%	39,690	15%	92,610	35%
Parent duck	0	22,995	1,380	6%	6,899	30%	2,300	10%	10,348	45%
Layer duck	3	169,000	13,520	8%	25,350	15%	-	0%	67,600	40%
Cow	0.378	620,865	-	0%	31,043	5%	93,130	15%	-	0%
Shrimp [t]	200,000	300,000	60,000	20%	60,000	20%	-	0%	-	0%
Fish [t]	339,600	509,980	50,998	10%	152,994	30%	152,994	30%	-	0%
Total		16,754,494	646,255		4,040,519		7,034,136		1,512,133	

TFA (2014)

Table 3-12 Nitrogen content and dry mass in feed reported by TFA

List	%DW (±10%)	%N (±25%)
Fishmeal	90%	10.6%
Soymeal	91%	7.3%
Maize	87%	1.3%
Broken rice	90%	2.2%

Sommart et al. (2014)

Imported feed; N_{imp_feed}

Data on imported feed is retrieved from OAE import/export statistics (OAE 2015).

$$\sum N_{imp\_feed} = \sum \textit{Import quantity [t/yr]} * \textit{Commodity N content [tN/t]}$$

Table 3-13 Import and export of feed

List	Import [t]	Export [t]
Maize	28,658	631,497
Full soy	1,568,371	-
Soy meal	2,889,223	-

OAE (2015)

OUTPUT

Output from FEED (N_{out_feed}) are the feeds consumed by ANIMAL, feed exported, feed industrial waste and feed unexplained. These can be expressed as the equation below;

$$N_{out\_feed} = N_{feed\_ani} + N_{feed\_exp} + N_{feed\_indw} + N_{feed\_unexp}$$

Feed consumption; N_{feed_ani}

Feed consumption is determined by the population of animal. It is determined by factors elaborated in ANIMAL subsystem. *See* Feed consumption in ANIMAL's input.

Exported feed; N_{feed_exp}

Data on exported feed is retrieved from OAE import/export statistics (OAE 2015) Table 3-13 and N content in Table 3-12. The equation can be expressed as follows;

$$\sum N_{feed\_exp} = \sum \textit{Export quantity [t]} * \textit{Commodity N content [tN/t]}$$

Feed industrial waste; N_{feed_indw}

Feed industrial waste refers to the fractions of destined feed crop that are harvested from field but is not contain in feed products. The equation can be expressed as follows;

$$\sum N_{feed\_indw} = \sum \textit{Feed industrial waste fraction [t]} * \textit{N content [tN/t]}$$

Feed unexplained; N_{feed_unexp}

Feed unexplained captures the difference between feed availability and feed consumption by ANIMAL combined with export. This parameter can only be derived from balancing of the top-down model but could be only partially completed in bottom-up model due to the data gap in Thai Feed Mill Association report (TFA, 2014), as shown in Table 3-11, only 4 types of concentrate feed are reported. The summation of percent feed used for each species is also less than 100% in some species. Moreover, non-concentrate feeds are omitted. The equation for feed unexplained is expressed as the following;

$$N_{feed\_unexp} = \textit{Domestic feed availability [tN] - Feed consumption [tN] – Feed export [tN]}$$

3. ANIMAL

In ANIMAL subsystem, the livestock population of Thailand are taken into account while Fishery and aquaculture are excluded to keep the system boundary manageable within time limit. The output of this subsystem considers animals in live forms for meat animals or animal product in case of layers and dairy cows. Besides the tiny amount of import and export of live animals, the sole input to ANIMAL is animal feed which is calculated based on animal feed demand. The output, apart from animal products, is a large amount of N in manure which is lost, directed to other uses (Fish feed) or retrieved to be made into fertilizer – one of re-utilizable N budgets of interest (Figure 3-3).

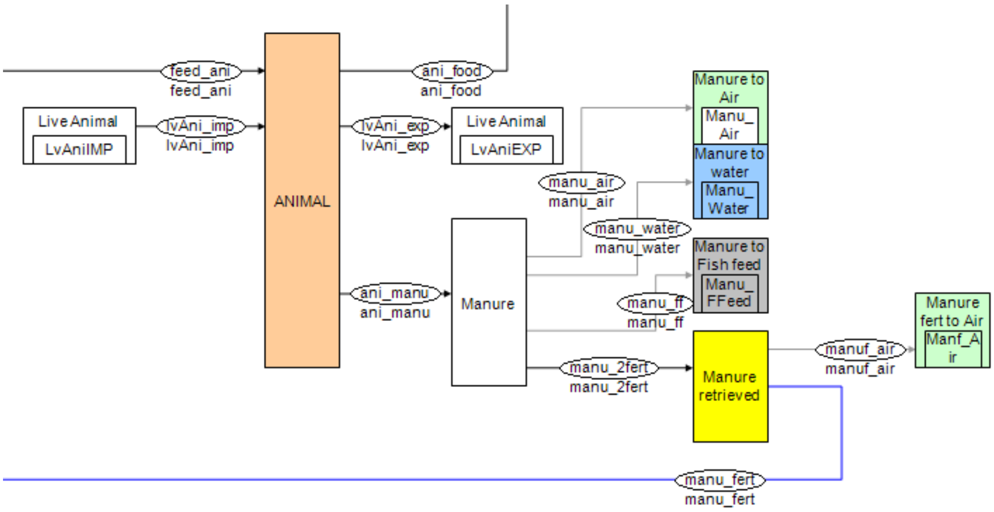


Figure 3-3 Subsystem ANIMAL structure

The equations that express ANIMAL subsystem are;

$$N_{in\_ani} = N_{out\_ani}$$

$$N_{in\_ani} = N_{feed\_ani} + N_{lvAni\_imp}$$

$$N_{out\_ani} = N_{ani\_food} + N_{lvAni\_exp} + N_{manu}$$

INPUT

Inputs for ANIMAL (N_{in_ani}) are animal feed and imported live animals.

$$N_{in\_ani} = N_{feed\_ani} + N_{lvAni\_imp}$$

Animal feed; N_{feed_ani}

According to Figure 2-3, major livestock production of Thailand are chickens and pigs followed by a much smaller extent of cattle. Sommart et al. (2014) illustrated the general farming practice of these livestock as follows. For chickens, both broilers and layers, are raised entirely in intensive farming using compound feed closed to 100%. Pigs are all produced in an intensive system with a feeding ratio of commercial and home-mixed feed of 70:30. Nearly all beef cows are raised in Mixed Crop Livestock System (MCLS) and fed on local available resources such as agricultural residue, agroindustry waste or weed/grass on the roadsides. Dairy cows are raised in an intensive system with concentrate feed and roughage. Half of ducks are raised in an intensive system and another half in semi-intensive system by small holders. Concentrate feed is used in intensive system while in semi-intensive system, a mix of both concentrate feed and local undefined feed is used.

The animal demand of protein, as employed by Division of Livestock Development (DLD), is obtained and converted into N by dividing by 6.25, a generic protein nitrogen factor (Sommart et al., 2014) Table 3-14. Multiplied by animal population reported in OAE yearbook (OAE, 2016), a national N demand for all livestock can be derived. The equation can be expressed as follows;

$$N_{feed\_ani} = \sum \textit{Animal population [head]} * \textit{Protein demand [t/head.yr]}/6.25$$

Table 3-14 Population and daily N demand of livestock

List	Population[1] [head]	N requirement[2] (±10%) [gN/head.day]
Broiler	235,950,423	2.4
Duck	10,212,848	4.6
Pig	7,591,530	47.1
Cattle	4,898,575	50.5
Buffalo	1,020,088	48.0
Dairy	591,642	132.3
Layer	46,230,645	2.7
Layer duck	11,446,647	3.4

[1] OAE (2016)
[2] Sommart et al. (2014)

One should note that the difference in population number in Table 3-11 and Table 3-14 is owed to the reason that Table 3-11 is an estimation with a tendency of misprediction. Furthermore, although lacking clear official description by TFA, Table 3-11 is a likely to be the number of animal production over a year 2014 while in Table 3-14 animal population is reported by animal place, a head count on 1 January 2014.

Live animal import; N_{lvAni_imp}

The figure of Animal imported alive obtained from OAE trade statistics (OAE, 2015) is shown in Table 3-15. These number are then multiplied by N content in the whole animal body to get the amount of N imported (Table 3-16). The equation can be expressed as follows;

$$\sum N_{lvAni\_imp} = \sum \textit{Import quantity [head]} * \textit{Body N content [tN/head]}$$

Table 3-15 Import/export of live animal in 2014

List	Import [head]	Export [head]
Cattle	110,430	232,393
Pigs	-	695,032

OAE (2015)

OUTPUT

Outputs for ANIMAL (N_{out_ani}) are live animals to become food, exported live animals and manure.

$$N_{out\_ani} = N_{ani\_food} + N_{lvAni\_exp} + N_{manu}$$

Animals to become food; N_{ani_food}

While calling this parameter animals to become food, it is not restricted to just live animals before processing but also includes output products such as milk and eggs when it comes to dairy cattle and layer poultry. The information on animal production are obtained from OAE yearbook (OAE, 2016).

$$\sum N_{ani\_food} = \sum \textit{Number of animal output [head]} * \textit{N content in animal body [kgN/head]}$$

To be precise, animal output here refers to amount of animal slaughtered in 2014. The population of animals in the farms are assumed to be stable over year. In case of milk or eggs the unit of *Number of animal production [head]* is adjusted accordingly to eggs and liter of fresh milk – as reported by OAE (Table 3-16).

Table 3-16 Output from ANIMAL and nitrogen content

List	No. Slaughtered or output products[1]	Weight per unit[2] [kg]	N content[3] [%]	Sources[3]
Broiler [head]	1,072,561,102	2	3.04%	Aletor et al. (2000)
Meat duck [head]	18,456,110	3	3.04%	Aletor et al. (2000)
Pig [head]	7,146,861	100	2.63%	Escobar et al. (2002)
Cattle [head]	472,550	350	3.10%	Boniha et al. (2011)
Buffalo [head]	82,610	500	3.10%	Boniha et al. (2011)
Dairy [t fresh milk]	1,111,481	1,033	0.05%	USDA (2015)
Layer chicken [eggs]	12,520,425,000	0.06	1.90%	USDA (2015)
Layer duck [eggs]	2,289,316,000	0.07	1.90%	USDA (2015)

[1] OAE (2016)
[2] OAE (2014c)
[3] Sources are indicated in the adjacent column

Live animal export; N_{lvAni_exp}

Same logic as live animal import (Table 3-15). The equation can be expressed as follows;

$$\sum N_{lvAni\_exp} = \sum \textit{Export quantity [head/yr]} * \textit{Body N content [tN/head]} /6.25$$

Manure; N_{manure}

Animal manure is a balanced term based on an assumption that the animal population is stable. Therefore, the difference between the feed consumption and output product is characterized directly as animal manure. Due to different farming systems, not all manure is generated and retrieved in the captive. Cattle and buffalo outdoor raising is a good example for this. Besides, there are other uses of manure such as biogas production or as fish feed – especially in case of poultry manure (Sommart et al., 2014). Furthermore, losses through direct discharge from farms into the environment is not rare (Schaffner, 2007; Leelapanang, 2011). The transfer factors of manure towards these fates are presented in Table 3-17 aggregated from several studies. The remaining manure for organic fertilizer will be composted before returning to agricultural land which shall be discussed in organic fertilizer section.

Since animal manure is a balanced term between N consumed in feed minus N content in animal body or its products. The equation is expressed by;

$$N_{manu} = N_{in\_ani} - (N_{ani\_food} + N_{lvAni\_exp})$$

The freshly excreted manure has 4 different fates allocated according to specific factors presented in Table 3-17 below. The equation that expresses the manure's fate is;

$$N_{manu} = N_{manu\_air} + N_{manu\_water} + N_{ff} + N_{manu\_2fert}$$

In equation, from left to right, the fates are air emission, water emission, fish feed and manure retrieved for organic fertilizer respectively.

Table 3-17 Transfer factors for N in manure from different livestock categories

List	Air	Water	Fish feed	Manure to fertilizer	Sources
Broiler	0.47	0.70	0.50	0.41	Based on Schaffner (2007)
Pigs	0.47	0.33	0.00	0.20	Based on Leelapanang (2010)
Duck	0.47	0.70	0.50	0.41	Based on Schaffner (2007)
Dairy	0.50	0.25	0.00	0.25	Based on Leelapanang (2010)
Cattle	0.50	0.25	0.00	0.25	Based on Leelapanang (2010)
Buffalo	0.50	0.25	0.00	0.25	Based on Leelapanang (2010)
Layer chicken	0.47	0.70	0.50	0.41	Based on Schaffner (2007)
Layer duck	0.47	0.70	0.50	0.41	Based on Schaffner (2007)

4. FOOD

FOOD is a subsystem in which all agricultural and animal produces are turned in to marketable commodities before being exported (Figure 3-4) or consumed. The imported food products are also considered here adding to the pool of food commodity. The inflows of FOOD from CROP and ANIMAL could be considered as in the forms removed from crop fields or stables as reported in OAE yearbook (OAE, 2016). Rice, for example, is the paddy rice while animals are alive ones except for layers and dairy cow where their products, eggs and milk, are considered instead of heads.

The output from FOOD are export, food byproduct to feed, food industrial waste and food available for domestic consumption. No stock over year is considered. As a conceptual space, there is no accumulation of N in FOOD. This is because while import/export, feed and industrial waste are determined by trade statistic and official definitions, food available for domestic consumption is a balanced term covering the rest of N.

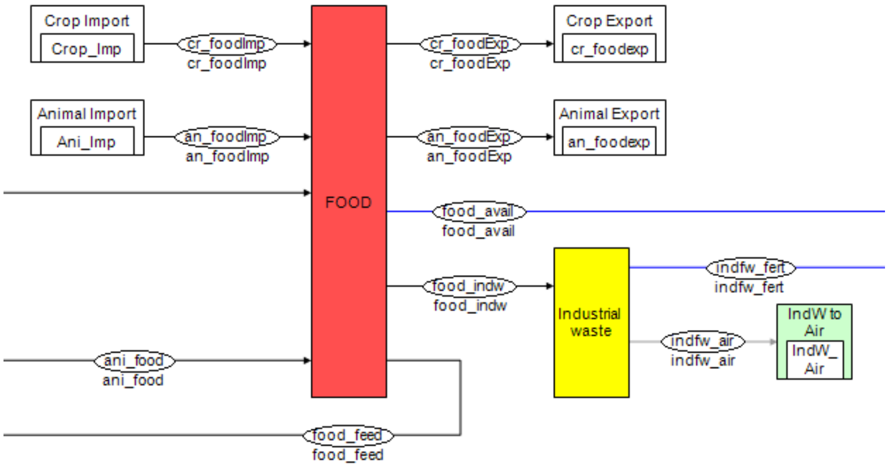


Figure 3-4 Subsystem FOOD structure

The equations that express FOOD system are;

$$N_{in\_food} = N_{out\_food}$$

$$N_{in\_food} = N_{crop\_food} + N_{ani\_food} + N_{imp\_food}$$

$$N_{out\_food} = N_{food\_avail} + N_{food\_feed} + N_{food\_indw} + N_{food\_exp}$$

INPUT

The inputs to FOOD are plant-based output from CROP and animal-based output from ANIMAL. Apart from these two flows of input, food commodities imported are also accounted. The equation can be expressed as follows;

$$N_{in\_food} = N_{crop\_food} + N_{ani\_food} + N_{imp\_food}$$

Agricultural product for food; N_{crop_food}

See Agricultural product for food in CROP's OUTPUT

Animals to become food; N_{ani_food}

See Animals to become food in ANIMAL's OUTPUT

Imported food; N_{imp_food}

Data of imported food products is obtained from OAE statistics (OAE, 2015). For clarity reason, imported foods in the model are divided into animal products and plant-based products as shown in Table 3-18 and 4-20. The equations can be expressed as follows;

$$N_{imp\_food} = N_{cr\_foodImp} + N_{an\_foodImp}$$

$$\sum N_{imp\_food} = \sum \textit{Import quantity [t]} * \textit{Commodity N content [tN/t]}$$

Table 3-18 Animal-based (Top) and plant-based (Bottom) product import and export in 2014

Products	Import quantity[1] [t]	Export quantity[1] [t]	%N in fresh weight[2]
Chicken	-	419,700	2.8%
Pork	21,741	11,441	2.3%
Beef	17,343	7,927	2.5%
Eggs	1,497	11,587	1.9%

[1] OAE (2015) [2]USDA (2015)

Export products	Quantity[1] [t]	Average %N in product[2] [%]	Sources[2]
Rice	10,970,000	1.08%	Based on Champagne et al. (2004)
Cassava products	3,987,194	0.20%	Based on Montagnac et al. (2009)
Longan	565,521	0.86%	Based on ECN (2012); USDA (2015)
Import products	**Quantity[1] [t]**	**Average %N in product[2] [%]**	**Sources[2]**
Soy	329923.67	5.13%	Sommart et al. (2014)

[1]OAE (2015)
[2]Sources are indicated in the adjacent column

OUTPUT

The outputs from FOOD are available food for domestic consumption, byproduct for feed, industrial waste and exported food. The equation can be expressed as follows;

$$N_{out\_food} = N_{food\_avail} + N_{food\_feed} + N_{food\_indw} + N_{food\_exp}$$

Food byproduct for feed; N_{food_feed}

Some food byproducts could be use as feed. This parameter captures these materials that are estimated to be used as feed based on DLD study (Sommart et al., 2014). Combined with the table of nitrogen content in different plant parts, the national food byproducts consumed by animals can be derived (Table 3-19).

Food industrial waste; N_{food_indw}

Food industrial waste, in case of animals, is the parts that are explicitly classified as waste according to OAE's definition (2014c). For CROP products, it refers to parts that do not end up in products and are not taken as FEED according to Division of Livestock Development (DLD) (Sommart et al., 2014). In reality, there could potentially be further uses of these waste materials. However, owing to the lack of documentation, in this study they are all regarded as a substrate for organic fertilizer for simplicity. This food industrial waste is one of the re-utilizable N budgets of interest. The transfer factors for food waste of CROP and ANIMAL inputs are presented in Table 3-19.

Exported food; N_{food_exp}

Data of exported food products is retrieved from OAE statistics as shown in Table 3-18. The equation consisting of plant-based and animal-based products can be expressed as follows;

$$N_{exp\_food} = N_{cr\_foodExp} + N_{an\_foodExp}$$

$$\sum N_{food\_exp} = \sum \text{Export quantity [t/yr]} * \text{Commodity N content [tN/t]}$$

Available food for domestic consumption; N_{food_avail}

From bottom-up, CROP and ANIMAL products are calculated for the fractions which become marketable food based on the table of nitrogen content. This pool of food products is then adjusted for import/export quantity. The remaining part is the available food for domestic consumption (Table 3-19).

$$N_{food\_avail} = N_{in\_food} - (N_{food\_indw} + N_{food\_feed} + N_{food\_exp})$$

Table 3-19 Transfer factors (TF) for food product outputs

List of CROP inputs	TF of N to products		TF of product fates			
			Export	FEED	Industrial waste	Domestic consumption
Paddy rice	1.00					
Rice full grain		0.36	50%			50%
Broken rice		0.12	38%	25%		38%
Bran		0.47		90%	10%	
Husk		0.05			100%	
Fresh cassava root	1.00					
Starch		0.25	70%			30%
Pulp		0.03	50%	50%		
Chip		0.72	70%	30%		
Sugarcane stem	1.00					
Molasse		0.40	50%	50%		
Bagasse		0.60	10%	90%		
Harvested Longan	1.00					
Harvested longan		0.34	95%			5%
Processed longan		0.55	100%			
Longan industrial waste		0.11			100%	
Garlic	1.00					
Garlic		1.00				100%

List of ANIMAL inputs	TF of N to products		TF of product fates			
			Export	FEED	Industrial waste	Domestic consumption
Broiler	1.00					
Marketable products		0.89	18%			82%
Waste		0.11			100%	
Meat duck	1.00					
Marketable products		0.59				
Waste		0.41			100%	
Pig	1.00		1%			99%
Marketable products		0.61				
Waste		0.39			100%	
Cattle	1.00		4%			96%
Marketable products		0.38				
Waste		0.62			100%	
Buffalo	1.00					
Marketable products		0.33				

Waste		0.67			100%	
Fresh milk	1.00					
Marketable products		1.00			100%	
Chicken egg	1.00					
Marketable products		1.00	2%			98%
Duck egg	1.00					
Marketable products		1.00			100%	

Own compilation based on OAE (2014c), Sommart et al. (2014)

5. HUMAN CONSUMPTION

All domestic food available are assumed to be entirely directed towards HUMAN CONSUMPTION. The food is either ingested and comes out in a form of feces and urine (excreta) or thrown away as food waste before being ingested (Figure 3-5). The latter one is the balance of food ingested and total input. The equation can be expressed as follows;

$$N_{in\_hum} = N_{out\_hum}$$

$$N_{in\_hum} = N_{food\_avail}$$

$$N_{out\_hum} = N_{food\_hum} + N_{hum\_fw}$$

Population of Thailand considered in this study refers to those above age 3 due to several reasons, such as, the different diet composition (ACFS, 2016), the relatively smaller diet portion, and the absence in data on nitrogen content of diets (Schouw et al., 2002). The population of Thailand in 2014 as reported by Official Statistics Registration Systems (n.d.) includes 63,954,350 inhabitants. Those lower than the age of 3 constitutes only 3.5% of the population, neglecting this group would not significantly affect the result. Therefore, the population of 61,746,039 is the operational size in this study. Furthermore, the population size is assumed to be constant in terms of number and average individual weight, thus, a stable population with input and output in equilibrium.

While food waste is discarded to the normal solid waste stream, human excreta is almost entirely ends up in on-site septic tank which shall be further elaborated in subsystem PUBLIC WWTP.

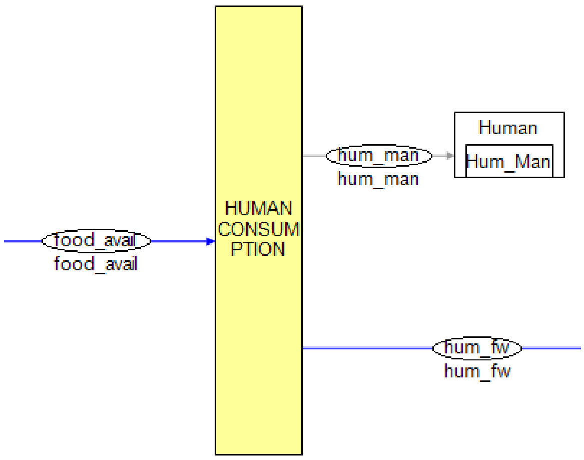


Figure 3-5 Subsystem HUMAN CONSUMPTION structure

INPUT

The input to human consumption is assumed to equal the entire available food for domestic consumption (N_{food_dom}).

$$N_{in\_hum} = N_{food\_dom}$$

Available food for domestic consumption; N_{food_avail}

See Available food for domestic consumption in FOOD's output.

OUTPUT

There are only two possible output flows form human consumption. The available food for domestic consumption is either ingested (N_{food_hum}) and directly becomes excreta ($N_{hum\_excreta}$) or discarded as food waste (N_{hum_fw}) before entering human body. This can be expressed as follows;

$$N_{out\_hum} = N_{food\_hum} + N_{hum\_fw}$$

$$N_{food\_hum} = N_{hum\_excreta}$$

Food ingested by human population; N_{food_hum}

The estimation of N in diet consumed by Thai population is based on N content in excreta studied by Schouw et al., (2002). It was found that Thai population in southern region of Thailand would excrete 7.75 gN/capita.day (±2%). This number is then simply multiplied by operational size of Thai population in this study, 61,746,039 inhabitants. Since a stable population with no accumulation of nutrients is considered, the N in diets consumed is equivalent to the manure excreted. The equations can be expressed as follows;

$$N_{food\_hum} = N_{hum\_excreta} = \textit{N content in manure per capita [kgN/person.yr] * Population [person]}$$

As a cross-reference, Thai Recommended Daily Intake (Thai RDI) and a national diet survey (MPH, 1998; INMU, 2013; Mahidol University and Wagenigen University, 2013) are compared. The Thai RDI of protein is 50 g/person.day. This amount, when converted to nitrogen with a generic 6.25 factor (Maclean et al., 2003), equals 8 gN/person.day. It should be noted that the actual diet may or may not follow this recommendation.

Additionally, the national diet survey in 2016, (ACFS, 2016) combined with a database on nutritional value of Thai food by Institute of Nutrition, Mahidol University (INMU, 2013) and SMILING project (Mahidol University and Wagenigen University, 2013), reveals that the nitrogen in Thai food consumed is approximately 11.4 gN $person^{-1}$ day^{-1} (5.7 – 17.3). The result in source of N in diet is also uncovered in result and discussion comparing with the modelling result in this study.

Food waste; N_{hum_fw}

This parameter is calculated as a balance of available food for domestic consumption which is not ingested.

$$N_{hum\_foodw} = N_{food\_avail} - N_{hum\_excreta}$$

6. FOOD WASTE

The input of FOOD WASTE subsystem is the refused fraction of domestic food available that is not ingested by human. The outputs are retrieved food waste for fertilizer and unretrieved food waste (Figure 3-6). This can be expressed by the following equations;

$$N_{in\_fw} = N_{out\_fw}$$

$$N_{in\_fw} = N_{hum\_fw}$$

$$N_{out\_fw} = N_{fw\_2fert} + N_{fw\_unretv}$$

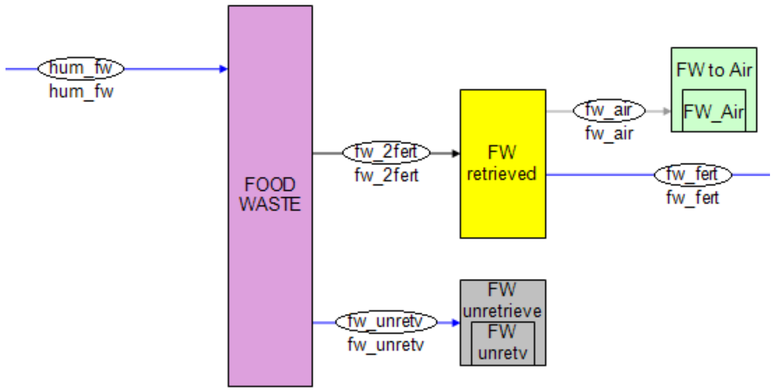


Figure 3-6 Subsystem FOOD WASTE structure

INPUT

Food waste; N_{hum_foodw}

In my modelling, N in of food waste, could simply be derived from the disparity of N in available food for domestic consumption and N in food ingested (See Food waste in HUMAN CONSUMPTION's OUTPUT). The result is then compared to another source of data, a report on solid waste composition by Pollution Control Department (PCD) (Pollution Control Department, 2015).

According to Department of Pollution Control Report (Department of Pollution Control, 2015), in 2014, Thailand generated 26,200 kt of solid waste. Of which, 14,800 kt (54.7%) was mistreated chiefly by open dumping, 7,050 kt (26.9%) was sent to landfill and 4,820 kt (18.4%) was retrieved for further utilization.

Food waste composition in municipal solid waste (MSW) from all regions of Thailand is invariably around 50% (Sajjakulnukit et al., 2005; CCAC, 2015). It is assumed that food waste in MSW is entirely from marketable commodities and no industrial waste. Using food waste N conversion factor by Zhang et al. (2007) and data in Table 3-20, the national N in from food waste is calculated as a reference for the balanced value of the model.

OUTPUT

According to PCD report (2015), food waste in normal waste stream is either retrieved or, otherwise, sent to landfill or open-dump unretrieved.

$$N_{out\_fw} = N_{fw\_2fert} + N_{fw\_unretv}$$

Food waste retrieved for fertilizer; N_{fw_2ferrt}

In MSW statistic, 22% of the retrieved waste (1,070 kt) was turned into organic fertilizer. Additionally, among the waste treated in line with the standard, 600 kt was sent to compost facilities. All in all, 1,130 kt of food waste from municipal source was recovered in total (Table 3-20). Food waste, according to Zhang et al. (2007), has 18% (±8%) dry weight and 3.2% (±0.2%) N content per dry weight. Food waste retrieved for fertilizer is regarded as one of the concerned re-utilizable N budgets.

$$N_{fw\_2fert} = \textit{Amount of food waste generated [t/y] * Percentage of retrieval [\%] * N content of food waste [tN/t]}$$

Unretrieved food waste; N_{fw_unretv}

Obtained by balancing, the untreated food waste is entirely regarded as a loss outside of system boundary.

Table 3-20 Statistics of food waste in Thailand

List	Percentage [%]	Quantity [kt]	Label
Municipal Solid Waste generated	100%	26,200	{1}
Waste mistreated [% of {1}]	56%	14,800	{2}
Waste treated in line with standard [% of {1}]	44%	11,400	{3}
Landfill [% of {3}]	62%	7,050	{4}
Turned into organic fertilizer [% of {4}]	1%	60	{5}
Waste retrieved for utilization [% of {3}]	42%	4,820	{6}
Turned into organic fertilizer [% of {6}]	22%	1,070	{7}
Total food waste turned into organic fertilizer [% of {8}]	9%	1,130	{5+7}
MSW generated	100%	26,200	{1}
Food waste [% of {1}]	50%	13,100	{8}*

(Department of Pollution Control, 2015)
* Based on Sajjakulnukit et al. (2005); Aleluia & Ferrão (2016)

7. PUBLIC WWTP

Wastewater treatment system refers to public wastewater treatment facilities that involves water quality refinement. We consider this subsystem as a broad receiver of N from various sources in a form of wastewater. The fate of N is either being retrieved in sludge or unretrieved which may be in the form of gas or effluent water (Figure 3-7). The equations that capture this subsystem are;

$$N_{in\_sew} = N_{out\_sew}$$

$$N_{in\_sew} = N_{inf\_sew}$$

$$N_{out\_sew} = N_{sew\_sludge} + N_{sew\_unretv}$$

Approximately 98% of Thai population have access to some form of sanitization facility. In 2013, Thai households generated around 10 million m3/day. Of which, around 27% was treated by the wastewater treatment plants across Thailand with a collective capacity of 2.7 million m3/day. Most commonly, the grey water from kitchen, laundry and showering enters the sewer line or canals directly while the black water from toilets ends up in septic tanks in which liquid waste can seep through the soil and enter the sewer line or canals.

The use of on-site septic tank is ubiquitous in both capital and rural area of Thailand even in areas covered by wastewater treatment plant service (Pasda et al., 2006; Boontanon and Buathong, 2013). Myriad factors could affect the availability of N in the influent ranging from the leaching rate of N from the septic tank, distance to sewage system, denitrification of wastewater by microorganisms on the way and addition of N from other sources along the canals. Moreover, inflows of canals and sewer lines could also be undistinguishably originated from other sources apart from households i.e. surface runoff and leaching, road drain, animal farms, slaughterhouses, and industries. Owing to this, the source of N present influent of WWTP cannot be directly identified to come from human manure.

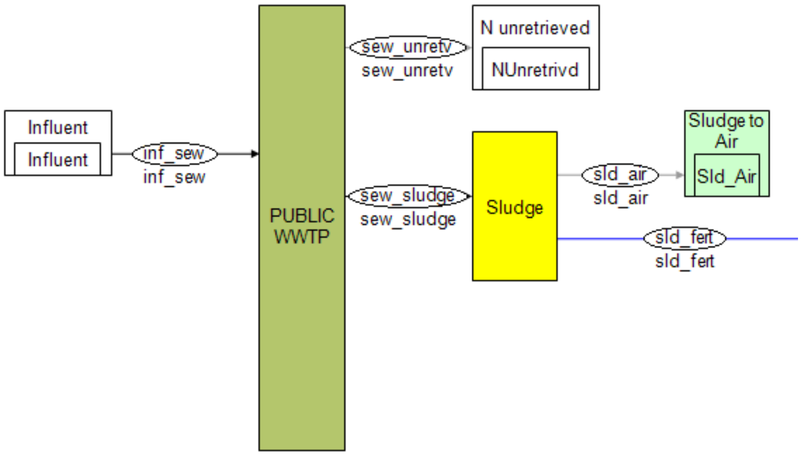


Figure 3-7 Subsystem PUBLIC WWTP structure

INPUT

WWTP influent; N_{sew_inf}

$$N_{in\_sew} = N_{inf\_sew}$$

The influent of WWTP is reversely calculated from N removal efficiency ranging from 5-50% of incoming N (Noopan et al., 2005). In waste water treatment, N is removed in the form of gaseous N losing through air or incorporated by microorganism and settled down in sludge. Lacking clear information on the transfer factor of N in these two fates, a broad N removal efficiency based on statistic of Thailand is taken and assumed that this removed N is all in the form of sludge. This is therefore an underestimation of N in influent water because the fugitive part is not accounted. The equation can be expressed as follows;

$$N_{sew\_inf} = Nitrogen\ in\ sewage\ sludge\ [tN/yr]\ /\ N\ removal\ efficiency\ [\%]$$

OUTPUT

$$N_{out\_sew} = N_{sew\_sludge} + N_{sew\_unretv}$$

Sewage sludge; N_{sew_retv}

Bangkok accounts for around 10% of all wastewater treatment capacity in *Thailand* (Boontanon and Buathong, 2013)*. JICA (1999) estimates that* in *Bangkok in 2010, 168 tDW of sludge would* be generated at public wastewater treatment plants daily. The concentration of N in sludge reported by Pasda et al. (2006) is incorporated to estimate the N in sludge retrieved nationwide (Table 3-21).

$$N_{sew\_retv} = Mass\ of\ sludge\ [tDW/yr]\ *\ N\ content\ of\ sludge\ [tN/tDW]$$

Table 3-21 Information on sewage of Thailand

List	Value	Uncertainty	Sources
Sewage sludge generation in Bangkok [tDW/day]	168	±50%	(JICA, 1999)
Percentage of wastewater received in Bangkok [% of Thailand]	10%	±5%	(Boontanon and Buathong, 2013)
Thai sewage sludge generation [tDM/yr]	613,200	±50%	Calculation.
N content in sludge	2.85%	±0.95%	(Pasda et al., 2006)
N removal efficiency [%]	30%	±24.9%	(Noopan et al., 2005)

Unretrieved sewage N ; N_{sew_loss}

Unretrieved sewage nitrogen is a balanced term of influent minus N retrieved in sewage sludge.

3.3.2 Re-utilizable N budgets and organic fertilizer composting

Once the data in subsystems are fulfilled and re-utilizable N budgets are quantified. These re-utilizable N budgets are then compared to one another before the next step.

In returning re-utilizable N budget to agriculture, the initial materials are assumed to be composted into organic fertilizer during which different rates of N loss are applied depending on the type of material. The factors are listed in Table 3-22. The only form of loss is through air emission. Leaching and run-off are considered negligible.

Table 3-22 Nitrogen loss from composting organic fertilizer by different substrate

Materials	%N loss form Compost	Uncertainty	Sources
Food industrial waste	55%	±10%	Carneiro et al. (2013)
Feed unexplained	55%	±10%	Carneiro et al. (2013)
Animal manure	31%	±11%	Eghball et al. (1997)
Food waste	45%	±25%	Bernstad and la Cour Jansen (2011)
Sewage sludge	20%	±10%	Matsuoka et al. (2006)

The equations that express aerial N loss through composting before returning to cropland are shown below. Note that on-field residue from CROP is not considered as composted but simply left on land. Instead, the loss through air is from biomass burning. Beyond this point, the remaining residue shall be regarded as organic fertilizer and takes on respective N loss potentials.

$$N_{crop\_onfld} = N_{cropburnt} + N_{res\_fert}$$

$$N_{feed\_unexp} = N_{feed\_air} + N_{feed\_fert}$$

$$N_{manu\_2fert} = N_{manuf\_air} + N_{manu\_fert}$$

$$N_{food\_indw} = N_{indfw\_air} + N_{indfw\_fert}$$

$$N_{fw\_2fert} = N_{fw\_air} + N_{fw\_fert}$$

$$N_{sew\_sludge} = N_{sld\_air} + N_{sld\_fert}$$

3.3.3 Sensitivity analysis

As a final step in model development, sensitivity analysis is commonly employed to identify sensitive parameters that are likely to largely affect the outcome of the model. This can be done by selecting sensitive indicator(s) in which the other varied parameters can be tested against. In this study, the indicators of our concern are the six re-utilizable N budgets of Thailand; on-field crop residue, feed unexplained, manure retrieved, food industrial waste, food waste retrieved, sludge retrieved. *See* yellow boxes in Figure 3.

Five sensitive parameter that are suspected to be influential on re-utilizable budget of N are selected covering all six potential areas. These parameters are much likely going to change in the future as the country develops and population grows. Besides, they can be affected by developmental decisions made by political leaders or influenced by market forces. These factors are

1. Crop production [$t.yr^{-1}$]
2. Animal population [heads]
3. Feed import [$t.yr^{-1}$]
4. Food waste retrieval [$t.yr^{-1}$]
5. Sludge retrieval [$t.yr^{-1}$]

Each sensitive parameter is then varied by increasing and decreasing 10% and reinput into the model with all other parameter fixed. Automatic calculation is carried out by the program STAN 2.0. The result of all six re-utilizable N budgets are then analyzed individually for their most sensitive influencer and as a whole.

4. Results and Discussions

4.1 System components in food production and consumption system

4.1.1 CROP

According to the result in Figure 4-1, from top to bottom, synthetic fertilizer is the largest N input followed by about half of its size in organic fertilizer input. The output N is most transferred into N in harvested crops which are further processed into food and feed, air emission and on-field residue. Balancing all inputs and outputs, there is also an unaccounted part which might be regarded as an accumulation of N in CROP system.

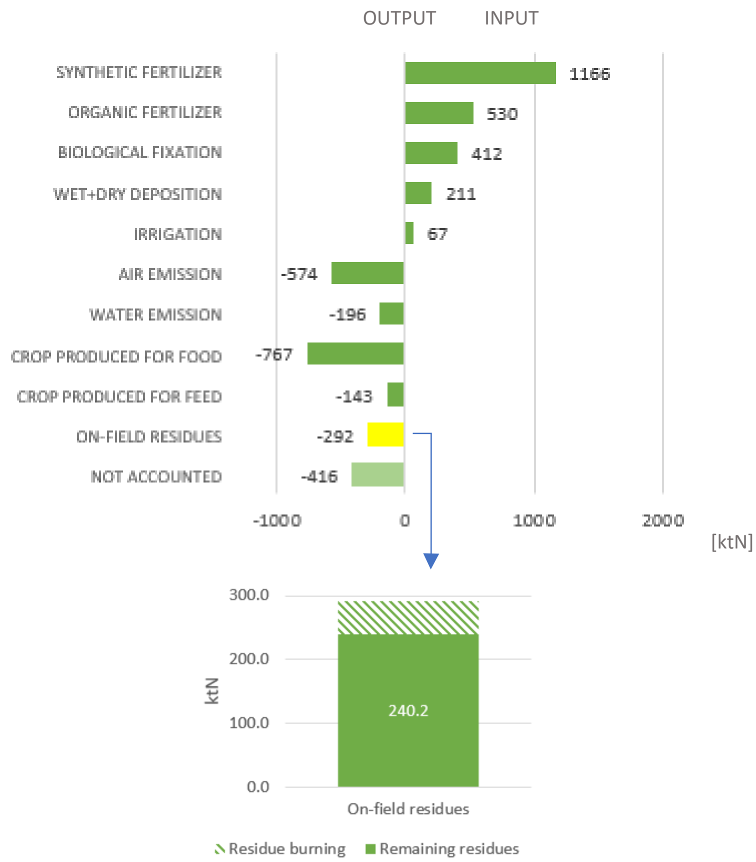


Figure 4-1 Nitrogen flow in Thailand food system – subsystem CROP

Half of synthetic fertilizer is applied to rice, followed by sugarcane (16%), fruits (11%), maize (9%), cassava (8%) and vegetables (6%) respectively (Figure 4-1.1.) Organic fertilizer is the second largest source of N input and is assumed to be equally applied in all crops (See more detail in section Decomposition of re-utilizable N). As a first study in national level, out result reveals that the amount of synthetic fertilizer assumed in previous Thai studies are too high (Schaffner, 2007; Leelapanang, 2010). This is evidenced by when those rates of fertilizer application by crop are extrapolated throughout the country, the amount exceeds N in fertilizer budget. The result appears to disconfirm the general notion that Thai farmers overuse fertilizer than necessary, oftentimes multiple times of suggested quantities (Kesavapitak,n.d.; Arschwanunthakul, 2016). If they do so, it would be clearly conflicting with the imported N budget.

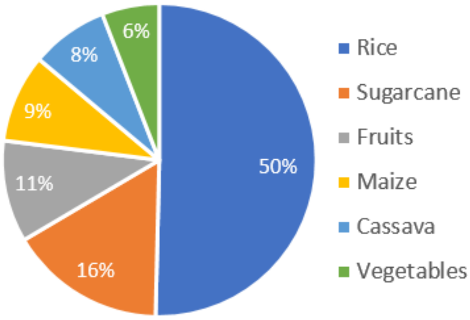


Figure 4-1.1 Share of synthetic fertilizer application by crop

Being the third biggest contribution to crop input, Biological Nitrogen Fixation (BNF) brings atmospheric N2 into use facilitated by soil microorganisms. This large amount is owed mainly to the large cultivation area of rice as well as sugarcane which can fix relatively higher N compared to other non-leguminous crops. The presented number could be an underestimation since the plantation of inter-cropping green manure plants is also becoming more and more in practice. However, due to the lack of reliable documentation, it is excluded from the consideration.

Additional N, around half the size of BNF, comes from wet and dry deposition. A potential closed-loop double counting could be possible here. The source of reactive N in the air may come from air emission of agricultural soil e.g. volatilization of NH3, and NOx in fertilizer applied, which originates from within food production system. The external source such as combustion of fossil fuel in transportation and energy production could also contribute to air reactive N in the form of NOx. Emission from agricultural machineries may take part in this as well but not as major compared to transportation.

Wet deposition of the rain, leaching, runoff or drainage of the land inside or outside of food production system are the source of N in irrigation water. Despite a large area of water-demanding rice cultivation, contribution of N from irrigation turns out to be relatively minor. After all, there are only 26% of paddy land under irrigation.

In terms of output, air emission accounts for a biggest loss of N. Air emission considered here is the fertilizer induced emission where the rate of synthetic and organic fertilizer are different. Organic fertilizer emits more N per unit of N in synthetic fertilizer, particularly by ammonia volatilization. The amount of N loss via fertilizer induced emission is shown in Table 4-1.

Table 4-1 Estimated air emission from synthetic and organic fertilizer.

	Fertilizer application [ktN]	Air Emission [ktN]	NH3 [ktN]	N2 [ktN]	N2O [ktN]	NO [ktN]
Synthetic fertilizer	1,166 ±5%	377±11%	210	146	15	7
Organic fertilizer	530±28%	196±28%	119	66	7	3
SUM	1,696	573	329	212	21	11

Water emission occurred with N foremost in the form of soluble NO3 is estimated to be 196 ktN annually. This value is meant to cover both leaching and run-off. While these phenomena depend largely on specific local condition such as the nature of soil and degree of slope, the same generic leaching rate is considered for all crop. The fact that leaching can be regarded as negligible in paddy field due to the water-tight nature of clay soil (Smil, 1999; Kataki and Babu, 2001, pp.35; Schepers and Raun, 2008, pp. 416) is counterbalanced by the loss through field drainage practiced only in rice (Zhu et al., 2000; Zhao et al., 2009).

The largest N output is transmitted from crop to food corresponding to 767 ktN, chiefly comprising of paddy rice over 80%. Feed output, on the other hand, compares only to one-fifth of the food consisting of maize 50% and rice straw 40% approximately (Table 4-2). The harvest leaves 292 ktN of residues on the field which is the re-utilizable N budget of interest. This resource is burnt after harvest in some areas to facilitate soil preparation for the next crop causing emission mainly in the form of NOx. Sugarcane fields may also be burned before the harvest to eliminate dried leaves making it easier for harvesting. Nonetheless, the lost from burning is relatively low in a big picture compared to other losses.

The remaining residue (unburnt fraction) is practically not an output as it never leaves the field but remains in the top soil. From this point, it is regarded as organic fertilizer in this study and undergone face losing of N similar to other organic fertilizers once applied to the land. There are numerous factors that determine availability of N in soil after biomass application. While no general rate of how much N in crop residues remained after a year was found, many studies supports that in a long-run, amending the soil with biomass leads to a higher yield compared to no treatment and field burning (RIRI, 1984).

Finally, the 'not accounted' part is a balanced term for the gap between identified inputs and outputs. A positive balance of 416 ktN is found from our model suggesting that the accumulation of nitrogen in agricultural sector might be occurring as soil accumulation or biomass of multi-year plants. Additionally, it could also imply that N losses to air and water emission are underestimated. The positive stock in agriculture was also found in MFA study by Leelapanang (2010) with a scope of Chaophraya river delta, Central Thailand. The range is fairly similar, approximately 15% of total input.

All in all, the new reactive N introduced to the system comes from synthetic fertilizer, biological fixation, combustion of fossil fuel and lightning in the atmosphere. Others, such as organic fertilizer, wet & dry deposition and irrigation could be constituted by the recycled N circulating from some point in the system.

Table 4-2 Quantity and share of N in outputs from CROP subsystem

List	Quantity	Internal %	Overall %
CROP to FOOD	[ktN]	[%]	[%]
Paddy rice	629	83	
Cassava root	29	4	
Sugarcane stem	64	8	
Vegetable	28	4	
Fruits	9	1	
SUM	759	100	64
Crop to feed	[ktN]	[%]	[%]
Maize derived	73	52	
Rice straw	57	40	
Cassava derived	10	7	
Sugarcane top	1	1	
SUM	142	100	12
On-field residue	[ktN]	[%]	[%]
Rice	172	60	
Cassava	83	29	
Maize	13	5	
Sugarcane	16	6	
Vegetable	0	0	
SUM	284	100	24
SUM Total uptake	1,185		100

4.1.2 FEED

The modeling result suggests that the largest flow into FEED comes from FOOD byproduct 341 ktN (±19%) accounted particularly by rice bran (80%), followed by imported feed, 316 ktN (±28%), which consists mainly of soymeal (70%) and full soy (30%). The input from CROP, 152 ktN (±31%) consists of maize (51%) and rice straw (40%). On the output side, the animal feed consumed in 2014 was 553 ktN (±4%). Maize was exported for 8 ktN (±25%). The industrial waste generated was mostly in a form of corn cob totaling 3 ktN (±25%). These leave 201 ktN (±40%) of feed unexplained open for nutrient-recycling (Figure 4-2 and Table 4.3).

Thailand relies greatly on import of high quality protein feed. The N from maize, although cultivated on large areas, accounts for only 152 ktN. This is understandable because maize is not a major source of protein like soymeal but rather a high-energy component in feed (Sauvant et al., 2002). Another high-protein, thus N-rich, crop byproduct material that deserves more attention is cassava leaves. This is because Thailand grows cassava as the third largest crop in but the use of its leaves in feed as predicted by DLD is only 25% (Sommart et al., 2014). Broader utilization of this material may ameliorate the need to import soy for protein (Khajarern and Khajarern, 1992; Phuc et al., 1995; Montagnac et al., 2009).

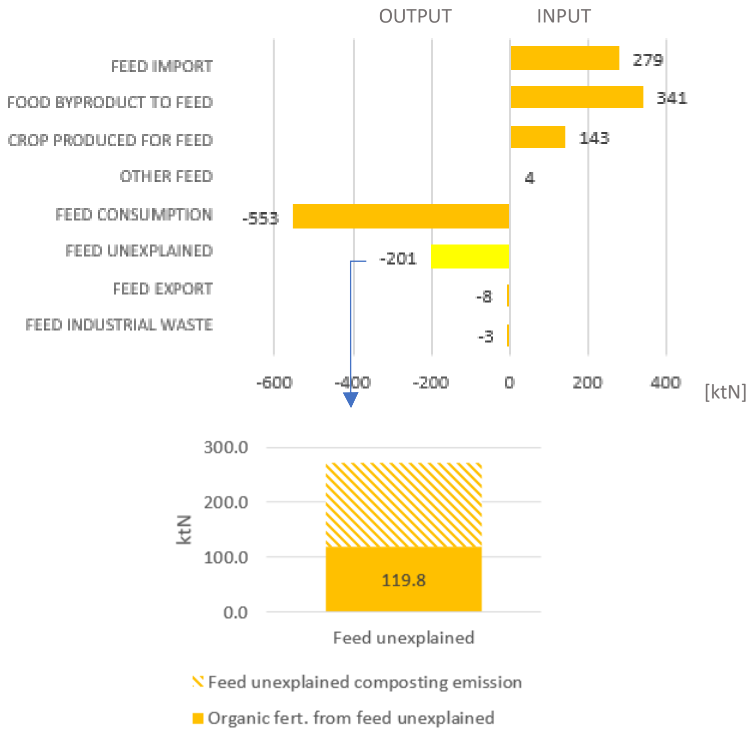


Figure 4-2 Nitrogen flow in Thailand food system – subsystem FEED

Since there will definitely be undocumented alternative uses of the feed unexplained, this estimation is an underestimation. This unexplained feed could be underestimated because forage is not included in our study. In practice, random grazing on road side or unoccupied land is common in beef cow farming. This would result in more availability of the remaining feed unexplained equaling the demand that is fulfilled by this extra feed.

The information on type, quantity and origin of feed are available but their fates, what feed are consumed by what species, are considerably unclear. On the input side, we have trade statistics and transfer coefficients of plant byproducts into feed which specify the materials going into feed pool. On the output side, however, the only reliable source is the feed demand estimation by Thai Feed Mill Association (TFA), which is partially complete shedding the light only on concentrate feed.

It is noteworthy that, in practice, feed composition could vary to a certain extent depending on local availability and price as long as the nutritional requirement is more or less fulfilled. Unfortunately, these are undocumented data which might even be infeasible to collect. This renders the complete tracing of flows implausible. Therefore, rather than finding the full detail, the top-down model offers the best picture we could get on N flow of the feed.

Table 4-3 Quantity and share of N in inputs of FEED subsystem

List	Quantity	% of source	Overall %
Crop to feed	[ktN]	[%]	[%]
Maize derived	73	52	
Rice straw	57	40	
Cassava derived	10	7	
Sugarcane top	1	0.8	
SUM	142	100	19
Food to feed	[ktN]	[%]	[%]
Rice derived	285	84	
Cassava derived	25	7	
Sugarcane derived	20	6	
Soy meal	11	3	
SUM	340	100	45
Other feed	[ktN]	[%]	[%]
Fishmeal	3.5	100	0.5
Import	[ktN]	[%]	[%]
Maize	0.4	0.1	
Full soy	81	30	
Soy meal	192	70	
SUM	272	100	36
SUM Total input	758		100

4.1.3 ANIMAL

The only significant input to ANIMAL is animal feed consumption totaling 551 ktN (±7%) was required for 2014. Import and export of live animals are negligible (Figure 4-3). The output, considered as full body animals or their products here, equals 110 ktN (±5%). The biggest outflow is animal manure accounting for 80% of total input, 439 ktN (±9%).

Chicken accounts for 40% of N consumption but generates 60% of output product to FOOD. Pig, on the other hand, requires almost to 25% of all N demand but produces only 17% of output. Relatively lower conversion efficiency was found for beef cow where 5% of output is generated while consuming up to 15% of N demand.

Due to different farming systems, not all manure is excreted in stables. A rather high recovery rate presents in poultry whereas in ruminants which are raised in non-intensive system, often grazing, the rate is low (Table 3-17). While pigs are also raised in intensive system, the loss via water is quite high compared to others. Regardless, emission through the air is equally around 50% in all livestock in the form of ammonia. Considering these, the portion of manure retrieved for organic fertilizer contributed from each livestock is shown in Table 4-4. The largest quantity of manure can be retrieved form chicken farm followed by pig and beef cow.

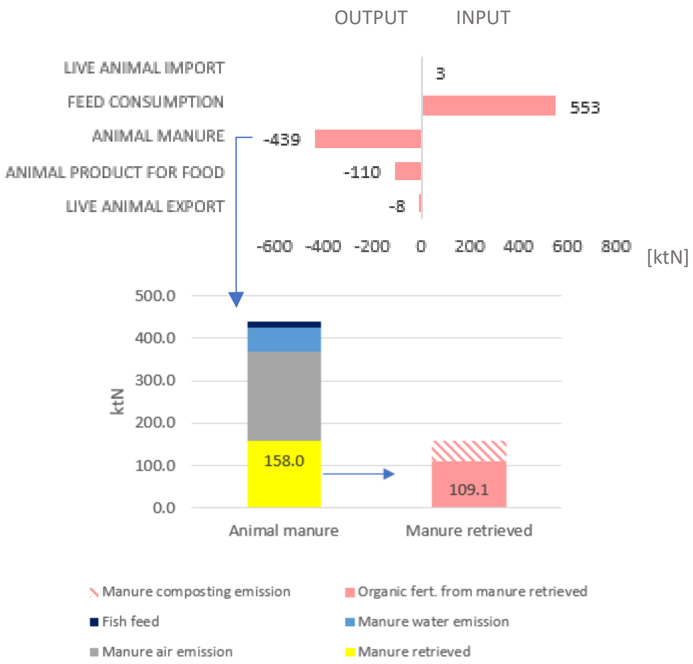


Figure 4-3 Nitrogen flow in Thailand food system – subsystem ANIMAL

Table 4-4 Share of N flows in ANIMAL subsystem by species

	N consumption	Output N	Manure generation	Manure retrieved
Annual flow [ktN] Uncertainty range	551 (±7%)	110 (±5%)	439 (±9%)	156 (±9%)
Accounted by;				
Broiler	38%	59%	32%	37%
Duck	3%	2%	4%	2%
Pig	24%	17%	25%	29%
Cattle	16%	5%	19%	14%
Buffalo	3%	1%	4%	3%
Dairy	5%	1%	6%	4%
Layer	8%	13%	7%	8%
Layer duck	3%	3%	2%	3%
SUM	100%	100%	100%	100%

4.1.4 FOOD

The largest inflow of FOOD comes from CROP, 767 ktN (±32%), consisting of 83% rice (Table 4-2). ANIMAL is the second largest contributor, albeit seven times smaller, adding 109 ktN (±5%) (Table 4-5). Interestingly, the largest outflow of FOOD does not go to HUMAN CONSUMTION but FEED. This is because, when examining the largest inflow from crop, it is rice that carries the most N into FOOD and the most N-rich byproduct of rice is rice bran over which 90% is transferred into feed (Table 4-3).

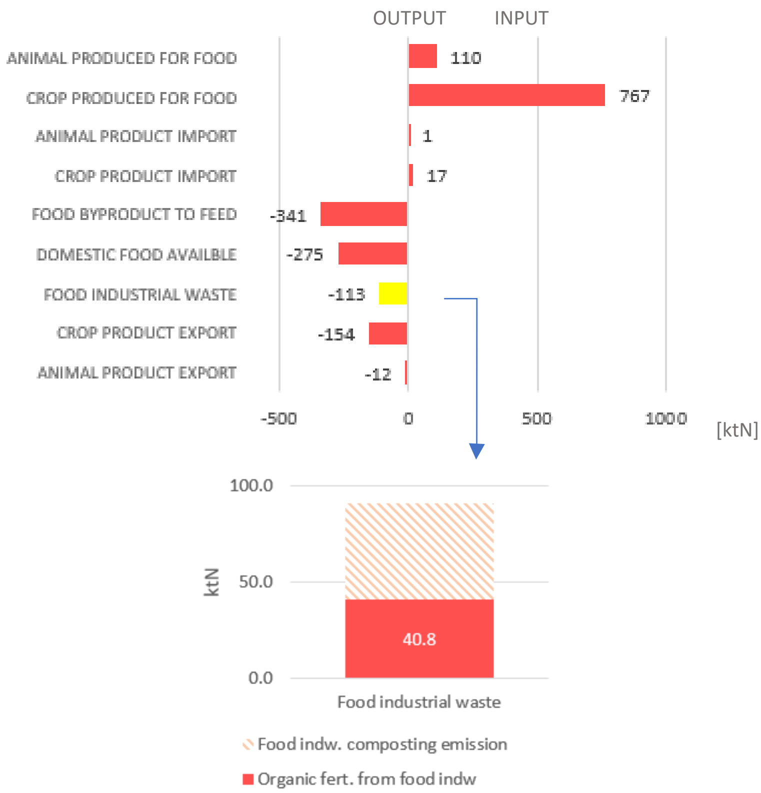


Figure 4-4 Nitrogen flow in Thailand food system – subsystem FOOD

Thailand's small food import is fulfilled by full soy and various processed meat. Despite a large volume of food export from Thailand, N exported is relatively low due to large portion of carbohydrate-based products; milled rice, cassava starch, sugar, for instance (Table 4-5). The majority of N contained in waste and byproducts is extracted and remained within country. Similarly, although N in exported animal products is low, the largest N output from animal production, manure, stays within the country.

Waste from the food industry consists of two parts; crop waste and animal waste totaling 113 ktN (±28%). Crop waste is a large part accounting for 88% compared to animal waste (Table 4-6). This could be an over estimation because no consideration is taken on waste water generated from food processing to keep the highly heterogenous food industry simple. Animal waste are regarded following OAE's definition of waste (OAE, 2014c). This may, however, be a small source of overestimation to regard the entire offal as marketable. For crops, wastes are fractions apparently not present in the marketable product and not taken for feed. Food industrial waste is one of the re-utilizable N budgets which are assumed returned to agriculture.

Finally, domestic food available is the output directed towards human consumption. It is a balanced parameter that remains after regarding all inputs minus outputs. More detail shall be discussed in HUMAN CONSUMPTION (Table 4-7).

Table 4-5 Quantity and share of N in export products

CROP products	Export [ktN]	%Export
Rice	141	92
Cassava	8	5
Fruits	5	32
SUM	154	100
ANIMAL products	Export [ktN]	%Export
Chicken	12	94
Pork	0.3	2
Beef	0.2	2
Eggs	0.2	2
SUM	12	100

Table 4-6 Quantity and share of N in industrial waste generated in FOOD subsystem

List	Quantity	Internal %	Overall %
CROP waste	[ktN]	[%]	[%]
Rice bran	30	22	
Rice husk	33	24	
Cassava undefined	8	6	
Molasses	14	10	
Bagasse	52	38	
Industrial fruits	1	0.5	
SUM	137	100	88
ANIMAL waste	[ktN]	[%]	[%]
Broiler	7	37	
Meat duck	1	4	
Pig	7	39	
Cattle	3	16	
Buffalo	1	4	
SUM	19	100	12
Grand SUM	156	100	100

4.1.5 HUMAN CONSUMPTION

From 275 ktN (±95%) domestic food available (Table 4-7), 175 ktN (±20%) was ingested leaving, around one third or 100 ktN (±264%) as food waste (Figure 4-5). With an assumption that the population is stable, thus, no accumulation of N in the population, N in excreta is rendered equal to N ingested.

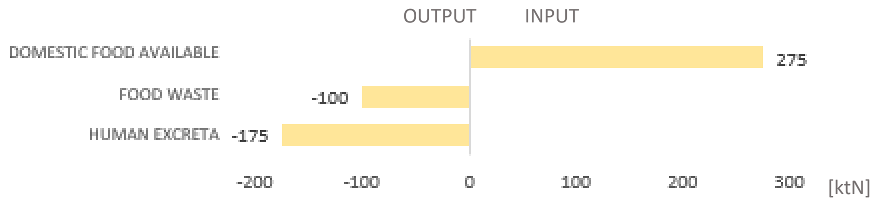


Figure 4-5 Nitrogen flow in Thailand food system – subsystem HUMAN CONSUMPTION

According to our employed value of N content in excretion, so ingestion, of 7.75 ±0.15 gN person^{-1} day^{-1} (Schouw et al., 2002). Similar ranges of number ware found in Thai Recommended Daily Intake (Thai RDI) and a national diet survey (MPH, 1998; INMU, 2013; Mahidol University and Wagenigen University, 2013). The Thai RDI of protein is 50 g day^{-1}. This amount, when converted to nitrogen with a generic 6.25 factor (Maclean et al., 2003), equals 8 gN person^{-1} day^{-1}. It should be noted that the actual diet may or may not follow this recommendation. Moreover, the national diet survey in 2016 (ACFS, 2016) combined with a database on nutritional value of Thai food (INMU, 2013; Mahidol University and Wagenigen University, 2013), reveals that the nitrogen in Thai food consumed is approximately 11.4 gN person^{-1} day^{-1} (5.7 – 17.3 gN).

The source of N consumed in Thai diet resonates with the calculated domestic food available (Figure 4-6 Right). Thai daily diet comprises of two large equal shares of N in rice and animal products, 38% vs 42% respectively. Our bottom-up result shows that N from rice and animal products are on an overlapping range, 140 ktN (±40%) for rice and 91 ktN (±7%) for animal products. This exhibits a possibility that these two foods are be consumed in the same magnitude considering that rice is more likely to be discarded as food waste more than meats or eggs.

Food waste is a balanced term receiving the rest of the food that are not ingested, in out result 35% of the domestic food available. This is higher than the estimated food waste in a study conducted in South and Southeast Asia by FAO (2011) where on average 11 % food waste is generated from distribution to consumption (Table 4-8).

While food waste is discarded to the normal solid waste stream, human excreta almost entirely ends up in on-site septic tank which shall be discussed in PUBLIC WWTP.

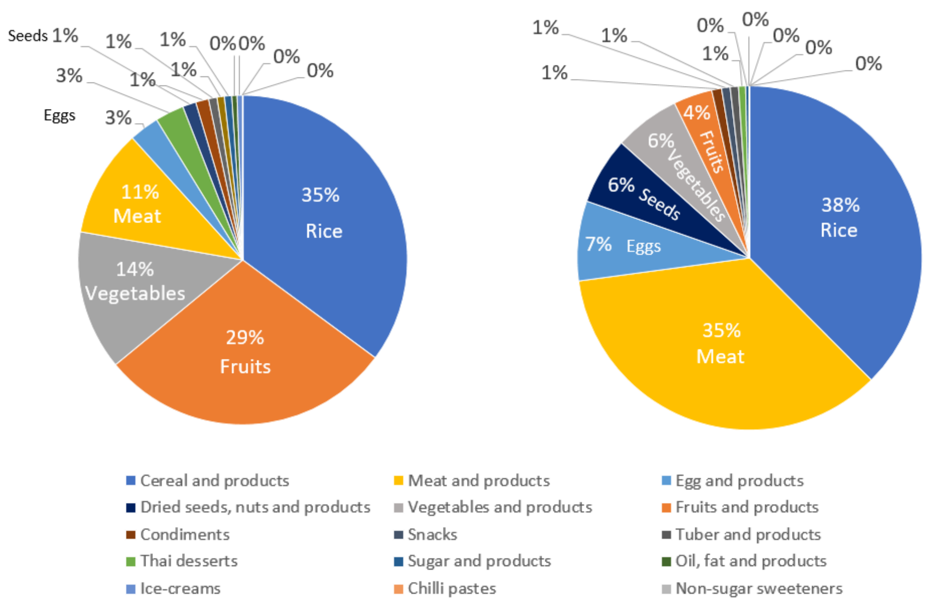
Table 4-7 Quantity and share of N in food available for domestic consumption

List	Quantity	Internal %	Overall %
Animal-based products	[ktN]	[%]	[%]
Chicken	46	59	
Duck	1	1	
Pork	12	15	
Beef	2	3	
Buffalo	0.4	0.5	
Dairy milk	1	0.7	
Chicken eggs	14	18	
Duck eggs	3	4	
SUM	79	100	33
Plant-based products	[ktN]	[%]	[%]
Rice	140	86	
Cassava starch	17	10	
Fruits	0.2	0.1	
Vegetables	0.5	0.3	
Soy products	6	4	
SUM	163	100	67
Grand SUM	242		100

Table 4-8 Estimated/assumed waste percentages for each commodity group in each step of the food supply chain for South and Southeast Asia.

	Agricultural production [%]	Postharvest handling and storage [%]	Processing and packaging [%]	Distribution [%]	Consumption [%]
Cereals	6	7	4	2	3
Roots and tubers	6	19	10	11	3
Oilseeds and pulses	7	12	8	2	1
Fruits and vegetables	15	9	25	10	7
Meat	5	0.3	5	7	4
Fish and sea food	8	6	9	15	2
Milk	4	6	2	10	1

(FAO, 2011)



(ACFS, 2016; INMU, 2013; Mahidol University and Wagenigen University, 2013)

Figure 4-6 Composition of Thai daily diets by weight (Left) and by N content (Right)

4.1.6 FOOD WASTE

The result reveals that around 100 ktN (±265%), of food waste was generated in Thailand (Figure 4-7). Its large uncertainty range maybe explained by the reason that it is a balanced term that is influenced by the large uncertainty range in domestic food available. Despite a mathematical possibility to be negative value, the food waste generated can never be negative in reality.

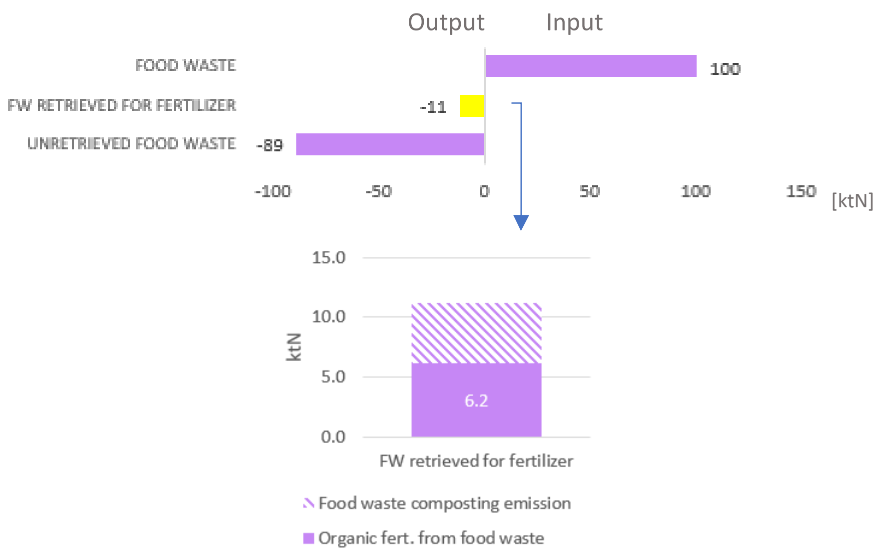


Figure 4-7 Nitrogen flow in Thailand food system – subsystem FOOD WASTE

The result from balancing is in the same range with food waste reported in the Pollution Control Department statistics (PCD, 2015). According to PCD, it could be derived that 13,100 ktons of food waste containing 128 ktN was generated nationwide. Of which, about 10% or 12 ktN (±7%) was recovered and leaving another 116 ktN (±7%) unretrieved. Using our calculated figure but the same transfer coefficient, our model suggests that the N amount recovered was 11 ktN (±27%) and 89 ktN (±27%) unretrieved (Figure 4-7).

While there is no clear measuring protocol provided in the DPC report, this disparity in this estimation and statistic might be owed to the impurity of food waste. If the waste is weighted at the collecting sites, it is very much likely mixed with plastics and all other waste since source separation of food waste is not widely practiced in Thailand.

4.1.7 PUBLIC WWTP

According to Figure 4-8, influent N represents the N received at public waste water treatment plant (WWTP) across country. Unretrieved N comprises of effluent and emission to the air. The difference between influent N and unretrieved N is N retrieved in sludge, the re-utilizable N budget of interest. The result suggests that around 10% of influent N has been retrieved nationwide.

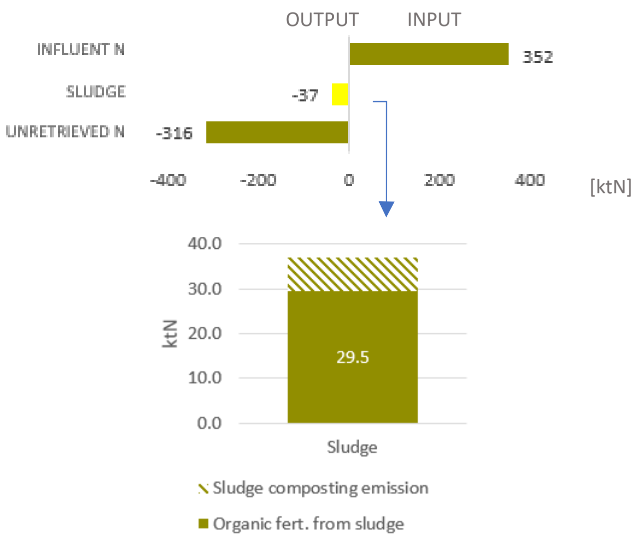


Figure 4-8 Nitrogen flow in Thailand food system – subsystem PUBLC WWTP

There is evidence suggesting that this 37 ktN of sludge retrieved in Thailand is an overestimate. Crucially, it is a highly possible that JICA (1999)'s estimation of sludge generation in Bangkok (168 tDM/yr), a fundamental parameter this calculation is based on, is an overestimation. This was confirmed when comparing to the average N removal efficiency; the average influent N and the volume of water received at public WWTP (Noopan et al. 2005; Boontnon and Buathong, 2013), that there is perhaps not enough N content in the influent to satisfy the equation. Furthermore, the majority of N removed should be in the form of nitrogen gas (Sinsupan et al, 2004). But, the current estimation regards the entire N removal as in the form of sludge (5-50% of influent N) (Noopan et al. 2005). The result could be more realistic if we have a reliable documentation on rate of sludge generation and fate of the removed N.

In Thailand, sewage sludge is commonly dried or incinerated before going to land fill. Otherwise, general usage tends to be directed towards urban landscape fertilization which is primarily for ornamental purpose. The applications in agriculture are also found but quite limited, for example, in public school's small-scale food growing program, or internal food growing plot of the municipality.

More recycling of sludge nutrient in agriculture is being encouraged by the Thai scholars. However, the change in policy to enable this 'public good' to be used more widespread is still largely needed. The current scenario presented in the result is an overestimation that shows the capacity of how much N we might have, given the current N retrieval rate and adjusting just the fate of sludge to solely agriculture.

Pasda et al. (2006) expressed some considerations about application of sewage sludge on agricultural land. The sludge should be heated before to kill the pathogens such as coliform bacteria contaminated in the sludge. This could be done by composting which saves more energy compared to other methods. Furthermore, the level of heavy metals needs to be monitored closely to ensure a safe use of fertilizer.

4.2 Re-utilizable N budget

Throughout seven subsystems, six re-utilizable N budget are identified as listed in Figure 4-9. Their relative importance compared to other flows in can be viewed in Figure 4-1 to 4-8 and Appendix I with these re-utilizable N budgets highlighted in Yellow.

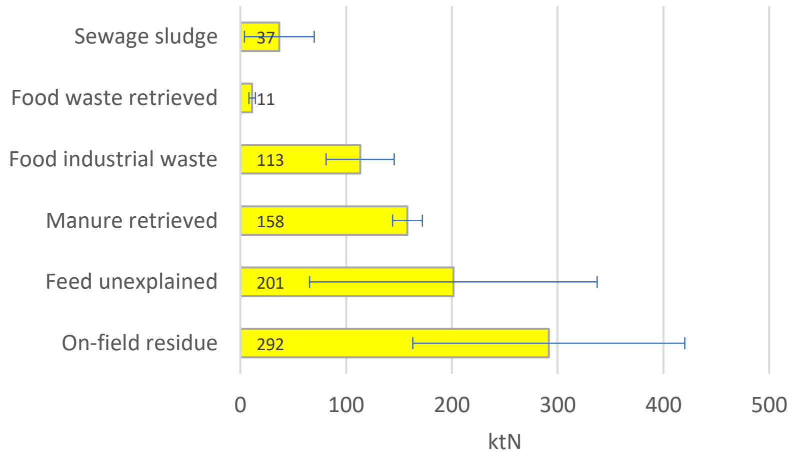


Figure 4-9 Six re-utilizable N budget in Thailand 2014

From bottom to top, on-field residue presents the largest budget followed by feed unexplained, manure retrieved and food industrial waste. Postconsumer, the current retrieval of N is greater in sewage sludge than food waste. All in all, this sums up into 812 ktN (±23%) of re-utilizable N budget of Thailand in 2014.

The result suggests that there is a higher re-utilization of N towards upstream of food production. This might be benefitted by the point-source generation and proximity to agricultural land. The opportunity drops drastically once the N is dissipated when reaching the consumers in the form of marketable products.

On-field residues presents the shortest pathway N is returned to the agriculture. One way to retain maximum use of N in on-field residual is to terminate field burning which not only results in N loss but also the emission of GHGs and particulate matter.

There are multiple factors determining the availability of feed unexplained, from both demand and supply side. Therefore, feed unexplained perhaps should not be relied on as a main source for re-utilization but more as a situational opportunity when the gap between excess supply and low demand arises. From the bottom-up perspective, it is not different form on-field residue only that it is taken out of the field.

The manure retrieved appears to be dependent considerably on animal production activity. However, minimization of manure loss can still play a significant role. In pig farms, for example, a large portion of small and medium farms still have a high rate of emission into water (Kupkanchanakul and Kwonpongsagoon, 2011). N loss may become a small issue compared to the deteriorated water quality and potential eutrophication. Reducing such irresponsible practice by advocating the better alternatives such as biogas production and organic fertilizer composting would have multiple benefits.

Retrieval of N in food waste from municipal waste stream is determined largely by human commitment. If the municipality decides to retrieve more food waste or promote source-separation with full cooperation from inhabitants, there are ten times more food waste possible to be recycled.

Retrieval of N from wastewater, on the other hand, may have technological and economic limitation to remove the entire N. But surely, there is still room for improvement for the current performance of Thai WWTPs. Expansion of waste water treatment capacity to support future population growth will also directly lead to more sludge availability. Efficiency improvement in N removal which favors the retrieval of N in sludge instead of gaseous loss will be beneficial for reutilization of nutrient.

While there might be other alternative uses that give more economic value to materials containing N than directly turning them into compost, it is good to always take into consideration the potential environmental impact of N in terms of greenhouse gas emissions and eutrophication before making the decision. So that we do not loss the opportunity to simply re-utilize N in the agriculture and avoid other externalities.

4.3 Decomposition of re-utilizable N

This section aims to discuss the process of turning re-utilizable N budgets into organic fertilizer. As these sources of N are differed in materials, the composting process can result in different proportion of N loss and remain in organic fertilizer.

As a reminder, crop residues are excluded from the organic fertilizer composting because it is regarded as being left unattended on field in this study. The other five re-utilizable N budgets are undergone decomposition process which has some distinction in the result based on the material. Feed unexplained and food industrial waste are assumed be similar in material in which a study by Carneiro et al. (2013) suggests a 55% N loss (±10%). Animal manure, food waste and sewage sludge decomposition would loss 31% (±11%), 45% (±25%) and 20% (±10%) N respectively (Eghball et al., 1997; Bernstad and la Cour Jansen, 2011; Matsuoka et al., 2006). The result of decomposition is shown in Figure 4-10.

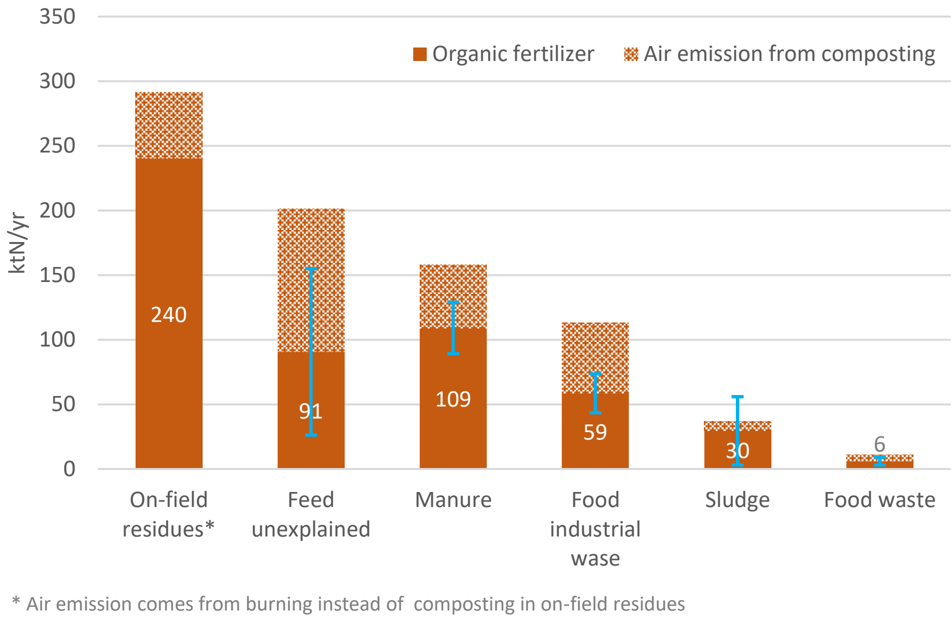


Figure 4-10 Estimated organic fertilizer returned to agriculture from six re-utilizable N budget

During the decomposition, numerous factors could affect the loss of N. These include initial N content, temperature, C/N ratio, substrate material, dry matter content and presence of oxygen (Jansen la Cour et al., 2007). The form of emission is >96% NH3, followed by small amount of N2, N2O respectively (Bernstad and la Cour Jansen, 2011). On food waste in particular, Swedish food waste composting emission rate was employed in this study (Jansen la Cour et al., 2007). However, one should bear in mind that the technology and investment in composting in Sweden is likely to be higher than Thailand, therefore N loss through the air in Thailand could be higher. Moreover, higher temperature in Thai climate can also contribute to a higher loss. As a result, the N remained in food waste composting might be overestimated. Despite this, only 6 ktN (±50%) of organic fertilizer is generated from food waste.

In manure fertilizer production, 31% of total N is lost to the air (Eghball et al., 1997) mainly in the form of ammonia (>90%), and NOx (<5%) (Martins and Dewes, 1992). Frequency in composting pile turning does not significantly affect the loss on N. Emission from leachate and runoff are negligible (Eghball et al., 1997). This results in 109 ktN (±18%) of organic manure fertilizer.

The composting of feed unexplained and industrial food waste would emit 55% N (±10%) into the air. This rate of N loss is perhaps the most representative of all composting because such substrate would hardly ever be composted in isolation. Rather, it is a mixture of various constituents to optimize the C/N ratio, moisture content and other properties. These constituents include manures, high water content food waste or high carbon agricultural residue o sometimes sludge (Carneiro et al., 2013).

The modelling result suggests that 36.9 ktN (±89%) is retrieved nationwide in sewage sludge. Due to a high inorganic N content in sludge, only 20% (±10%) of N is volatized into the air, relatively lower compared to other types of substrate. The sludge composting would generate 29.5 ktN (±90%) of sludge fertilizer nationally.

Ultimately, 530 ktN (±28%) of organic fertilizer plus on-field residue is estimated to be re-utilized in agriculture. Further loss once the organic matter and crop residual are applied on land will occur as reported in Table 3-8. The one way to prevent this N loss to air is to cover such organic matter underneath the soil by incorporating (e.g. ploughing) the material directly after application.

4.4 Sensitivity analysis

The result of sensitivity analysis of six re-utilizable N budget when each five selected parameters are varied by +/- 10% and all others are fixed is shown in Table 4-9. On-field residues is sensitive to agricultural production solely. Linear shift can be found with 10% increase in agricultural production translated into 10% increase in agricultural residue and vice versa. Feed unexplained is influenced by agricultural production, animal population and feed import. While the increase in agricultural production and feed import positively affect the availability of feed unexplained, more animals consumes its budget. Animal population is the parameter that feed unexplained is most sensitive to in negative relationship. As the amount of manure retrieved is a function of manure generated, increase in animal population directly translated to the manure retrieved.

Table 4-9 Sensitivity analysis of selected parameters against six re-utilizable N budgets

Parameters		On-field residues	Feed unexplained	Manure retrieved	Food Industrial waste	Sludge retrieved	Food waste retrieved	%Total Change
Base Case		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Agricultural production	+10%	**+10.0%**	**+6.9%**	0.0%	**+5.4%**	0.0%	0.0%	+6.1%
	-10%	**-10.0%**	**-6.9%**	0.0%	**-5.8%**	0.0%	0.0%	-6.1%
Animal population	+10%	0.0%	**-27.4%**	**+10.1%**	**+1.5%**	0.0%	0.0%	-4.8%
	-10%	0.0%	**+27.4%**	**-10.1%**	**-1.5%**	0.0%	0.0%	+4.8%
Feed import	+10%	0.0%	**+13.9%**	0.0%	0.0%	0.0%	0.0%	+3.5%
	-10%	0.0%	**-13.9%**	0.0%	0.0%	0.0%	0.0%	-3.5%
Food waste retrieval	+10%	0.0%	0.0%	0.0%	0.0%	0.0%	**+9.0%**	+0.1%
	-10%	0.0%	0.0%	0.0%	0.0%	0.0%	**-9.0%**	-0.1%
Sludge retrieval	+10%	0.0%	0.0%	0.0%	0.0%	**+10.0%**	0.0%	+0.5%
	-10%	0.0%	0.0%	0.0%	0.0%	**-10.0%**	0.0%	-0.5%

Food industrial waste consists of waste from crops and animals. The change in these two parameters thus causes the change in food industrial waste volume with agricultural production having a stronger force due to its larger share than animal products. Sludge retrieved is dependent on sedimentation capacity of WWTP. Similarly, food waste retrieved is solely sensitive to food waste recovered volume taken by municipalities.

Zooming out to the total change requires us to take into account the weight of each budget. Figure X illustrate the size of these budgets from largest to the smallest. This rank is displayed in the same order from left to right in Table 4-9 above. The most to least sensitive parameters are sorted from top to bottom. Parameter-wise, agricultural production is the most sensitive parameter in the big picture because of its exclusive influence on on-field residue which accounts for the largest share of all re-utilizable N budget. Animal population is the second most sensitive in a negative way, the higher the number, the less re-utilizable N is available. The rest three parameters are all confined in its power to positively affect its own single area.

When the animal population increases whereas other parameters are fixed, it could be viewed that feed unexplained which acts as a buffer is consumed and converted into manure. The more animal product outcome leads to more industrial food waste. This chain would lead to more domestic food available but since the consumption is fixed it will be translated into more food waste where the flow gets disconnected. The addition of food waste does not lead to higher food waste retrieved because this absolute volume is determined by the municipality. All in all, the change in animal population could bring about change in 3 budgets, feed unexplained, manure retrieved and food industrial waste.

5. Conclusion

A flow diagram of N entailing 6 subsystems; CROP, FEED, ANIMAL, FOOD, HUMAN CONSUMPTION, FOOD WASTE and PUBLIC WWTP, is constructed and used to identify the source, size and reutilization of N in food production and consumption in Thailand. The re-utilizable N budgets identified are 1) on-field residue from CROP, 2) feed unexplained form FEED, 3) Manure retrieved form ANIMAL, 4) food waste retrieved form FOOD WASTE and 5) sludge from PUBLIC WWTP.

In the overview, on-field residual is found to represent the biggest re-utilizable N budget (36%) followed by feed unexplained (25%), animal manure (19%), food industrial waste (14%), sludge (5%) and food waste (1%). This sums up into 812 ktN (±23%) of re-utilizable N budget of Thailand in 2014.

Undergone a dissipative distribution, post-consumption budgets including food waste retrieved and sludge are significantly smaller than the re-utilizable N budgets prior to HUMAN CONSUMPTION. Correspondingly, it can be inferred that the closer to upstream of food production and consumption system the larger stream of N are returned to the agricultural soil.

As a final step, turning these re-utilizable budgets into organic fertilizer (except for on-field residue which is directly left on land) could potentially add up to 530 ktN (±28%) back to agricultural soil. During the composting, 28% (±43%) of N is lost to air chiefly in the form of NH3 (>90%), and minor amount of N2 and N2O.

A sensitivity analysis with five suspected sensitive parameters; crop production, animal population, feed import, food waste retrieval and sludge retrieval; reveals that crop production is the most influential factor to affect the summation of all re-utilizable N budgets. This is due to its cascading connections with on-field residue, feed unexplained and food industrial waste, three of which covering 75% of the entire budget. Since on-field residual accounts for the largest share of all re-utilizable N budget, the factors that affect its pool shall have a high impact too. Besides, crop production is the only one out of five factors that has the impact on on-field residue.

In terms of specific source N in material, rice straw contains 172 ktN (±41%) accounting for 60% of all on-field residue followed by 29% of cassava residue. Among livestock, manure retrieved consists of chicken manure 37% pig manure 29% and beef cow 14%, quite similar to the order of animal prevalence. In feed unexplained, it is unfortunately not possible to decisively identify the material due to unknown consumption of specific feed.

This study is an initial attempt to understand the flow of nitrogen in a big picture of food production and consumption system Thailand. Further research in each subsystem is necessary to gain deeper insights in capacity and practical limitations within certain areas at a higher resolution which would bring Thailand another step closer to sustainability.

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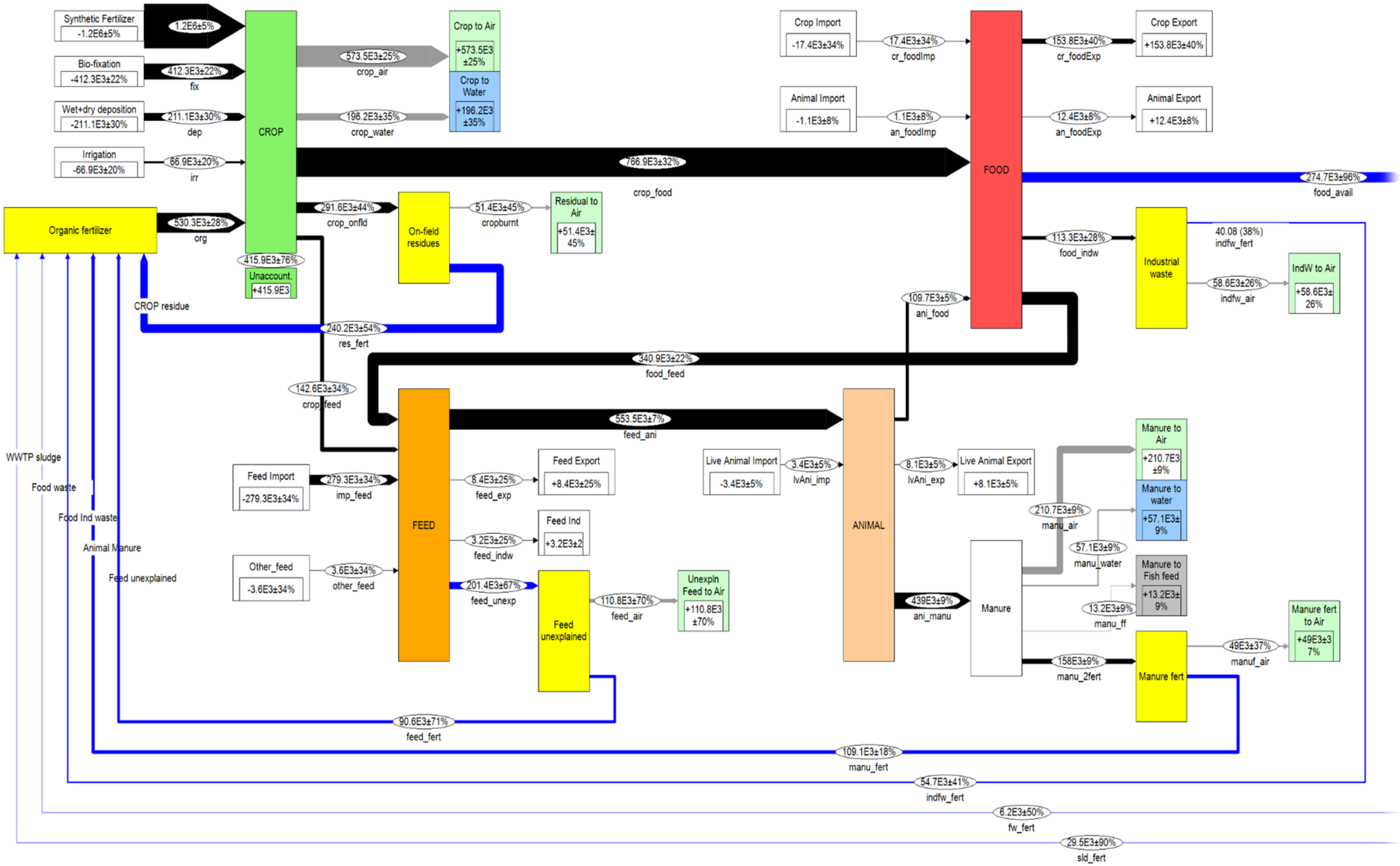
Appendix

Flow diagram of nitrogen in food production and consumption system of Thailand (1/2)



Flow diagram of nitrogen in food production and consumption system of Thailand (2/2)