Understanding the Nitrogen Metabolism of Coastal Regions: Cape Cod

An Interactive Qualifying Project

submitted to the faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfilment of the requirements for the

degree of Bachelor of Science

by

Dang K Nguyen

Vincent Boothroyd

Date:

May 3rd, 2024

Report Submitted to:

Harold Walker

Worcester Polytechnic Institute

Table of Content

Abstract

Human interaction and excess release of nitrogen in coastal regions like Cape Cod have led to an imbalance in the cycling of nitrogen. This has created accumulation of nitrogen within the region on a scale that exceeds the environment's capacity leading to damage to the local environment. Some solutions have been proposed but their efficacy is not fully understood.

To better understand the situation and the possible solutions, we have modeled the flow of nitrogen throughout Cape Cod as a network of nodes representing different aspects of the region. We constructed the model by calculating how much nitrogen flows between the nodes from data found in our research and compiling it all into a flow matrix. By using Ecological Network Analysis in the R programming language (enaR), we were able to analyze the network to better understand the nitrogen "metabolism" in the region. In general, a healthy nitrogen metabolism minimizes inputs and outputs and provides for effective cycling within the system.

Our results show that an increase in Innovative/Advanced (I/A) onsite wastewater treatment systems significantly decreases the amount of reactive nitrogen going to the biosphere while increasing the amount of non-reactive nitrogen (N_2) going to the atmosphere.

Increasing I/A systems, however, has little impact on the recovery and cycling of nitrogen in the Cape Cod region. As a result, this intervention does not reduce the inputs of reactive nitrogen to Cape Cod. We also found that an increase in composting on Cape Cod would greatly increase the cycling of nitrogen within the Cape Cod region (the Cape plus areas adjacent to the Cape not modeled in our network). Overall, examining the nitrogen metabolism of coastal regions provides a more holistic perspective of the nitrogen issue in coastal regions like Cape Cod and greater insight into possible solutions.

Introduction

The release of nitrogen to the environment through human activity has surpassed safe planetary boundaries, resulting in eutrophication, harmful algal blooms, and other deleterious effects proven by the UN Environmental Programme (2023). In healthy, natural ecosystems the fixation of nitrogen (conversion of inert, atmospheric nitrogen gas into reactive nitrogen) is balanced by denitrification (conversion of reactive nitrogen back into nitrogen gas). The large-scale fixation of nitrogen in industrial processes and subsequent release to the environment, however, surpasses the denitrification capacity of most ecosystems. While cycling nitrogen in social and ecological systems is critical to understand, we know little about how human activity affects the system.

According to the United States Environmental Protection Agency - EPA (Updated 2023), nitrogen beside phosphorus is a macronutrient that algae need to survive and reproduce and is often the limiting nutrient, especially in coastal waters and estuaries. As a result, nitrogen has become one of the prime suspects for excessive algal bloom events worldwide. The EPA (Update 2023) further stated that too much nitrogen and phosphorus in the water causes algae to grow faster than ecosystems can handle. Significant increases in algae harm water quality, food resources, and habitats, and decrease the oxygen that fish and other aquatic life need to survive.

To understand how excess nitrogen appeared in the first place on Cape Cod, another article from Walton & Gosselin (2020) notes that as the population of Cape Cod grew many new homes were not connected to the centralized sewer system. Instead, these homes utilized various onsite approaches that were not effective at removing nitrogen from wastewater. As a result, the households still using the old septic systems are responsible for 78-81% of the nitrogen load. Thus, nitrogen from homes with conventional septic systems or older technologies are a major source of nitrogen to the coastal waters of Cape Cod.

To address the nitrogen problem on Cape Cod, one option is to utilize Innovative/Alternative (I/A) onsite wastewater treatment systems, as summarized by Gosselin and Walton (2020). This option will reduce nitrogen outputs to the biosphere (e.g., groundwater and coastal estuaries) but their impact on the rest of the nitrogen cycle in the region is less clear. Therefore, further research is needed to understand how nitrogen flows between different segments of Cape Cod (e.g., households, agriculture, industry, etc.) and how various interventions may impact this cycling. A good way to start to understand these flows in Cape Cod is to develop a nitrogen balance for the region. However, constructing a nitrogen balance for Cape Cod is a major challenge given that information on nitrogen flow in the region is scattered.

Once the flows of nitrogen between different segments or compartments in Cape Cod are developed, these flows can be used to construct a network model for the region. With a network model, a more sophisticated analysis of the nitrogen flows between segments or "nodes" can be carried out. This type of network analysis provides information not only on the magnitude of nitrogen flows but also on metrics such as nitrogen cycling in the network, the relationships between nodes, and other measures. These flows and additional measures provide a more holistic understanding of the so-called network "metabolism." This "metabolic" understanding of

nitrogen flows in the network provides insight into the optimal efficiency of nitrogen use within the system.

The research and network model construction for the work presented here was based on an article by Zhang et al., (2016). This paper was a valuable resource for the development of the nitrogen flow matrix for Cape Cod. In short, a group of researchers compiled data related to nitrogen in the city of Beijing and used this data to create formulas to estimate how nitrogen flows through different aspects of the city. Using these formulas, a flow matrix was constructed to represent how nitrogen interacts with the different aspects of the city. In this study of Beijing, important nodes such as industry, atmosphere, and households stand out due to their significant role in the system. They are distinguished by large arrow sizes indicating substantial nitrogen loads passing through them. As for the color, green indicates organic segmentation and yellow indicates urban segmentation.
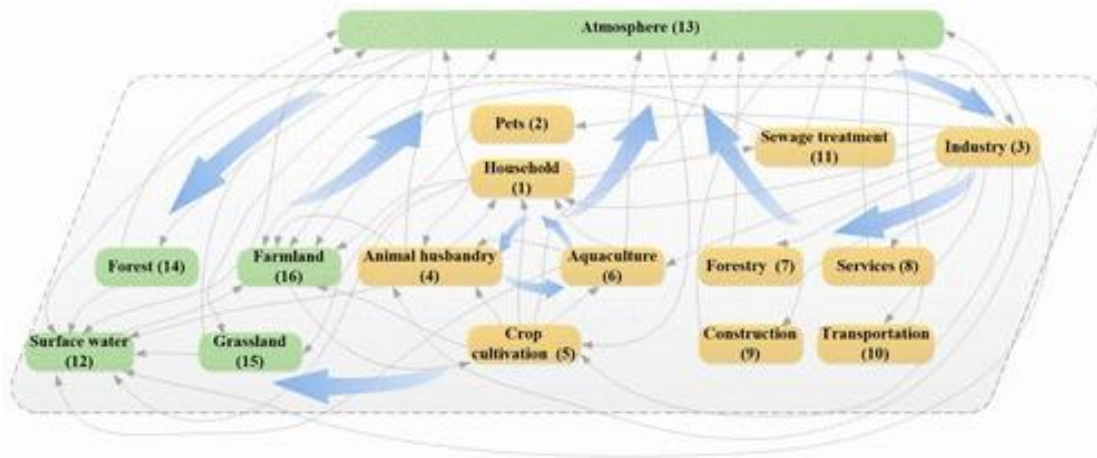

Figure 1.1 - *The depiction of the nitrogen flow chart of Beijing from the article by Zhang et al., (2016)*

The methodology in calculating the flows in **Figure 1.1** involved creating nodes to represent aspects of the city where high amounts of nitrogen exist, and developing equations to represent how much nitrogen flows between each of the individual nodes and putting it together in a matrix to model the entire flow of nitrogen in the city. For instance:

$$D10 \times P8 \times P9_{cm}$$

Equation 1.1 - *The equations to determine the direct flow from node 3 to node 1 of the Nitrogen Network from Figure 1.1*

Equation 1.1 is the flow of nitrogen from node 3 (Industry) to node 1 (Households) from chemical materials. The parameters are different values used to calculate the flow. D10 is the human population, P8 is the industrial nitrogen flux per capita, and $P9_{cm}$ is the assumed local production of chemical materials. The product of the parameters is an estimation of the flow of nitrogen between the nodes. This equation represents only a single flow between two nodes in the model. Additional equations are then developed to represent all the flows in the network. All these flows are then organized into a "flow matrix."Using the network model and flows for Beijing, the authors characterized the metabolism of the city as the usage of nitrogen increased.

The main finding from this article by Zhang et al., (2016) discovered that the high consumption of protein by the residents, the demand for animal feed, and the high usage of fossil fuels were the main causes of the excessive amount of nitrogen released into the environment. This article demonstrated how ecological network analysis can provide important insights into the flow of an element (nitrogen in this case) through an urban system. These insights can then guide the management of that element to control the imprint on environmental impacts.

Objective

Due to the effectiveness concluded by the nitrogen network model of Beijing, the objective of this Interactive Qualifying Project (IQP) is to develop a network model of Cape Cod to evaluate the nitrogen metabolism in this coastal region. Once the model has been developed, several future scenarios (e.g., greater centralized wastewater treatment, expansion of I/A onsite nitrogen removing systems, greater collection of organic waste, and composting) will be analyzed to characterize their impact on nitrogen metabolism.

Methodology

Following this project's objective, three sections of the methodology are involved which align with each other. The methods included:

Data gathering: As mentioned above, the collection of data for use in calculating the flows between all nodes in an urban network is challenging. Significant research was carried out to identify data sets on the demographics of residents, businesses, industry, agricultural, and waste management on Cape Cod as it relates to nitrogen. This data is not in a single database, so this activity was labor-intensive. In some cases, data was not available, and assumptions were made.

Nitrogen flow: Once enough reasonable evidence was gathered, the research data was used to calculate nitrogen flows between various nodes. The matrices were put together and drawn as flow charts. The flow networks were used to create visualizations of different scenarios.

ENAR analysis: Once the flow network was completed, the metabolism of the network was determined using Ecological Network Analysis in the R programming language (so-called enaR). This method utilizes the R programming platform with the library packages of enaR to produce the network model. This library is used to provide further details of flow cycles, by calculating different network analysis metrics. Another expectation from the enaR experiment is that once the flow chart is fully developed, the method can potentially apply to other regions, not just Cape Cod.

Data gathering

To create the model, we collected data that gave insight into how nitrogen moves through Cape Cod. We collected general demographic data such as the population and the number of households. We also investigated the nitrogen concentration of many of the actual substances that were traveling through Cape Cod, such as the concentration of nitrogen in organic waste. For some calculations, we looked for more general numbers like averages. For example, when calculating the flow of nitrogen from municipal solid waste, we used an average of 36% of municipal solid waste in Cape Cod is organic waste to calculate some of the flows.

Most of the research was focused on three major ways that nitrogen travels through Cape Cod: wastewater systems, fertilizer use, and municipal solid waste.

For wastewater systems, we looked at three different types of systems: wastewater treatment plants, conventional septic systems, and new innovative/alternative (I/A) systems, focusing on the latter two since typical septic systems are the most prevalent. We examined how many households used each type of system and how much nitrogen was processed by them to see the amounts that went into the atmosphere and the biosphere.

For fertilizer use on Cape Cod, we examined the amounts of fertilizer used by households and non-residential properties and the concentration of nitrogen within the fertilizer.

For municipal solid waste, we investigated how much solid waste was produced by people in Cape Cod and noticed that most of it was shipped out of the region. However, a small fraction of it (mostly yard waste) was composted and used on Cape Cod.

Nitrogen Flow

After the data gathering process, all the data was compiled together in a spreadsheet to estimate the flows between each node of the flow matrix. To calculate the data needed for the network model, we used a mix of assumptions and data collected from the articles. For example, we assume that the average household contains 2.1 people. In the end, the calculation amounted to a rough estimation as to how nitrogen would flow independently between different nodes. We added these calculations to R files to prepare them to be used in the flow matrix.

An example of how we calculated a flow for the matrix is:

$$HHtoSep = (SepHH * pplPerHH * sewPerP * 365 * nConc * 10^{(-9)});$$

Equation 2.1 - *depicts the formula to determine the direct flow from the node house to septic of the Nitrogen Network*

From the example above, we use many different constants in the code to organize our code. SepHH represents the number of households that use traditional septic systems, pplPerHH represents the number of people per household, sewPerP represents the amount of sewage each person produces per day, and nConc represents the concentration of nitrogen in sewage. The value being calculated, HHtoSep, represents the value of the flow from households to traditional septic systems. We take the product of all the constants and 365 representing days in the year to get the flow in milligrams per year. We then multiply it by $10^{(-9)}$ to convert it to Tonnes per year to get our final flow.

The comprehensive summary of all the calculations used to determine the flows and sources of our data is detailed in Appendix A. For easy reference, all the R code for the analysis is compiled in Appendix B.

Scenarios

In this project, 5 different scenarios were analyzed. Scenario 1 represented the status quo or current situation based on the best available data and reasonable assumptions where data were not available. Scenario 2 assumes all households compost their organic material at maximum capacity. Scenario 3 represents 100% of households using septic systems are using the I/A systems. Scenario 4 represents 50% of the households using septic systems use conventional systems and the rest use I/A systems. Scenario 5 represents a scenario where 100% of households using septic systems are using the I/A systems and all households are composting all their organic waste.

ENAR analysis

To analyze the network model and scenarios we created above, we used R and the enaR library. This library allowed us to do a more in-depth analysis of the network model. While doing our analysis, we focused on certain metrics:

Total system throughflow (TST) is the sum of all flows within the system, excluding inputs and outputs. This gives a scope of how much nitrogen movement there is within Cape Cod. In general, greater TST represents greater utilization of nitrogen within the network.

Total system throughput (TSTp) is the sum of all flows within the system, including the inputs and outputs. Similarly to total system throughflow, this gives us a good understanding of the nitrogen movement including its entrance and exit from the system within Cape Cod. Since the amount of nitrogen total between the scenarios does not actually change, this metric stays the same between all scenarios.

Finn's cycling index (FCI) is a ratio that represents the amount of nitrogen cycling between nodes compared to the throughflow. This allows us to get a grasp of the amount of nitrogen being recycled within Cape Cod. Greater recycling reflects more effective utilization of nitrogen within the network and potentially reduces the need for nitrogen inputs to the region.

Ascendency (ASC) is an index used to represent how well the network can resist disturbances.

Results

Scenario Flow Matrices

Scenario 1:

For this scenario, the flows were determined based on the following data and/or assumptions:

Households using Septic Systems = 70,000

Households using I/A Systems = 2,300

Percent of households composting = 28%

y/x	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Household	0.00	0.00	885	29.1	236	261	0.00	81.8
Non-Residential	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35.8
Septic	0.00	0.00	0.00	0.00	0.00	0.00	338	547
I/A	0.00	0.00	0.00	0.00	0.00	0.00	19	10
Compost	391	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WWTP	0.00	0.00	0.00	0.00	0.00	0.00	237	23.7
Atmosphere	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biosphere	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

I/O	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Input	1890	179	0	0	0	0	0	0
Output	155	0	0	0	0	0	0	0

Table 1.1 *- The depiction of a matrix from the current data that have been gathered from numerous sources*

Table 1.1 shows the data matrix put together from different sources. The Y-axis of the matrix represents the nitrogen emitted by each category from row, the X-axis represents where the nitrogen values are emitted to each category from the column.

For example: There are 885 Tonnes/years of nitrogen in the septic system and 29.1 Tonnes/year of nitrogen produced in the I/A.

Underneath the flow matrix is a table representing the inputs and outputs of the system. The system was defined geographically as Cape Cod and the islands of Martha's Vineyard and Nantucket. The outputs represent the flow of nitrogen leaving the system from a particular node.
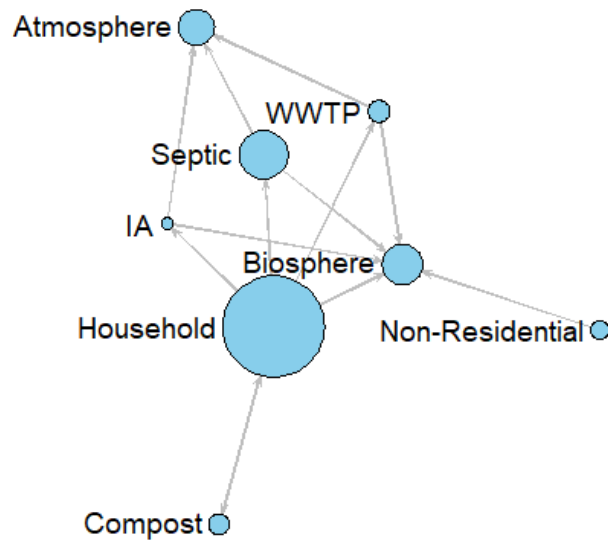
Figure 2.1 *- The depiction of the nitrogen flow chart of the current data of Cape Cod from **Table 1.1***

From **Figure 2.1**, within the current state, each node in the graph represents a node in the flow matrix, with the size of the node in the graph being proportional to the throughflow of the flow matrix node. The flow direction arrow is based on formulas such as **Equation 2.1.**

Scenario 2:

The second scenario represents if we assume every household in Cape Cod composted their organic municipal solid waste. We raised the percentage of households composting to 100%. To portray this in the model, we changed the value representing the percentage of households composting from 28% to 100%. The results of this change are portrayed below:

Households using Septic Systems = 70000

Households using I/A Systems = 2300

Percent of households composting = 100%

y/x	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Household	0.00	0.00	885	29.1	391	261	0.00	81.8
Non-Residential	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35.8
Septic	0.00	0.00	0.00	0.00	0.00	0.00	338	547
I/A	0.00	0.00	0.00	0.00	0.00	0.00	19	10
Compost	391	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WWTP	0.00	0.00	0.00	0.00	0.00	0.00	237	23.7
Atmosphere	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biosphere	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

I/O	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Input	1890	179	0.00	0.00	0.00	0.00	0.00	0.00
Output	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 1.2 - *The depiction of a matrix of what happened if everyone is composting*

When the rate of households composting rises to 100%, the flow of nitrogen between households and compost will increase by 155 Tonnes/year both ways. Additionally, with the assumption of 100% organic composting, there is now zero output from the household node.
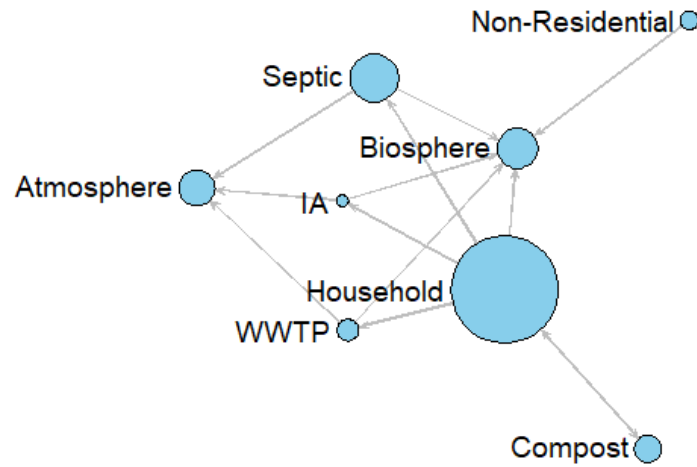
Figure 2.2 *- The depiction of the nitrogen flow chart of what happened if everyone composting based on*
Table 1.2

The visualization of **Figure 2.2** displayed a minor change. Due to a small increment of 155
Tonnes/year going between the household and compost nodes as seen in **Table 1.2**, the compost
node in **Figure 2.2** is slightly bigger than **Figure 2.1.**

Scenario 3:

The third scenario comprised the changes of values in the matrix if all households using septic systems used I/A systems, indicating that everybody abandoned the old septic system. The results of this change are portrayed below:

Households using Septic Systems = 0

Households using I/A Systems = 72300

Percent of households composting = 28%

y/x	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Household	0.00	0.00	0.00	914	236	261	0.00	81.8
Non-Residential	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35.8
Septic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I/A	0.00	0.00	0.00	0.00	0.00	0.00	599	315
Compost	236	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WWTP	0.00	0.00	0.00	0.00	0.00	0.00	237	23.7
Atmosphere	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biosphere	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

I/O	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Input	1890	179	0	0	0	0	0	0
Output	155	0	0	0	0	0	0	0

Table 1.3 - *The depiction of a matrix of what would happen if everyone only used I/A system*

Due to no traditional septic systems being used, there would be no nitrogen per year flowing through the traditional septic systems. Instead, the nitrogen flow will increase for I/A systems up to 914 Tonnes/year.

However, this affects the nitrogen load into the atmosphere, which increases by 242 Tonnes/year. The nitrogen flow into the biosphere will decrease by 244 Tonnes/year.
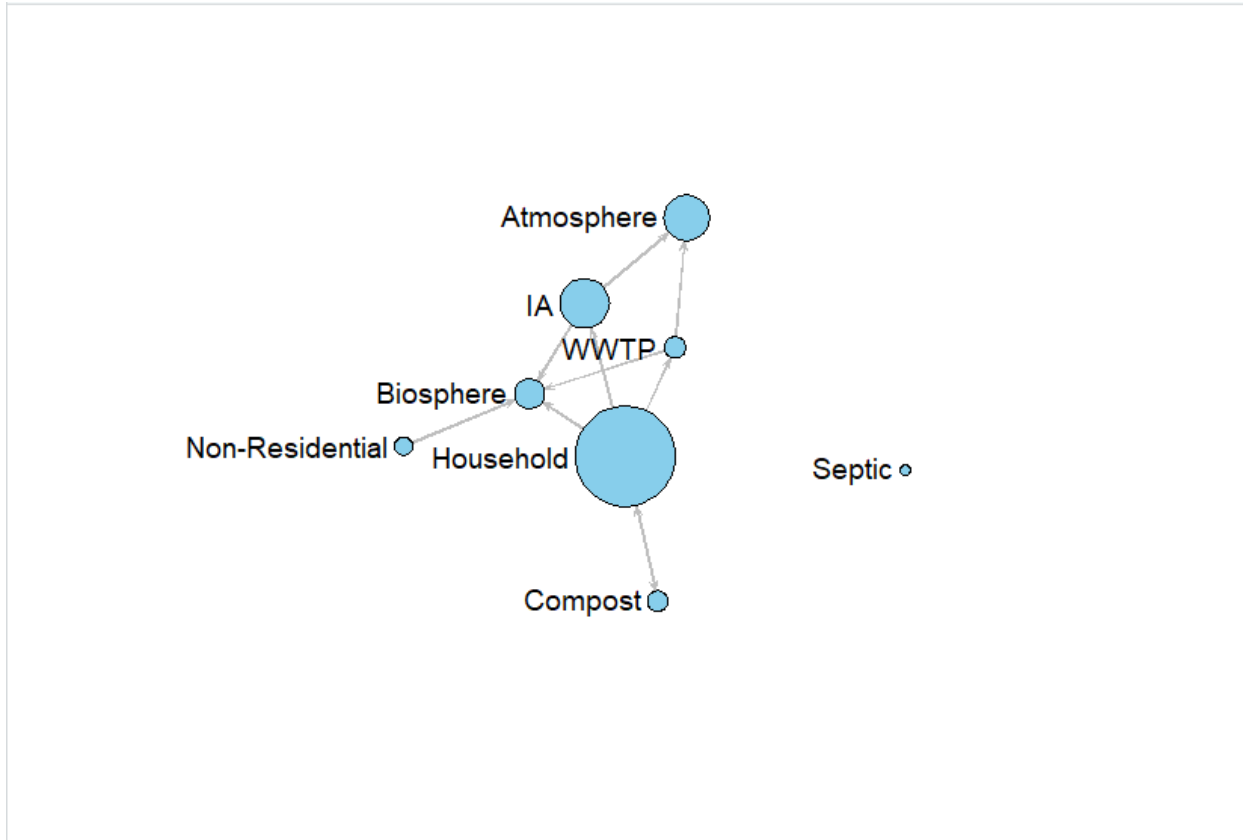
Figure 2.3 - The depiction of the nitrogen flow chart of what happened if everyone using I/A system

Due to the traditional septic system usage being set to 0, the node for the septic system becomes a point that has no flow direction going through and from the septic system.

Due to the increment of nitrogen into the I/A system, the graph shown in **Figure 2.3** shows the node size of that element increase when compared to the current scenario. As for the other nodes, they all change according to the value alteration, such as the biosphere node size shrinking since the total throughflow of the node decreased. In turn, the atmosphere node grew since the total throughflow of the node increased.

Analysis of the table and the network of the scenario shows that if everyone used the IA system and the atmosphere would take in more nitrogen, but the biosphere would take in less.

Scenario 4:

The fourth scenario represents if 50% of septic systems were the old traditional septic systems, and the other 50% of septic systems were the I/A systems. The total number of households using any form of septic system is 72,300, so we set both households using traditional septic systems and households using I/A systems to half of that, which is 36,150. The results of this change are portrayed below:

Households using Septic Systems = 36150

Households using I/A Systems = 36150

Percent of households composting = 28%

y/x	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Household	0.00	0.00	457	457	236	261	0.00	81.8
Non-Residential	0.00	0.00	0.00	0.00	0.00	0.000	0.00	35.8
Septic	0.00	0.00	0.00	0.00	0.00	0.000	175	283
I/A	0.00	0.00	0.00	0.00	0.0000	0.000	299	158
Compost	236	0.00	0.00	0.00	0.0000	0.000	0.00	0.00
WWTP	0.00	0.00	0.00	0.00	0.0000	0.000	237	23.7
Atmosphere	0.00	0.00	0.00	0.00	0.0000	0.000	0.00	0.00
Biosphere	0.00	0.00	0.00	0.00	0.0000	0.000	0.00	0.00

I/O	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Input	1890	179	0	0	0	0	0	0
Output	155	0	0	0	0	0	0	0

Table 1.4 - The depiction of a matrix of what happened if 50% household using I/A and 50% using composted system

In **Table 1.4**, both I/A and septic take in an equal amount of nitrogen (about 457 Tonnes/year). Compared to **Table 1.1**, the atmosphere takes 117 Tonnes/year more nitrogen. As for the biosphere, in **Table 1.4**, the nitrogen intake decreased by 116 Tonnes/year due to more nitrogen flowing through I/A systems.
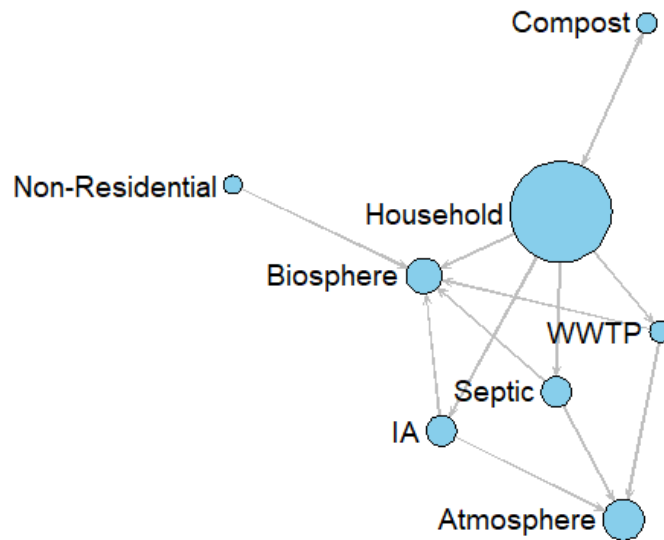
Figure 2.4 - *The depiction of the nitrogen flow chart of what would happen if half of the population uses the I/A system and the other half using the traditional septic system based on **Table 1.4***

From **Figure 2.4** it is noticeable that the increased usage of I/A systems and decreased usage of traditional septic systems result in the node size of the traditional septic system being reduced and the node size of the I/A increased. These results further show the changes of the node size corresponded to the distribution of the values.

With the analysis of the flow matrix and the visualization for this scenario, if half of the households using septic systems used the I/A system and the other half used the traditional systems, there would roughly be a 50% increase in nitrogen going to the atmosphere and a 50% decrease in nitrogen going to the biosphere.

Scenario 5:

The fifth scenario depicts an ideal scenario where all households are using I/A system and fully composting, abandoning the old septic systems. The results of this change are portrayed below:

Households using Septic Systems = 0

Households using I/A Systems = 72,300

Percent of households composting = 100%

y/x	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Household	0.00	0.00	0.00	914	391	261	0.00	81.8
Non-Residential	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35.8
Septic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I/A	0.00	0.00	0.00	0.00	0.00	0.00	599	316
Compost	391	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WWTP	0.00	0.00	0.00	0.00	0.00	0.00	237	23.7
Atmosphere	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biosphere	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

I/O	Household	Non-Residential	Septic	I/A	Compost	WWTP	Atmosphere	Biosphere
Input	1890	179	0	0	0	0	0	0
Output	0	0	0	0	0	0	0	0

Table 1.5*- The depiction of a matrix of what happened if 100% household using I/A and 100% using composted system*

The intake of nitrogen into the biosphere and into the atmosphere is the same as **Table 1.3**, but the compost intake would be increasing by 155 Tonnes/year. Due to no traditional septic systems being used, there is no nitrogen flowing from the septic system. However, the nitrogen intake will be increased into the I/A system up to 29.1 Tonnes/years

However, since traditional septic system usage has dropped to 0%, the nitrogen intake for the atmosphere will increase by 241 Tonnes per year. Also, the nitrogen intake of the biosphere will decrease by 244 Tonnes/year.

Also, just like in Scenario 2, with the assumption of complete organic composting, there is now zero output from the household node.
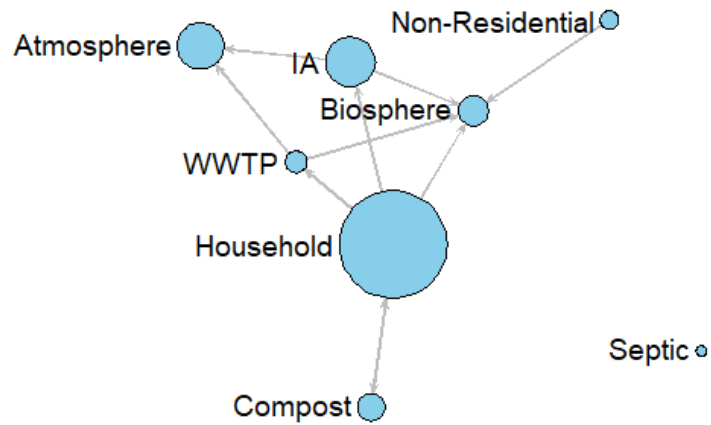
*Figure 2.5 - The depiction of the nitrogen flow chart of what happened if everyone composting and only uses the I/A system based on **Table 1.5***

Figure 2.5 is like the network model shown in **Figure 2.3**. They both portray an increase in nitrogen flow through I/A systems due to more households using them. **Figure 2.5** also portrays an increase in nitrogen flow between households and compost, increasing a similar amount due to the 100% of households composting.

ENAR Analysis Results

After the flow matrix was created as described above, we analyzed the network model using the ENAR library on each scenario and compiled the resulting values. The results are portrayed in the table below:

	Scenario 1 (Current)	Scenario 2 (100% Composting)	Scenario 3 (100% I/A Systems)	Scenario 4 (50% I/A Systems)	Scenario 5 (100% Composting 100% I/A Systems)
TST	5005	5316	5005	5005	5316
TSTp	5161	5316	5161	5161	5316
FCI	0.05242	0.08627	0.05242	0.05242	0.08627
ASC	7813	8007	7764	7822	7958

***Table 2.1**- The results from the analysis of the flow matrix using the enaR library in R*

TST: Comparing the current scenario value with any scenario including 100% of households composting (Scenario two and five), the TST value increases by 310. However, increasing the percentage of other systems doesn't change the value. The lack of greater change in TST is largely due to these scenarios not dramatically changing the amount of cycling and input of nitrogen to the Cape Cod region (as described below).

TSTp: Like TST, the TSTp value only changes when the scenario includes 100% of households composting (Scenario two and five). In these cases, the TSTp value increases by 155.

FCI: Comparing the current scenario with any scenario including 100% of households composting (Scenario two and five), the value of Finn's cycling index increases by 0.05568. However, increasing the percentage of other systems doesn't apply any changes.

ASC: Compared to the value for the current scenario, scenario two's value increased by 194. For scenario three, the value decreased by 49. For scenario four, the value increased by 9. And finally, for scenario five, the ASC value increased by 145.

Discussion

Although the model is a rough estimation, there are still a lot of observations to be made from examining the results.

The first thing that is apparent when looking at the different network models produced from the different scenarios is the substantial decrease in nitrogen going to the biosphere. Even considering the amount of nitrogen from fertilizer use, the significant difference between scenarios three and four compared to scenario one shows the flow of nitrogen increasing to the atmosphere and decreasing to the biosphere.

For instance, scenario four having 50% of households using traditional septic systems and 50% using I/A systems decreases the amount of nitrogen going to the biosphere by 116 Tonnes/year to the current scenario. However, scenario three shows more significant results, since the nitrogen flow to biosphere decreases by 244 Tonnes/year. This is due to I/A systems pulling more nitrogen out of the wastewater and sending it into the atmosphere.

When we look at composting within the system, increasing the number of households that compost their organic waste shows an increase in cycling within the system as shown with the increase in the FCI between scenario one and two. However, since all the trash within the model is assumed to be shipped out of Cape Cod, this does not have any effect on much of the rest of the internal model. Nonetheless, this is beneficial to the rest of the nitrogen flow outside of the model, as the increase in compost helps to contain more nitrogen in a useful cycle.

Therefore, the fifth scenario is the ideal scenario with nitrogen flow to the biosphere reduced by 244 Tonnes/year and 100% of households composting to increase cycling.

However, while many of these scenarios directly address the issue of groundwater and surface water being contaminated by excess nitrogen, these interventions do not as effectively deal with the issue on a more holistic way by better utilizing nitrogen in the system.

Conclusion

The scenarios tested are potential combinations of values for the variables in the flow matrices calculations. These were adjusted with decreasing nitrogen flow to the groundwater and coastal waters in mind. This allowed us to further explore and understand possible solutions to the excess nitrogen problem in Cape Cod. The nitrogen network models have proven helpful in understanding how these flows interact. Using the metrics provided by enaR such as TST and FCI have been beneficial to fully grasping the current situation and its relationship with the possible solutions.

Both matrix and flow chart gave good representations of how nitrogen travels through Cape Cod and gave insight into how effective I/A systems would be especially in scenario three, four, and five.

However, these theoretical models increase the nitrogen going to the atmosphere instead of encouraging more cycling of the nitrogen within the system. Since the model was restricted to only the flow of nitrogen within Cape Cod, it is not entirely clear how this change would affect the surrounding regions or even the rest of the world.

Another aspect to consider is fertilizer use and municipal solid waste. Our scenarios focused on wastewater treatment, specifically with septic systems, and examined how nitrogen flows would be affected when wastewater was handled differently. However, fertilizer use and municipal solid waste are also both major areas where nitrogen flows through Cape Cod. Therefore, more research into how they are handled may lead to a better understanding of how to handle the excess nitrogen issue in Cape Cod.

Above all, from the development of the nitrogen flow, it provides a more holistic measure to understand the fundamental behavior of nitrogen throughout metabolism, but more research should be conducted to get a wider perspective of the issue.

Appendix A

The formulas for the flow matrix (each flow is in Tonnes per year):

Flow	Formula	Data Description	Sources
Household -> Septic	D1 x D2 x D3 x 365 x D4 x 10^{-9}	**D1:** Number of Households using Septic **D2:** People per Household **D3:** Sewage per Person per Day **D4:** Concentration of Nitrogen in sewage	**D1:** 8 **D2:** Assumption **D3:** Assumption **D4:** 7
Household -> I/A	D5 x D2 x D3 x 365 x D4 x 10^{-9}	**D5:** Number of Households using I/A Systems	**D5:** 7
Household -> Compost	((D6 x D7 x D8) + D9) x D10 x 0.907185	**D6:** Municipal Solid Waste **D7:** Percent organic waste **D8:** Percent composting **D9:** Compost **D10:** Percent nitrogen in organic waste	**D6:** 6 **D7:** 3 **D8:** 1 **D9:** 6 **D10:** 10
Household -> WWTP	D11 x 365 x D4	**D11:** Sewage Flow to wastewater treatment plants	**D11:** 2
Household -> Biosphere	D12 x D13 x D14 x 10^{-9}	**D12:** Acres of households using fertilizers **D13:** Fertilizer usage rate for households **D14:** Nitrogen in fertilizers	**D12:** 5 **D13:** 5 **D14:** 5
Non-Residential -> Biosphere	((D15 x D16) + (D17 x D18) + D19 + (D20 x D21)) x D14 x D22 x 10^{-9}	**D15:** Acres of commercial land using fertilizers **D16:** Fertilizer usage rate for commercial land **D17:** Acres of golf courses using fertilizers **D18:** Fertilizer usage rate for golf courses **D19:** Fertilizer usage by municipal buildings **D20:** Acres of agricultural land using fertilizers **D21:** Fertilizer usage for agricultural land **D22:** Nitrogen leakage	**D15:** 5 **D16:** 5 **D17:** 5 **D18:** 5 **D19:** 5 **D20:** 5 **D21:** 5 **D22:** 5
Septic -> Atmosphere	((D23 - D4) / D4) x D1 x D2 x D3 x 365 x D4 x 10^{-9}	**D23:** Septic system nitrogen outflow	**D23:** 7
Septic -> Biosphere	(D23 / D4) x D1 x D2 x D3 x 365 x D4 x 10^{-9}		
I/A -> Atmosphere	((D24 - D4) / D4) x D5 x D2 x D3 x 365 x D4 x 10^{-9}	**D24:** I/A system nitrogen outflow	**D24:** 7
I/A -> Biosphere	(D24 / D4) x D5 x D2 x D3 x 365 x D4 x 10^{-9}		
Compost -> Household	((D6 x D7 x D8) + D9) x D10 x 0.907185		
WWTP -> Atmosphere	((D25 - D4) / D4) x D11 x 365 x D4	**D25:** Wastewater system nitrogen outflow	**D25:** 7
WWTP -> Biosphere	(D25 / D4) x D11 x 365 x D4		
Input -> Household	(D6 x D7 x D10 x 0.907185) + (D12 x D13 x D14 x 10^{-9}) + (D26 x D27 x D28 x 365 x 10^{-6})	**D26:** Population of Cape Cod **D27:** Protein consumed per day **D28:** Percent nitrogen in protein	**D26:** 4 **D27:** Assumption **D28:** 11
Input -> Non-Residential	((D15 x D16) + (D17 x D18) + D19 + (D20 x D21)) x D14 x 10^{-9}		
Household -> Out	D6 x D7 x (1-D8) x D10 x 0.907185		

The values for the data:

Data	Values	Units	Source
D1: Number of Households using Septic	Scenario 1: 70,000 Scenario 2: 70,000 Scenario 3: 0 Scenario 4: 36,150 Scenario 5: 0	Households	8
D2: People per Household	2.1	person/household	Assumption
D3: Sewage per Person per Day	300	L/person/household	Assumption
D4: Concentration of Nitrogen in sewage	55	mg/L	7
D5: Number of Households using I/A Systems	Scenario 1: 2,300 Scenario 2: 2,300 Scenario 3: 72,300 Scenario 4: 36,150 Scenario 5: 72,300	Households	7
D6: Municipal Solid Waste	66010	Tons/year	6
D7: Percent organic waste	36	%	3
D8: Percent composting	Scenario 1: 28 Scenario 2: 100 Scenario 3: 28 Scenario 4: 28 Scenario 5: 100	%	1
D9: Compost	19,376	Tons/year	6
D10: Percent nitrogen in organic waste	1	%	10
D11: Sewage Flow to wastewater treatment plants	13,000,000	L/day	2
D12: Acres of households using fertilizers	8407	acres	5
D13: Fertilizer usage rate for households	429	lb/acre/year	5
D14: Nitrogen in fertilizers	113,398	mg/lb	5
D15: Acres of commercial land using fertilizers	430	acres	5
D16: Fertilizer usage rate for commercial land	429	lb/acre/year	5
D17: Acres of golf courses using fertilizers	2500	acres	5
D18: Fertilizer usage rate for golf courses	354	lb/acre/year	5
D19: Fertilizer usage by municipal buildings	257,000	lb/year	5
D20: Acres of agricultural land using fertilizers	1800	acres	5

D21: Fertilizer usage for agricultural land	140	lb/acre/year	5
D22: Nitrogen leakage	20	%	5
D23: Septic system nitrogen outflow	34	mg/L	7
D24: I/A system nitrogen outflow	19	mg/L	7
D25: Wastewater system nitrogen outflow	5	mg/L	7
D26: Population of Cape Cod	209,660	People	4
D27: Protein consumed per day	103	g/day	Assumption
D28: Percent nitrogen in protein	16	%	11

Data Sources:

1. Association, National Waste & Recycling. "National Waste & Recycling Association Survey Finds Most Americans Would Compost If It Was More Convenient in Their Community." PR Newswire: Press Release Distribution, Targeting, Monitoring and Marketing, 30 June 2018, www.prnewswire.com/news-releases/national-waste--recycling-association-survey-finds-most-americans-would-compost-if-it-was-more-convenient-in-their-community-239232261.html.
2. Cape Cod Commission. "208 Cape Cod Area Wide Water Quality Management Plan Update." Cape Cod Commission, June 2015.
3. Cape Cod Commission. "SCLIMATE ACTION FACT SHEET Promote Waste Reduction and Diversion DIVERT RECYLABLE AND ORGANIC WASTE FROM LANDFILLS FOR ALTERNATIVE MANAGEMENT OR REUSE." Cape Cod Commission.
4. Cape Cod Commission. "Initial 2020 Census Results Released." Initial 2020 Census Results Released | Cape Cod Commission, 20 Jan. 2020, www.capecodcommission.org/about-us/newsroom/initial-2020-census-results-released/.
5. "Cape Cod Pesticide and Fertilizer Use Inventory Final Report April 2014." Horsley Written Group, Apr. 2014.
6. Darby, Debra. "Barnstable County MSW Diversion Options for Recyclable, Reusable and Hard to Dispose Waste Materials; Task 1 – Quantify and Characterize Cape Cod MSW Components." Debra Darby, 1 Nov. 2021.
7. Gosselin, Jordan, and Bruce H Walton. "Distributed Nitrogen Removing I/a Septic Systems: A 2020 Primer for Cape Cod - Newea - New England Water Environment Association." NEWEA, 26 Oct. 2020, www.newea.org/2020/10/09/distributed-nitrogen-removing-i-a-septic-systems-a-2020-primer-for-cape-cod/.
8. "Innovative/Alternative Septic Systems: Barnstable Clean Water Coalition." Barnstable County Clean Water Coalition, bcleanwater.org/what-we-do/mitigate/innovative-alternative-septic-systems/. Accessed 19 Apr. 2024.
9. Services, Regulatory. "Compost Interpretation." Compost Interpretation | Public | Clemson University, South Carolina, www.clemson.edu/public/regulatory/ag-srvc-lab/compost/interpretation.html. Accessed 29 Apr. 2024.
10. Wang, Lan et al. "Exploring the nitrogen reservoir of biodegradable household garbage and its potential in replacing synthetic nitrogen fertilizers in China." PeerJ vol. 10 e12621. 18 Jan. 2022, doi:10.7717/peerj.12621

11. National Research Council. 1989. Recommended Dietary Allowances: 10th Edition. Washington, DC: The National Academies Press. https://doi.org/10.17226/1349.

Appendix B

Code for Scenario 1:

```
library(enaR);

#Get the required networks
library(enaR);
library(network);

#Some Constants
tonsToTonnes = 0.907185; # ton/Tonnes
pplPerHH = 2.1; #on average
sewPerP = 300; # L/day
nConc = 55; #in sewage mg/L
SepNO = 34; # mg/L
IANO = 19; # mg/L
WWTPNO = 5; # mg/L
NinFert = 0.25*453592;
population = 209660;
proteinPerDayConsumed = 103; #in grams
NinProtein = 0.16; # percent
NinWaste = 0.01; # percent
yardWasteComposted = 19376 * tonsToTonnes; # in Tonnes
MSW = 66010 * tonsToTonnes; # in Tonnes
PercentOrganicWaste = 0.36; # Percent of organic waste in MSW
WWTPFPerD = 13000000;
HHAcre = 8407;
ComAcre = 430;
GCAcre = 2500;
AgrAcre = 1800;
HHFUsage = 429;
ComFUsage = 429;
GCFUsage = 354;
MunFUsage = 43.5; # to 760
AgrFUsage = 140;



#Create the variables
SepHH = 70000;
IAHH = 2300;
PercentComp = 0.28;

#Create the Flows
HHtoSep = (SepHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoIA = (IAHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoWWTP = (WWTPFPerD * 365 * nConc * 10^(-9));
SeptoAtmos = HHtoSep * ((nConc - SepNO) / nConc);
IAtoAtmos = HHtoIA * ((nConc - IANO) / nConc);
WWTPtoAtmos = HHtoWWTP * ((nConc - WWTPNO) / nConc);
SeptoGW = HHtoSep * (SepNO / nConc);
IAtoGW = HHtoIA * (IANO / nConc);
WWTPtoGW = HHtoWWTP * (WWTPNO / nConc);
HHtoGW = HHAcre * HHFUsage * NinFert * 0.2 * 10^(-9); #Where did 0.2 come
from?
```

```
NRtoGW = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 + (AgrAcre *
AgrFUsage)) * NinFert * 0.2 * 10^(-9);
HHtoComp = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);
ComptoHH = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);

#Creating the Input
SolidWasteToHH = MSW * PercentOrganicWaste * NinWaste;
FoodToHH = population * proteinPerDayConsumed * NinProtein * 365 * 10^(-6);
FertToHH = HHAcre * HHFUsage * NinFert * 10^(-9);
FertToNonRes = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 +
(AgrAcre * AgrFUsage)) * NinFert * 10^(-9);

#Creating the Outputs
HHToSolidWaste = MSW * PercentOrganicWaste * NinWaste * (1-PercentComp);

#Create the Flow Matrix
flow.mat<-matrix(c(0,0,0,0,ComptoHH,0,0,0,
                   0,0,0,0,0,0,0,0,
                   HHtoSep,0,0,0,0,0,0,0,
                   HHtoIA,0,0,0,0,0,0,0,
                   HHtoComp,0,0,0,0,0,0,0,
                   HHtoWWTP,0,0,0,0,0,0,0,
                   0,0,SeptoAtmos,IAtoAtmos,0,WWTPtoAtmos,0,0,
                   HHtoGW,NRtoGW,SeptoGW,IAtoGW,0,WWTPtoGW,0,0), ncol=8);

#name the nodes
rownames(flow.mat)<-colnames(flow.mat)<-c("Household", "Non-Residential",
"Septic", "IA", "Compost", "WWTP","Atmosphere","Biosphere");

## Generate the inputs
inputs <- c(FoodToHH+FertToHH+SolidWasteToHH,FertToNonRes,0,0,0,0,0,0);
inputs
## Generate the respiration
respiration <- c(0,0,0,0,0,0,0,0);

## Generate the exports
exports <- c(HHToSolidWaste,0,0,0,0,0,0,0);

## Generate the storage
storage <- c(0,0,0,0,0,0,0,0);

## "Pack" the model into a network object
CapeCod <- pack(flow = flow.mat,
                input = inputs,
                export = exports,
                storage = storage,
                respiration = respiration,
                living = c(NA,NA,NA,NA,NA,NA,NA,NA));

## Extract all the model data elements
coefficient <- unpack(CapeCod);
coefficient
## Give a summary of the model
summary(CapeCod)
```

```
## Characterize the network flow
flow_object <- enaFlow(CapeCod, balance.override = FALSE)
flow_object

## Characterize Ascendancy
enaAscendency(CapeCod)

## Characterize the cycling
enaCycle(CapeCod)

## Plot the network

T <- flow_object$T

plot(CapeCod,
     vertex.col = "skyblue", # Node color
     edge.col = "gray",      # Edge color
     vertex.cex = 1+ T/250,      # Node size
     edge.lwd = 2,           # Edge width
     label.cex = 1.2,        # Label size
     label.pos = 2,          # Label position
     label = c("Household", "Non-Residential", "Septic", "IA", "Compost",
"WWTP", "Atmosphere", "Biosphere"))
```

Code for Scenario 2:

```r
library(enaR);

#Get the required networks
library(enaR);
library(network);

#Some Constants
tonsToTonnes = 0.907185; # ton/Tonnes
pplPerHH = 2.1; #on average
sewPerP = 300; # L/day
nConc = 55; #in sewage mg/L
SepNO = 34; # mg/L
IANO = 19; # mg/L
WWTPNO = 5; # mg/L
NinFert = 0.25*453592;
population = 209660;
proteinPerDayConsumed = 103; #in grams
NinProtein = 0.16; # percent
NinWaste = 0.01; # percent
yardWasteComposted = 19376 * tonsToTonnes; # in Tonnes
MSW = 66010 * tonsToTonnes; # in Tonnes
PercentOrganicWaste = 0.36; # Percent of organic waste in MSW
WWTPFPerD = 13000000;
HHAcre = 8407;
ComAcre = 430;
GCAcre = 2500;
AgrAcre = 1800;
HHFUsage = 429;
ComFUsage = 429;
GCFUsage = 354;
MunFUsage = 43.5; # to 760
AgrFUsage = 140;



#Create the variables
SepHH = 70000;
IAHH = 2300;
PercentComp = 1;

#Create the Flows
HHtoSep = (SepHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoIA = (IAHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoWWTP = (WWTPFPerD * 365 * nConc * 10^(-9));
SeptoAtmos = HHtoSep * ((nConc - SepNO) / nConc);
IAtoAtmos = HHtoIA * ((nConc - IANO) / nConc);
WWTPtoAtmos = HHtoWWTP * ((nConc - WWTPNO) / nConc);
SeptoGW = HHtoSep * (SepNO / nConc);
IAtoGW = HHtoIA * (IANO / nConc);
WWTPtoGW = HHtoWWTP * (WWTPNO / nConc);
HHtoGW = HHAcre * HHFUsage * NinFert * 0.2 * 10^(-9); #Where did 0.2 come
from?
NRtoGW = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 + (AgrAcre *
AgrFUsage)) * NinFert * 0.2 * 10^(-9);
```

```r
HHtoComp = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);
ComptoHH = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);

#Creating the Input
SolidWasteToHH = MSW * PercentOrganicWaste * NinWaste;
FoodToHH = population * proteinPerDayConsumed * NinProtein * 365 * 10^(-6);
FertToHH = HHAcre * HHFUsage * NinFert * 10^(-9);
FertToNonRes = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 +
(AgrAcre * AgrFUsage)) * NinFert * 10^(-9);

#Creating the Outputs
HHToSolidWaste = MSW * PercentOrganicWaste * NinWaste * (1-PercentComp);

#Create the Flow Matrix
flow.mat<-matrix(c(0,0,0,0,ComptoHH,0,0,0,
                   0,0,0,0,0,0,0,0,
                   HHtoSep,0,0,0,0,0,0,0,
                   HHtoIA,0,0,0,0,0,0,0,
                   HHtoComp,0,0,0,0,0,0,0,
                   HHtoWWTP,0,0,0,0,0,0,0,
                   0,0,SeptoAtmos,IAtoAtmos,0,WWTPtoAtmos,0,0,
                   HHtoGW,NRtoGW,SeptoGW,IAtoGW,0,WWTPtoGW,0,0), ncol=8);

#name the nodes
rownames(flow.mat)<-colnames(flow.mat)<-c("Household", "Non-Residential",
"Septic", "IA", "Compost", "WWTP","Atmosphere","Biosphere");

## Generate the inputs
inputs <- c(FoodToHH+FertToHH+SolidWasteToHH,FertToNonRes,0,0,0,0,0,0);
inputs
## Generate the respiration
respiration <- c(0,0,0,0,0,0,0,0);

## Generate the exports
exports <- c(HHToSolidWaste,0,0,0,0,0,0,0);

## Generate the storage
storage <- c(0,0,0,0,0,0,0,0);

## "Pack" the model into a network object
CapeCod <- pack(flow = flow.mat,
                input = inputs,
                export = exports,
                storage = storage,
                respiration = respiration,
                living = c(NA,NA,NA,NA,NA,NA,NA,NA));

## Extract all the model data elements
coefficient <- unpack(CapeCod);
coefficient
## Give a summary of the model
summary(CapeCod)

## Characterize the network flow
flow_object <- enaFlow(CapeCod, balance.override = FALSE)
```

```r
flow_object

## Characterize Ascendancy
enaAscendency(CapeCod)

## Characterize the cycling
enaCycle(CapeCod)

## Plot the network

T <- flow_object$T

plot(CapeCod,
     vertex.col = "skyblue", # Node color
     edge.col = "gray",      # Edge color
     vertex.cex = 1+ T/250,     # Node size
     edge.lwd = 2,           # Edge width
     label.cex = 1.2,        # Label size
     label.pos = 2,          # Label position
     label = c("Household", "Non-Residential", "Septic", "IA", "Compost",
"WWTP", "Atmosphere", "Biosphere"))
```

Code for Scenario 3:

```
library(enaR);

#Get the required networks
library(enaR);
library(network);

#Some Constants
tonsToTonnes = 0.907185; # ton/Tonnes
pplPerHH = 2.1; #on average
sewPerP = 300; # L/day
nConc = 55; #in sewage mg/L
SepNO = 34; # mg/L
IANO = 19; # mg/L
WWTPNO = 5; # mg/L
NinFert = 0.25*453592;
population = 209660;
proteinPerDayConsumed = 103; #in grams
NinProtein = 0.16; # percent
NinWaste = 0.01; # percent
yardWasteComposted = 19376 * tonsToTonnes; # in Tonnes
MSW = 66010 * tonsToTonnes; # in Tonnes
PercentOrganicWaste = 0.36; # Percent of organic waste in MSW
WWTPFPerD = 13000000;
HHAcre = 8407;
ComAcre = 430;
GCAcre = 2500;
AgrAcre = 1800;
HHFUsage = 429;
ComFUsage = 429;
GCFUsage = 354;
MunFUsage = 43.5; # to 760
AgrFUsage = 140;




#Create the variables
SepHH = 0;
IAHH = 72300;
PercentComp = 0.28;

#Create the Flows
HHtoSep = (SepHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoIA = (IAHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoWWTP = (WWTPFPerD * 365 * nConc * 10^(-9));
SeptoAtmos = HHtoSep * ((nConc - SepNO) / nConc);
IAtoAtmos = HHtoIA * ((nConc - IANO) / nConc);
WWTPtoAtmos = HHtoWWTP * ((nConc - WWTPNO) / nConc);
SeptoGW = HHtoSep * (SepNO / nConc);
IAtoGW = HHtoIA * (IANO / nConc);
WWTPtoGW = HHtoWWTP * (WWTPNO / nConc);
HHtoGW = HHAcre * HHFUsage * NinFert * 0.2 * 10^(-9); #Where did 0.2 come
from?
NRtoGW = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 + (AgrAcre *
AgrFUsage)) * NinFert * 0.2 * 10^(-9);
```

```r
HHtoComp = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);
ComptoHH = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);

#Creating the Input
SolidWasteToHH = MSW * PercentOrganicWaste * NinWaste;
FoodToHH = population * proteinPerDayConsumed * NinProtein * 365 * 10^(-6);
FertToHH = HHAcre * HHFUsage * NinFert * 10^(-9);
FertToNonRes = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 +
(AgrAcre * AgrFUsage)) * NinFert * 10^(-9);

#Creating the Outputs
HHToSolidWaste = MSW * PercentOrganicWaste * NinWaste * (1-PercentComp);

#Create the Flow Matrix
flow.mat<-matrix(c(0,0,0,0,ComptoHH,0,0,0,
                   0,0,0,0,0,0,0,0,
                   HHtoSep,0,0,0,0,0,0,0,
                   HHtoIA,0,0,0,0,0,0,0,
                   HHtoComp,0,0,0,0,0,0,0,
                   HHtoWWTP,0,0,0,0,0,0,0,
                   0,0,SeptoAtmos,IAtoAtmos,0,WWTPtoAtmos,0,0,
                   HHtoGW,NRtoGW,SeptoGW,IAtoGW,0,WWTPtoGW,0,0), ncol=8);

#name the nodes
rownames(flow.mat)<-colnames(flow.mat)<-c("Household", "Non-Residential",
"Septic", "IA", "Compost", "WWTP","Atmosphere","Biosphere");

## Generate the inputs
inputs <- c(FoodToHH+FertToHH+SolidWasteToHH,FertToNonRes,0,0,0,0,0,0);
inputs
## Generate the respiration
respiration <- c(0,0,0,0,0,0,0,0);

## Generate the exports
exports <- c(HHToSolidWaste,0,0,0,0,0,0,0);

## Generate the storage
storage <- c(0,0,0,0,0,0,0,0);

## "Pack" the model into a network object
CapeCod <- pack(flow = flow.mat,
                input = inputs,
                export = exports,
                storage = storage,
                respiration = respiration,
                living = c(NA,NA,NA,NA,NA,NA,NA,NA));

## Extract all the model data elements
coefficient <- unpack(CapeCod);
coefficient
## Give a summary of the model
summary(CapeCod)

## Characterize the network flow
flow_object <- enaFlow(CapeCod, balance.override = FALSE)
```

```r
flow_object

## Characterize Ascendancy
enaAscendency(CapeCod)

## Characterize the cycling
enaCycle(CapeCod)

## Plot the network

T <- flow_object$T

plot(CapeCod,
     vertex.col = "skyblue", # Node color
     edge.col = "gray",      # Edge color
     vertex.cex = 1+ T/250,       # Node size
     edge.lwd = 2,           # Edge width
     label.cex = 1.2,        # Label size
     label.pos = 2,          # Label position
     label = c("Household", "Non-Residential", "Septic", "IA", "Compost",
"WWTP", "Atmosphere", "Biosphere"))
```

Code for Scenario 4:

```
library(enaR);

#Get the required networks
library(enaR);
library(network);

#Some Constants
tonsToTonnes = 0.907185; # ton/Tonnes
pplPerHH = 2.1; #on average
sewPerP = 300; # L/day
nConc = 55; #in sewage mg/L
SepNO = 34; # mg/L
IANO = 19; # mg/L
WWTPNO = 5; # mg/L
NinFert = 0.25*453592;
population = 209660;
proteinPerDayConsumed = 103; #in grams
NinProtein = 0.16; # percent
NinWaste = 0.01; # percent
yardWasteComposted = 19376 * tonsToTonnes; # in Tonnes
MSW = 66010 * tonsToTonnes; # in Tonnes
PercentOrganicWaste = 0.36; # Percent of organic waste in MSW
WWTPFPerD = 13000000;
HHAcre = 8407;
ComAcre = 430;
GCAcre = 2500;
AgrAcre = 1800;
HHFUsage = 429;
ComFUsage = 429;
GCFUsage = 354;
MunFUsage = 43.5; # to 760
AgrFUsage = 140;




#Create the variables
SepHH = 36150;
IAHH = 36150;
PercentComp = 0.28;

#Create the Flows
HHtoSep = (SepHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoIA = (IAHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoWWTP = (WWTPFPerD * 365 * nConc * 10^(-9));
SeptoAtmos = HHtoSep * ((nConc - SepNO) / nConc);
IAtoAtmos = HHtoIA * ((nConc - IANO) / nConc);
WWTPtoAtmos = HHtoWWTP * ((nConc - WWTPNO) / nConc);
SeptoGW = HHtoSep * (SepNO / nConc);
IAtoGW = HHtoIA * (IANO / nConc);
WWTPtoGW = HHtoWWTP * (WWTPNO / nConc);
HHtoGW = HHAcre * HHFUsage * NinFert * 0.2 * 10^(-9); #Where did 0.2 come
from?
NRtoGW = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 + (AgrAcre *
AgrFUsage)) * NinFert * 0.2 * 10^(-9);
```

```r
HHtoComp = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);
ComptoHH = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);

#Creating the Input
SolidWasteToHH = MSW * PercentOrganicWaste * NinWaste;
FoodToHH = population * proteinPerDayConsumed * NinProtein * 365 * 10^(-6);
FertToHH = HHAcre * HHFUsage * NinFert * 10^(-9);
FertToNonRes = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 +
(AgrAcre * AgrFUsage)) * NinFert * 10^(-9);

#Creating the Outputs
HHToSolidWaste = MSW * PercentOrganicWaste * NinWaste * (1-PercentComp);

#Create the Flow Matrix
flow.mat<-matrix(c(0,0,0,0,ComptoHH,0,0,0,
                   0,0,0,0,0,0,0,0,
                   HHtoSep,0,0,0,0,0,0,0,
                   HHtoIA,0,0,0,0,0,0,0,
                   HHtoComp,0,0,0,0,0,0,0,
                   HHtoWWTP,0,0,0,0,0,0,0,
                   0,0,SeptoAtmos,IAtoAtmos,0,WWTPtoAtmos,0,0,
                   HHtoGW,NRtoGW,SeptoGW,IAtoGW,0,WWTPtoGW,0,0), ncol=8);

#name the nodes
rownames(flow.mat)<-colnames(flow.mat)<-c("Household", "Non-Residential",
"Septic", "IA", "Compost", "WWTP","Atmosphere","Biosphere");

## Generate the inputs
inputs <- c(FoodToHH+FertToHH+SolidWasteToHH,FertToNonRes,0,0,0,0,0,0);
inputs
## Generate the respiration
respiration <- c(0,0,0,0,0,0,0,0);

## Generate the exports
exports <- c(HHToSolidWaste,0,0,0,0,0,0,0);

## Generate the storage
storage <- c(0,0,0,0,0,0,0,0);

## "Pack" the model into a network object
CapeCod <- pack(flow = flow.mat,
                input = inputs,
                export = exports,
                storage = storage,
                respiration = respiration,
                living = c(NA,NA,NA,NA,NA,NA,NA,NA));

## Extract all the model data elements
coefficient <- unpack(CapeCod);
coefficient
## Give a summary of the model
summary(CapeCod)

## Characterize the network flow
flow_object <- enaFlow(CapeCod, balance.override = FALSE)
```

```
flow_object

## Characterize Ascendancy
enaAscendency(CapeCod)

## Characterize the cycling
enaCycle(CapeCod)

## Plot the network

T <- flow_object$T

plot(CapeCod,
     vertex.col = "skyblue", # Node color
     edge.col = "gray",      # Edge color
     vertex.cex = 1+ T/250,     # Node size
     edge.lwd = 2,           # Edge width
     label.cex = 1.2,        # Label size
     label.pos = 2,          # Label position
     label = c("Household", "Non-Residential", "Septic", "IA", "Compost",
"WWTP", "Atmosphere", "Biosphere"))
```

Code for Scenario 5:

```
library(enaR);

#Get the required networks
library(enaR);
library(network);

#Some Constants
tonsToTonnes = 0.907185; # ton/Tonnes
pplPerHH = 2.1; #on average
sewPerP = 300; # L/day
nConc = 55; #in sewage mg/L
SepNO = 34; # mg/L
IANO = 19; # mg/L
WWTPNO = 5; # mg/L
NinFert = 0.25*453592;
population = 209660;
proteinPerDayConsumed = 103; #in grams
NinProtein = 0.16; # percent
NinWaste = 0.01; # percent
yardWasteComposted = 19376 * tonsToTonnes; # in Tonnes
MSW = 66010 * tonsToTonnes; # in Tonnes
PercentOrganicWaste = 0.36; # Percent of organic waste in MSW
WWTPFPerD = 13000000;
HHAcre = 8407;
ComAcre = 430;
GCAcre = 2500;
AgrAcre = 1800;
HHFUsage = 429;
ComFUsage = 429;
GCFUsage = 354;
MunFUsage = 43.5; # to 760
AgrFUsage = 140;




#Create the variables
SepHH = 0;
IAHH = 72300;
PercentComp = 1;

#Create the Flows
HHtoSep = (SepHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoIA = (IAHH * pplPerHH * sewPerP * 365 * nConc * 10^(-9));
HHtoWWTP = (WWTPFPerD * 365 * nConc * 10^(-9));
SeptoAtmos = HHtoSep * ((nConc - SepNO) / nConc);
IAtoAtmos = HHtoIA * ((nConc - IANO) / nConc);
WWTPtoAtmos = HHtoWWTP * ((nConc - WWTPNO) / nConc);
SeptoGW = HHtoSep * (SepNO / nConc);
IAtoGW = HHtoIA * (IANO / nConc);
WWTPtoGW = HHtoWWTP * (WWTPNO / nConc);
HHtoGW = HHAcre * HHFUsage * NinFert * 0.2 * 10^(-9); #Where did 0.2 come
from?
NRtoGW = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 + (AgrAcre *
AgrFUsage)) * NinFert * 0.2 * 10^(-9);
```

```
HHtoComp = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);
ComptoHH = (yardWasteComposted * NinWaste) + (MSW * PercentOrganicWaste *
PercentComp * NinWaste);

#Creating the Input
SolidWasteToHH = MSW * PercentOrganicWaste * NinWaste;
FoodToHH = population * proteinPerDayConsumed * NinProtein * 365 * 10^(-6);
FertToHH = HHAcre * HHFUsage * NinFert * 10^(-9);
FertToNonRes = ((ComAcre * ComFUsage) + (GCAcre * GCFUsage) + 257000 +
(AgrAcre * AgrFUsage)) * NinFert * 10^(-9);

#Creating the Outputs
HHToSolidWaste = MSW * PercentOrganicWaste * NinWaste * (1-PercentComp);

#Create the Flow Matrix
flow.mat<-matrix(c(0,0,0,0,ComptoHH,0,0,0,
                   0,0,0,0,0,0,0,0,
                   HHtoSep,0,0,0,0,0,0,0,
                   HHtoIA,0,0,0,0,0,0,0,
                   HHtoComp,0,0,0,0,0,0,0,
                   HHtoWWTP,0,0,0,0,0,0,0,
                   0,0,SeptoAtmos,IAtoAtmos,0,WWTPtoAtmos,0,0,
                   HHtoGW,NRtoGW,SeptoGW,IAtoGW,0,WWTPtoGW,0,0), ncol=8);

#name the nodes
rownames(flow.mat)<-colnames(flow.mat)<-c("Household", "Non-Residential",
"Septic", "IA", "Compost", "WWTP","Atmosphere","Biosphere");

## Generate the inputs
inputs <- c(FoodToHH+FertToHH+SolidWasteToHH,FertToNonRes,0,0,0,0,0,0);
inputs
## Generate the respiration
respiration <- c(0,0,0,0,0,0,0,0);

## Generate the exports
exports <- c(HHToSolidWaste,0,0,0,0,0,0,0);

## Generate the storage
storage <- c(0,0,0,0,0,0,0,0);

## "Pack" the model into a network object
CapeCod <- pack(flow = flow.mat,
                input = inputs,
                export = exports,
                storage = storage,
                respiration = respiration,
                living = c(NA,NA,NA,NA,NA,NA,NA,NA));

## Extract all the model data elements
coefficient <- unpack(CapeCod);
coefficient
## Give a summary of the model
summary(CapeCod)

## Characterize the network flow
flow_object <- enaFlow(CapeCod, balance.override = FALSE)
```

```
flow_object

## Characterize Ascendancy
enaAscendency(CapeCod)

## Characterize the cycling
enaCycle(CapeCod)

## Plot the network

T <- flow_object$T

plot(CapeCod,
     vertex.col = "skyblue", # Node color
     edge.col = "gray",      # Edge color
     vertex.cex = 1+ T/250,      # Node size
     edge.lwd = 2,           # Edge width
     label.cex = 1.2,        # Label size
     label.pos = 2,          # Label position
     label = c("Household", "Non-Residential", "Septic", "IA", "Compost",
"WWTP", "Atmosphere", "Biosphere"))
```

Resources

Association, National Waste & Recycling. "National Waste & Recycling Association Survey Finds Most Americans Would Compost If It Was More Convenient in Their Community." *PR Newswire: Press Release Distribution, Targeting, Monitoring and Marketing*, 30 June 2018, www.prnewswire.com/news-releases/national-waste--recycling-association-survey-finds-most-americans-would-compost-if-it-was-more-convenient-in-their-community-239232261.html.

Cape Cod Commission. "208 Cape Cod Area Wide Water Quality Management Plan Update." Cape Cod Commission, June 2015.

Cape Cod Commission. "SCLIMATE ACTION FACT SHEET Promote Waste Reduction and Diversion DIVERT RECYLABLE AND ORGANIC WASTE FROM LANDFILLS FOR ALTERNATIVE MANAGEMENT OR REUSE." Cape Cod Commission.

Cape Cod Commission. "Initial 2020 Census Results Released." Initial 2020 Census Results Released | Cape Cod Commission, 20 Jan. 2020, www.capecodcommission.org/about-us/newsroom/initial-2020-census-results-released/.

Darby, Debra. "Barnstable County MSW Diversion Options for Recyclable, Reusable and Hard to Dispose Waste Materials; Task 1 – Quantify and Characterize Cape Cod MSW Components." Debra Darby, 1 Nov. 2021.

Gosselin, Jordan, and Bruce H Walton. "Distributed Nitrogen Removing I/a Septic Systems: A 2020 Primer for Cape Cod - Newea - New England Water Environment Association." *NEWEA*, 26 Oct. 2020, www.newea.org/2020/10/09/distributed-nitrogen-removing-i-a-septic-systems-a-2020-primer-for-cape-cod/.

Horsley Written Group "Cape Cod Pesticide and Fertilizer Use Inventory Final Report April 2014." Horsley Written Group, Apr. 2014.

"Innovative/Alternative Septic Systems: Barnstable Clean Water Coalition." *Barnstable County Clean Water Coalition*, bcleanwater.org/what-we-do/mitigate/innovative-alternative-septic-systems/. Accessed 19 Apr. 2024.

Kazanci, Caner, and Qianqian Ma. "System-Wide Measures in Ecological Network Analysis - (UGA ..." *ScienceDirect*, 20 Aug. 2015, doi.org/10.1016/B978-0-444-63536-5.00003-X.

National Research Council. 1989. *Recommended Dietary Allowances: 10th Edition*. Washington, DC: The National Academies Press. https://doi.org/10.17226/1349.

Services, Regulatory. "Compost Interpretation." *Compost Interpretation | Public | Clemson University, South Carolina*, www.clemson.edu/public/regulatory/ag-srvc-lab/compost/interpretation.html. Accessed 29 Apr. 2024.

United State Environmental Protection Agency. "The Problem." *EPA*, Environmental Protection Agency, 23 Apr. 2023, www.epa.gov/nutrientpollution/problem.

UNEP. "Four Reasons Why the World Needs to Limit Nitrogen Pollution." *UNEP*, 16 Jan. 2016, www.unep.org/news-and-stories/story/four-reasons-why-world-needs-limit-nitrogen-pollution.

Wang, Lan et al. "Exploring the nitrogen reservoir of biodegradable household garbage and its potential in replacing synthetic nitrogen fertilizers in China." *PeerJ* vol. 10 e12621. 18 Jan. 2022, doi:10.7717/peerj.12621

Yan Zhang, Hanjing Lu, Brian D. Fath, Hongmei Zheng, Xiaoxi Sun, and Yanxian Li *Environmental Science & Technology* **2016** *50* (16), 8558-8567 DOI: 10.1021/acs.est.6b00181