# *iFarm Student Investigation*

## Welcome to iFarm!

> *Walk into any grocery store, and you will find bananas from Brazil, rice from China, olive oil from Italy, strawberries from Mexico, and more. As we move boatloads and plane loads of food all around the world every day, we are transporting massive amounts of water, nutrients and energy from one continent to the other. As a consequence, we can no longer manage farms on a county-by-county basis or even a country-by-country basis.*

This project gives high school teachers and students the opportunity to partner with our University of Maryland Center for Environmental Science research team to explore and address critical issues of global food-system sustainability. Guided by our team, you will develop and explore computer models using complex real-world datasets to help understand environmental, economic and social dimensions of the sustainability of this global food-system. You will also have the opportunity to share findings with participating students in the US and China and receive guidance and possibly financial support to present at a professional science conference (e.g., American Geophysical Union's annual meeting). The iFarm project is funded by the National Science Association (grant #CNS-1739823).

This document provides general background information and guidance for conducting the iFarm sustainable agriculture investigation. It is divided into two parts:

- Part 1: Foundational elements for conducting this type of research
  - Part 1a: Introduction to sustainable agriculture
  - Part 1b: Nitrogen budget in crop production
  - Part 1c: Key steps of scientific inquiry
  - Part 1d: Key steps of modeling
  - Part 1e: Nitrogen budget database
- Part 2: Practice inquiries applying these foundational elements
  - Part 2a Practice question #1
  - Part 2b Practice question #2
- Part 3: Ideas for your own independent investigations

We recommend that you proceed as follows:

1. Read over the foundational elements sections and associated articles (Part 1).
2. Complete each of the practice questions to gain some experience with these types of inquiries and with the provided nitrogen budget database (Part 2).
3. Building from your practice inquiries, identify a research question for your own independent inquiry on sustainable agriculture using the provided nitrogen budget database. Share this with our team for feedback and support.
4. Develop and run one or more computer model(s) to address your research question, and write up a science paper based on your findings. Share this with our team for feedback and support.


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Our research team, led by Dr. Xin Zhang, will be available to help you via email and at least two video chats (midway and close to the conclusion of your research).

Contact education coordinator Cassie Doty at cdoty@umces.edu with questions or to set up a meeting with Dr. Zhang.

## Part 1: Foundational elements for conducting this type of research

### Part 1a: Introduction to Sustainable Agriculture

Sustainable agriculture requires consideration of multiple factors including economic, social, cultural and environment. For the iFarm investigations, we will focus on the nitrogen budget (inputs and outputs) and impacts on economic and environmental factors. We can use modeling to understand current and future trends and propose possible solutions.

We are providing several articles that will build your understanding of nitrogen and sustainable agriculture. We strongly recommend you read the first set. You might also read the second set to deepen your understanding or as resources for your own independent investigation.

Required Readings

- Managing nitrogen for sustainable development. Zhang, X, Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., and Shen, Y. 2015 Nature (https://www.nature.com/articles/nature15743)
- The environmental and socioeconomic trade-offs of importing crops to meet domestic food demand in China. Huang, G., Yao, G., Zhao, J. Lisk, M.D., Yu C, and Zhang, X. 2019 Environmental Research Letters (https://iopscience.iop.org/article/10.1088/1748-9326/ab3c10)
- Biogeochemistry: A plan for efficient use of nitrogen fertilizers (https://www.nature.com/articles/543322a)
- EPA Sustainability Primer (https://www.epa.gov/sites/production/files/2015-05/documents/sustainability_primer_v7.pdf)

Additional Readings

- The Economic and Environmental Consequences of Implementing Nitrogen-Efficient Technologies and Management Practices in Agriculture - https://www.princeton.edu/~mauzeral/papers/Zhang%20et%20al%202015.pdf
- The global nitrogen cycle in the twenty-first century - http://rstb.royalsocietypublishing.org/content/368/1621/20130164
- A safe operating space for humanity - https://www.nature.com/articles/461472a
- Declining spatial efficiency of global cropland nitrogen allocation - https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GB005515


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- The three pillars of sustainability - http://www.gogreenacademy.com/the-three-pillars-of-sustainability/
- Sustainability and Sustainable Development - http://www.circularecology.com/sustainability-and-sustainable-development.html
- What is sustainable development? - http://www.cepn-paris13.fr/epog/wp-content/uploads/2016/01/CONSOLO_Kates-et-al.pdf
- Multi-indicator sustainability assessment of global food systems - https://www.nature.com/articles/s41467-018-03308-7
- Links between the pillars of sustainable development - http://feaa.ucv.ro/annals/v1_2012/EIB-12.pdf
- Report of the World Commission on Environment and Development: Our Common Future - http://www.un-documents.net/our-common-future.pdf
- Worries grow that climate change will quietly steal nutrients from major food crops - https://www.sciencenews.org/article/nutrition-climate-change-top-science-stories-2017-yir
- Importing food damages domestic environment: Evidence from global soybean trade http://www.pnas.org/content/115/21/5415

## Part 1b: Nitrogen Budget in Crop Production

As noted in the readings, nitrogen (N) plays an important role in crop production. It is often the limiting factor when growing crops but can also be a major environmental pollutant. Therefore, the N budget in crop production is a key aspect of sustainable agriculture.

We established a nitrogen budget database for each country and crop type for 1961-2011. Major N inputs to the cropland include

- fertilizer application ($N_{fer}$)
- manure application ($N_{man}$)
- biological fixation ($N_{fix}$), and
- atmospheric deposition ($N_{dep}$).

Major N outputs from cropland are N in yield ($N_{yield}$), including any part of the crop that is removed from the field.

The difference between the inputs and the outputs is either lost to the environment, or it remains in the soil ($N_{sur}$).

By assuming that over the long term (e.g. over a decade), the average change of N in soil is negligible and is small relative to the annual N input, then we can assume that N surplus ($N_{sur}$) is a reasonable index of N lost to the environment over the long term. It can then be calculated as follows:

$$N_{sur} = N_{fer} + N_{man} + N_{fix} + N_{dep} - N_{yield}$$

The nitrogen use efficiency ($NUE$), sometimes also called the recovery ratio, is defined as

$$NUE = \frac{N_{yield}}{N_{fer} + N_{man} + N_{fix} + N_{dep}}$$


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Given the above definitions, $N_{sur}$, an important measure of the environmental impact of crop production, is determined by two efficiency terms in crop production, namely land use efficiency (i.e., yield) and nitrogen use efficiency:

$$N_{sur} = N_{yield}(\frac{1}{NUE} - 1)$$

For a specific farm with certain technology conditions, the crop yield usually has diminishing returns to N inputs; therefore, increasing yield by adding more nitrogen usually leads to decreasing NUE, resulting in increasing $N_{sur}$ (ref. 1). Increasing NUE while maintaining or increasing yield requires the implementation of new technologies or management practices, which change the yield response to nitrogen input. However, increasing NUE does not always result in lower $N_{sur}$, because the increase in fertilizer use may exceed the increase in crop yield (Equation 1). However, even then, the increase in NUE has the environmental benefit of producing more food per unit of N input and per unit of land, thus feeding more people while sparing land and inputs.

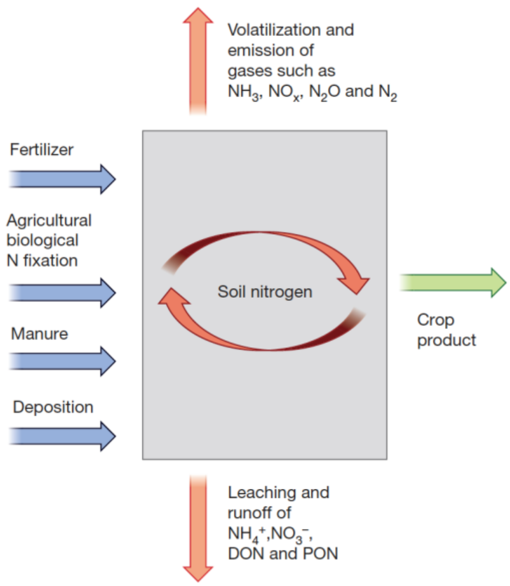


Figure 1 An illustration of the N budget in crop production and resulting N species released to the environment. Inputs to agriculture are shown as blue arrows and harvest output as a green arrow. NUE is defined as the ratio of outputs (green) to inputs (blue) (i.e. NUE = $N_{yield}/N_{input}$). The difference between inputs and outputs is defined as Nsur, which is shown here as orange arrows for N losses to the environment and as N recycling within the soil (grey box) (that is, $N_{sur} = N_{input} - N_{yield}$). Abbreviations: ammonia ($NH_3$), nitrogen oxides ($NO_x$), nitrous oxide ($N_2O$), dinitrogen gas ($N_2$), ammonium ($NH_4^+$), nitrate ($NO_3^-$), dissolved organic nitrogen (DON) and particulate organic nitrogen (PON).

### Part 1c: Key steps of scientific inquiry

For your iFarm project, you will conduct independent scientific research using computer modeling. You will be applying science practices to support your work. These practices are outlined below and pulled from the US Next Generation Science Standards (https://www.nextgenscience.org/).



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- **Asking questions**: This practice is on asking a scientific question that can be empirically tested to explain how the natural and designed world works. You will use the provided information and readings (Parts 1a and 1b), the practice inquiries (Part 2), and your own background and interests to identify a science question about national or global level agricultural sustainability that can be addressed through computer modeling of the provided nitrogen dataset.
- **Planning and carrying out investigations**: This practice involves planning and carrying out investigations in the field, laboratory or on the computer. You will plan and carry out an investigation for your selected research question. You will determine a systematic way to address your research question using a computer model (see Part 1c) and the provided dataset (see Part 1e).
- **Developing and using models**: This practice involves creating models, including computer models, to represent ideas and explanation. You will create a computer model to answer your research question with the provided nitrogen dataset (see Part 1e).
- **Analyzing and interpreting data:** This practice involves analyzing and interpreting data to identify significant features and patterns in data. You will analyze and interpret the results from your computer model to address your scientific question.
- **Engaging in Argument from Evidence and Communicating Information**: This practice involves the process by which explanations are reached, clearly and persuasively communicated, and critiqued by others. You will write up your question, methods, results and interpretation, and share this with the iFarm team. The team and possibly other students will review and provide feedback on your interpretation. You may make some refinements to your interpretation based on these critiques.

## Part 1d: Key steps of modeling

As described above, you will use computer modeling to analyze data for your scientific investigation. You will likely use Matlab, R or Python to develop and run models for the practice inquiries and your own scientific investigation. The practice inquiries will illustrate how you can develop simple computer models for the provided data to answer questions about national- or global-scale sustainable agriculture. Please contact our team if you have any specific questions about the data or modeling.

A computer model usually includes three key components: an information input, an information processor, and an output of expected results. A model could be as simple as a two-parameter linear function (see figure below), or as complex as the Earth System Models that involve a range of complex algorithms and have to be run on a supercomputer.


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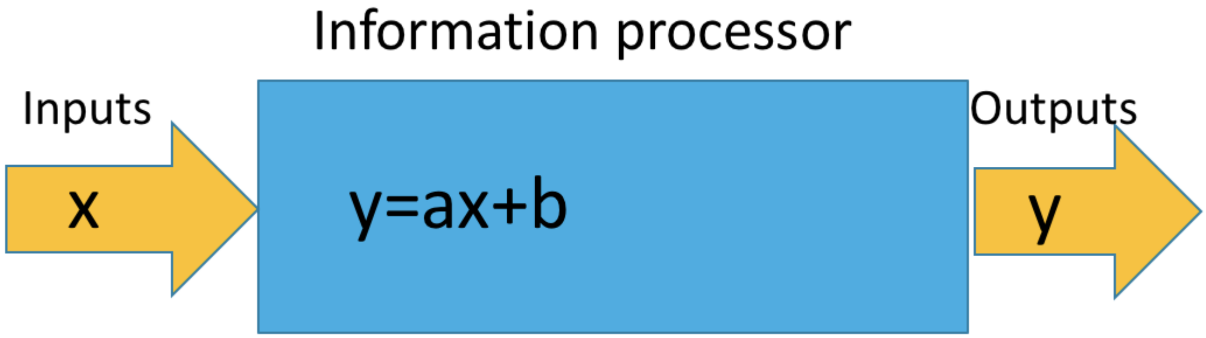


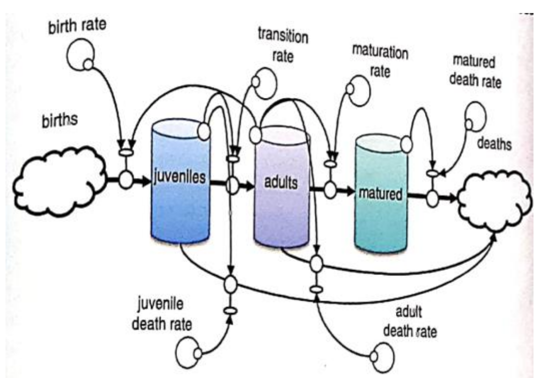

*An illustration of major components of a model with a simple example in which X and Y are the input and output variables, respectively, and a and b are the parameters of the model.*

When you are developing computer models for scientific investigations or other purposes, you should consider the following three steps:

1. Based on the research question, define the system for investigation and its key feature to be represented in the model. For example, if the research question is the impact of our food consumption on nitrogen (N) pollution, the system to model will be food production and consumption, and the key features may include N flows in the system and our consumption patterns.

2. Conceptualize the system by identifying key modeling components (e.g., outputs, system components, inputs). The conceptualization process could be guided by following questions:
   - What will be the key outputs from the model that will answer your research question?
   - What components are critical for determining the outputs, so that it is important to include?
   - What kind of inputs to the model are needed?

Often, it is helpful to use diagrams (see example below) to lay out the major system components and their interconnections for modeling.




*A diagram for a simple population model that considers the population changes in three age groups and the impacts of birth and death rate.*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3. Quantify the linkages among system components/actors. Based on the conceptualized major model components and their interconnections, you may define key variables for each of the components, then design mathematical formulas or statistical analyses to quantify the relationships among these variables.

After a model has been developed, three approaches are recommended for testing the model:

1. Calibration - a process to obtain better agreement between model output and observations by adjusting parameters. The parameters should remain within their uncertainty range.

2. Validation - a process to assess the robustness of the model by comparing the model output to an **independent** observation or estimate.

3. Sensitivity analysis - a test to determine the magnitude of change in the model output in response to changes in model input, initial conditions, or parameters.

## Part 1e: Nitrogen budget database

As mentioned in section 1a, we have created a nitrogen budget database for various countries and various crop types (Table 1). Most data are provided for 1961 to 2015 (note that data through 2011 are included in Zhang et al. 2015 from your *Recommended Readings* in section 1a). However, trade data are only available from 1986 to 2011; so, if your research question includes trade data, you will have a shorter window to investigate.

You will use this provided dataset with your computer model to answer your research question. Note that the database is configured for MATLAB. We can also provide the data in a format that can be modeled using R or Python upon request.

Table 1. Major parameters in the nitrogen database

| **Name** | **Description** | **Unit** | **Dimension** |
|---|---|---|---|
| | ***Definition Objects*** | | |
| **FAOSTAT_CoName_FAO** | country name | | (co) |
| **FAOSTAT_CrName_FAO** | crop name | | (cr) |
| **FAOSTAT_CoCODE_FAO** | country code (FAO) | | (co) |
| **FAOSTAT_CrCODE_FAO** | crop code (FAO) | | (cr) |
| **Yr** | year | | (yr) |
| **cr_group_com** | ID of crops that are commonly used in analysis, excluding crops that do not have data reported in FAOSTAT | | (cr) |
| **Co_ID_group_X** | ID of a group of countries defined in Zhang et al. (2015), excluding countries with small harvested areas or short historical records | | (co) |
| | | | |


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| *Nitrogen Budget in Crop Production* | | | |
|---|---|---|---|
| **Nyield_kgkm** | $N_{yield}$, nitrogen content in crop yield | kg N/km$^2$ | (co, cr, yr) |
| **Nfer_kgkm** | $N_{fer}$, nitrogen fertilization rate | kg N/km$^2$ | (co, cr, yr) |
| **Nman_kgkm** | $N_{man}$, manure application rate | kg N/km$^2$ | (co, cr, yr) |
| **Nfix_kgkm** | $N_{fix}$, nitrogen fixation rate (after adjustment, considering crop rotation, etc.) | kg N/km$^2$ | (co, cr, yr) |
| **Ndep_kgkm** | $N_{dep}$, nitrogen deposition rate | kg N/km$^2$ | (co, cr, yr) |
| **NUE_3d** | *NUE*, nitrogen use efficiency | kg N/kg N | (co, cr, yr) |
| **Nexc_kgkm** | $N_{sur}$, nitrogen lost to the environment | kg N/km$^2$ | (co, cr, yr) |
| **Yield_FAO** | *Yield*, crop yield | kg/km$^2$ | (co, cr, yr) |
| **AreaH_FAO** | *A*, harvested area | km$^2$ | (co, cr, yr) |
| **NfixR_kgkm_HDF** | $N_{fix\_HDF}$, nitrogen fixation rate (original fixation rate by plants | kg N/km$^2$ | (co, cr, yr) |
| ***Trade*** | | | |
| **netImTrade** | *Import*, net import quantity, with coIm as the importing country and coEx as the exporting country | kg | (cr, yr, coIm, coEx) |
| **netImTradeVal** | net import value, with coIm as the importing country and coEx as the exporting country | 1000 US Dollars | (cr, yr, coIm, coEx) |
| ***Other Related Information*** | | | |
| **NC_Bou** | *NC*, nitrogen content in crop | kg N/kg | (cr) |
| **GDPPCAP_WB** | GDP per capita | US Dollar/ person | (co, yr) |
| **Popu_FAO** | Population | # of persons | (co, yr) |
| **Popu_rural_FAO** | Rural population | # of persons | (co, yr) |
| **Pr_Crop_US** | Crop price at farmer's gate (US$2005) | US Dollar/kg crop | (co, cr, yr) |


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## Part 2: Practice inquiries applying these foundational elements

To prepare you for your own independent investigations, we have provided a primer with two practice inquiries. These will help you become familiar with (1) the type of sustainable agricultural research questions you can ask with the provided datasets, (2) the provided datasets, and (3) ways to analyze the data using computer modeling.

Below we guide you through the first practice research question. We do not provide such guidance for the second practice research question; instead, you will adapt and apply the steps from the first question to answer the second one.

After completing the primer, you will be better prepared to design and tackle your own independent investigation. If you need additional ideas, we have provided optional follow-up questions at the end of this primer. These are just ideas; you are not required to complete any of these.

### Part 2a Practice question #1

The first practice question is as follows:
*How much nitrogen pollution will be **added** if **China (a net import country)** has to produce all her crop demand domestically?*

To answer Primer Question #1, you will tackle several sub-questions and associated steps that are listed below.

1.1 How much nitrogen has been lost (or $N_{sur}$) during the crop production in China, and what is the Nitrogen Use Efficiency ($NUE$) in China?

a. Calculate nitrogen lost ($N_{sur}$) and $NUE$ for **rice** production in the year 2010?

$$N_{input} = N_{fer} + N_{man} + N_{fix} + N_{dep}$$
$$N_{sur} = N_{input} - N_{yield}$$
$$NUE = \frac{N_{yield}}{N_{input}}$$

b. Calculate and aggregate $N_{sur}$ and $NUE$ for all crops? Note that *co* denotes country, *cr* is crops, *yr* is year, and *A* is area harvested.

$$N_{sur,co,yr} = \frac{\sum_{cr} (N_{sur,co,cr,yr} * A_{co,cr,yr})}{\sum_{cr} A_{co,cr,yr}}$$

$$NUE_{co,yr} = \frac{\sum_{cr} (N_{yield,co,cr,yr} * A_{co,cr,yr})}{\sum_{cr} (N_{input,co,cr,yr} * A_{co,cr,yr})}$$


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1.2 How much nitrogen embedded in crop products has been imported to China?

a. Calculate nitrogen imported (*NT*) from crop trade products (*Import*) using nitrogen contents for each crop (*NC*), where *coIm* is the importing country and *coEx* is the exporting country.

$$NT_{cr,yr,coIm,coEx} = NC_{cr} * Import_{cr,yr,coIm,coEx}$$

b. Record the net nitrogen imported to China through trade (*netNT_China*) by crop type and year

$$netNT\_China_{cr,yr} = \sum_{coEx} NI_{cr,yr,China,coEx}$$

c. Aggregate net nitrogen input to China through trade for all crop types

$$aggNT\_China_{yr} = \sum_{cr} netNT\_China_{cr,yr}$$

1.3 If the imported crop product will be produced in China with the same Nitrogen Use Efficiency ($NUE$), how much nitrogen input is required and how much nitrogen lost will be associated with this production?

a. Determine the amount of N surplus (*Nsur_China*). Note that the imported N is used as the yield in this scenario

$$Nsur\_China_{cr,yr} = netNT\_China_{cr,yr}((1/NUE_{China,cr,yr})-1)$$

b. Aggregate net nitrogen produced without trade

$$aggNsur\_China_{yr} = \sum_{cr} Nsur\_China_{cr,yr}$$

1.4 (*optional*) What are the potential issues with this method? Hint: Think about crops China might import that it does not produce.

## Part 2b: Practice question #2

The second practice question is as follows:
*How much nitrogen pollution will be* ***reduced/changed*** *if the US* ***(net export country)*** *only has to produce crops for domestic demand?*

As noted, you need to adapt and use the workflow from practice question #1 to address practice question #2.


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## Part 3: Ideas for your own independent investigations

Now you will pursue your own independent research investigation. Your research can come from the readings and your own interest. However, if you are having trouble thinking of a question, below are some suggested questions. Remember you aren't required to use any of these.

- What are the impacts of increasing domestic production on land use? Groundwater depletion? Greenhouse gas emission? Air pollution?
- Which crop types are most polluting? How does the crop mix in domestic production affect N surplus?
- How will shifting the crop demand by changing diet affect N surplus?
- What are the trade-offs between importing crop product and food security (e.g., Self-sufficiency Ratio, stability of the food supply)? What about the impacts on farmer's profit and social welfare?
- What are the socioeconomic drivers (economic development, policy change, diet) for nitrogen pollution or/and nitrogen Use Efficiency change in various countries?

You could also one of the below ideas to inspire your research question.

- Expand questions from the modeling process practice or explore the same questions for other countries.
- Use another country or crop type as a case for investigation (e.g., palm oil, Brazil).
- Consider a dynamic relationship between NUE and crop yield changes during intensification of crop production (Zhang et al., 2015, JEQ) instead of projecting yield and NUE separately.
- Consider the implication of advanced agricultural technologies (e.g., sensor-based precision farming, LED farming) on NUE and/or crop yield.


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