Study and Analysis of the Robustness of Hudson River Species

Urmi Ghosh-Dastidar[1], Eugene Fiorini[2], and Steven Miguel Lora[3]

[1] ughosh-dastidar@citytech.cuny.edu, Mathematics Department, New York City College of Technology, CUNY, Brooklyn, NY 11201
[2] gfiorini@dimacs.rutgers.edu, DIMACS, Rutgers University, Piscataway, NJ 08854
[3] steven.lora@gmail.com, Mathematics Department, New York City College of Technology, CUNY, Brooklyn, NY 11201

Abstract: The Hudson River is home to diverse populations of fish, birds, and mammals that cohabit and compete among themselves for resources. The North Hudson River flows from the Lake Tear of the Clouds and journeys 315 miles dropping 4,322 feet in elevation before emptying itself into New York Harbor. This work addresses the food web of species in the Hudson River using a graph theoretic approach to analyze the Hudson River habitats and their intricacies. The robustness of this food web is studied using a measure of connectance. As noticed in other networks, it is observed that removing species with few links has little effect on the Hudson River food web. Strong negative correlations between the species loss and the normalized connectance are observed for all four regions.

Introduction

Background

The American shad, Atlantic sturgeon, river herring (blue back herring and alewife), American eel, and largemouth bass are in decline [p. 80, 8]. Intense economic harvesting pressure and overexploitation have caused coastal and marine species to decline. Therefore, harvesting and fishing should be managed properly and carefully to avoid further decline of the current population. Food web analysis provides an understanding of predator-prey relationships and stability and robustness of the ecosystem [2, 3] and the nature of competition among species. Food webs are represented by directed graphs (digraphs) [9, 10] through direct or indirect connections – a directed arc points from the preys to predators to signify energy transfers or the flow of nutrients from one organism (food source) to another (consumer). Thus food webs can play a crucial role for understanding our ecosystem. We assume that the given food web is acyclic *i.e*. the directed graph has no cycles. Therefore, there are no species s_1, s_2, …, s_n, such that s_{i-1} preys on s_i for all i, and s_n preys on s_1. A particular case is that there are no two species that feed on each other. The following figure (Fig. 1) shows a partial food web for the Hudson River Shallow Water region.

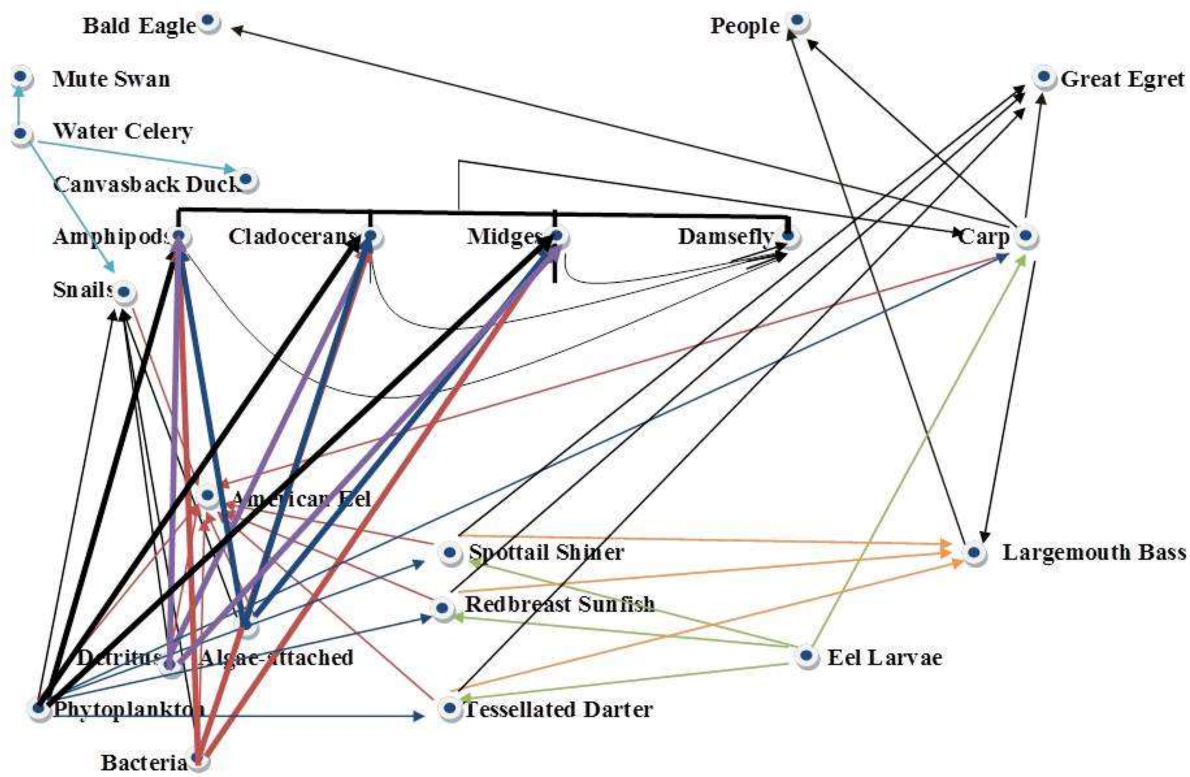

Figure 1. Partial food web of the Shallow Water Hudson River food web

Understanding the robustness of an ecosystem is vital in the context of rapidly increasing habitat modification. If a small change in an ecosystem brings system instability, then the system is said to be sensitive and unstable. Otherwise the food web is said to be robust [4, 5, 6]. Studying robustness of a food web is important for analysis of species extinction or rapid changes. There are several ways to measure the robustness of a system when that system is subjected to species loss. One measure of the robustness of a food web used by ecologists when studying food webs subjected to species loss is connectance [7]. Connectance, or directed connectance in this case, indicates the proportion of all possible interactions within a binary food web that can be realized [7]. It is calculated by:

$$\frac{L}{S^2},$$

where S is the number of species (nodes) in the food web and L is the number of links or connections between species (nodes). That is, it is the ratio of the number of observed links to the number of all possible links. Note that S^2 is the maximum number of possible interactions or links, if each species could potentially interact with every other species including itself.

When cannibalism is excluded (an arc from a species to itself), connectance is represented as $\frac{L}{S(S-1)}$. Furthermore, when cannibalism and 2-cyclic feeding relationships are excluded, connectance is defined as:

$$C_S = \frac{2L}{S(S-1)}, S > 1 \qquad \textbf{(1)}$$

Note that the minimum value of links L to link all species in a single food web is $L = S - 1$. Similarly, when all components are connected to each other and no self-linking or 2-cyclic feeding relations exist, the maximum number of links that can be observed is $L \le \binom{S}{2} = \frac{S(S-1)}{2}$ *for all* $S > 1$. Therefore, the maximum connectance value is $C_S = 1$. Note the maximum connectance value is $S(S-1)$ without cannibalism but including cyclic feeding relationships We define normalized connectance as follows [7].

$$C_{norm(S)} = \frac{C_S - C_{\min(S)}}{C_{\max(S)} - C_{\min(S)}} = \frac{C_S - C_{\min(S)}}{1 - C_{\min(S)}} \qquad (2)$$

where $C_{norm(S)}$ is normalized (directed) connectance for S species; C_S is (directed) connectance for S species; and $C_{min(S)}$ is minimum value of directed connectance i.e., $\frac{2}{S}$.

Connectance specifies the degree to which the species within a food web are connected to each other. Ithas an important role when studying a given food web since it provides a measure of the interactions and energy transfer between species in that food web. Martinez showed that connectance, particularly directed connectance, was one of the most robust measures for studying various food web resolutions [12].

Modeling and Analysis of the Hudson River Food Web

Flowing from the Lake Tear of the Clouds, the north Hudson River journeys 315 miles and drops 4,322 feet in elevation before emptying into New York Harbor . The Hudson River is home to diverse populations of fish, birds, and mammals that cohabit and compete among themselves for resources. The Hudson River provides habitats, each with its own intricate food web. In this paper, we focus mainly on four significant regions of the Hudson River food web: namely, Brackish Channel, Marsh, Fresh Water Shallows, and Freshwater Channel. Data are collected from Cary Institute of Ecosystem Studies [1].

Table I lists the total number of links in the original data set and the original measure of connectance before links are removed for all four regions. We observe Marsh and Brackish are the most connected whereas, Fresh Water Channel is the least connected food web.

Table I

	Marsh	**Brackish**	**Fresh Water Channel**	**Fresh Water Shallows**
# of Species	18	23	22	22
# of links	60	99	51	87
Connectance	0.392156863	0.391304348	0.220779221	0.376623377
Cmin	0.111111111	0.086956522	0.090909091	0.090909091
Cnorm	0.316176471	0.333333333	0.142857143	0.314285714

Tables II, III, IV, and V show the removal of one species, and the number of links lost due to this species' removal, respectively, for Marsh, Brackish, Fresh Water Channels, and Fresh Water Shallows regions. The second column lists the names of the species, the third column shows the number of links left after removal of that species, the fourth indicates the change in the number of links lost due to a species removal, and the fifth column provides a measure of connectance, determined by Eq. 1, due to species removal.

Table II
Marsh

	Removal of 1 Species	**Links after Removal**	**Change in Links**	**Connectance** $C_S = \frac{2L}{S(S-1)}$	**% Change in Connectance**	**Cmin**	**Cnorm** $C_{norm(S)} = \frac{C_S - C_{min(S)}}{1 - C_{min(S)}}$	**Change in Cnorm**
1	Algae	56	4	0.4118	5	0.1176	0.3333	0.0172
2	**Spartina Alterniflora**	**50**	**10**	**0.3676**	**-6.25**	**0.1176**	**0.2833**	**-0.0328**
3	**Typha(Cottail)**	**50**	**10**	**0.3676**	**-6.25**	**0.1176**	**0.2833**	**-0.0328**
4	**Phragmites**	**50**	**10**	**0.3676**	**-6.25**	**0.1176**	**0.2833**	**-0.0328**
5	Deltritus	51	9	0.375	-4.375	0.1176	0.2916	-0.0245
6	Microbes	55	5	0.4044	3.125	0.1176	0.325	0.0088
7	Fungi	55	5	0.4044	3.125	0.1176	0.325	0.0088
8	**Midges**	**51**	**9**	**0.375**	**-4.375**	**0.1176**	**0.2917**	**-0.0245**
9	**Mud worms**	**51**	**9**	**0.375**	**-4.375**	**0.1176**	**0.2917**	**-0.0245**
10	**Amphipods**	**51**	**9**	**0.375**	**-4.375**	**0.1176**	**0.2917**	**-0.0245**
11	**Snails**	**51**	**9**	**0.375**	**-4.375**	**0.1176**	**0.2917**	**-0.0245**
12	Killifish	55	5	0.4044	3.125	0.1176	0.325	0.0088
13	Mouse	55	5	0.4044	3.125	0.1176	0.325	0.0088
14	Marsh Wren	53	7	0.3897	-0.625	0.1176	0.3083	-0.0078
15	Red-wing Blackbird	53	7	0.3897	-0.625	0.1176	0.3083	-0.0078
16	**Great Blue Heron**	**58**	**2**	**0.4265**	**8.75**	**0.1176**	**0.35**	**0.0338**
17	**Muskrat**	**57**	**3**	**0.4191**	**6.875**	**0.1176**	**0.3417**	**0.0255**
18	**Snapping Turtle**	**58**	**2**	**0.4265**	**8.75**	**0.1176**	**0.35**	**0.0338**

Table III
Brackish

	Removal of 1 Species	**links after removal**	**change in links**	**Connectance** $C_S = \frac{2L}{S(S-1)}$	**% Change in Connectance**	**Cmin**	**Cnorm** $C_{norm(S)} = \frac{C_S - C_{min(S)}}{1 - C_{min(S)}}$	**Change in Cnorm**
1	Bacteria	92	7	0.398268398	1.779702	0.0909	0.3381	0.004761905
2	Phyto-plankton	92	7	0.398268398	1.779702	0.0909	0.3381	0.004761905
3	Detritus	92	7	0.398268398	1.779702	0.0909	0.3381	0.004761905
4	Mud Worms	90	9	0.38961039	-0.4329	0.0909	0.3286	-0.004761905
5	Midges	90	9	0.38961039	-0.4329	0.0909	0.3286	-0.004761905
6	Amphipods	90	9	0.38961039	-0.4329	0.0909	0.3286	-0.004761905
7	Polychaetes	90	9	0.38961039	-0.4329	0.0909	0.3286	-0.004761905
8	Copepods	88	11	0.380952381	-2.6455	0.0909	0.3190	-0.014285714
9	Crab larvae	88	11	0.380952381	-2.6455	0.0909	0.3190	-0.014285714
10	Rotifers	88	11	0.380952381	-2.6455	0.0909	0.3190	-0.014285714
11	**Rangia Clam**	**94**	**5**	**0.406926407**	**3.992304**	**0.0909**	**0.3476**	**0.014285714**
12	Opossum Shrimp	87	12	0.376623377	-3.7518	0.0909	0.3143	-0.019047619
13	Blue Crab	94	5	0.406926407	3.992304	0.0909	0.3476	0.014285714
14	Blueback Herring	89	10	0.385281385	-1.5392	0.0909	0.3238	-0.00952381
15	Bay Anchovy	89	10	0.385281385	-1.5392	0.0909	0.3238	-0.00952381
16	Bluefish	89	10	0.385281385	-1.5392	0.0909	0.3238	-0.00952381
17	Shad	89	10	0.385281385	-1.5392	0.0909	0.3238	-0.00952381
18	White Perch	89	10	0.385281385	-1.5392	0.0909	0.3238	-0.00952381
19	Atlantic Tomcod	89	10	0.385281385	-1.5392	0.0909	0.3238	-0.00952381
20	**Striped Bass**	**85**	**14**	**0.367965368**	**-5.96441**	**0.0909**	**0.3048**	**-0.028571429**
21	**Sturgeon**	**94**	**5**	**0.406926407**	**3.992304**	**0.0909**	**0.3476**	**0.014285714**
22	**Cormorant**	**98**	**1**	**0.424242424**	**8.417508**	**0.0909**	**0.3667**	**0.033333333**
23	**People**	**93**	**6**	**0.402597403**	**2.886003**	**0.0909**	**0.3429**	**0.00952381**

Table IV
Fresh Water Channels

	Removal of 1 Species	**links after removal**	**change in links**	**Connectance** $C_S = \frac{2L}{S(S-1)}$	**% Change in Connectance**	**Cmin**	**Cnorm** $C_{norm(S)} = \frac{C_S - C_{min(S)}}{1 - C_{min(S)}}$	**Change in Cnorm**
1	Bacteria	45	6	0.214285714	-2.94118	0.0952381	0.13157895	-0.011278195
2	Phyto-	45	6	0.214285714	-2.94118	0.0952381	0.13157895	-0.011278195

	plankton							
3	Detritus	42	9	0.2	-9.41176	0.0952381	0.11578947	-0.027067669
4	Mud Worms	46	5	0.219047619	-0.78431	0.0952381	0.13684211	-0.006015038
5	Midges	46	5	0.219047619	-0.78431	0.0952381	0.13684211	-0.006015038
6	Amphipods	46	5	0.219047619	-0.78431	0.0952381	0.13684211	-0.006015038
7	Copepods	45	6	0.214285714	-2.94118	0.0952381	0.13157895	-0.011278195
8	Cladocerans	45	6	0.214285714	-2.94118	0.0952381	0.13157895	-0.011278195
9	Rotifers	45	6	0.214285714	-2.94118	0.0952381	0.13157895	-0.011278195
10	**Zebra Mussels**	**43**	**8**	**0.204761905**	-7.2549	**0.0952381**	**0.12105263**	**-0.021804511**
11	**Blue Crab**	**49**	**2**	**0.233333333**	5.686274	**0.0952381**	**0.15263158**	**0.009774436**
12	BlueBack Herring	46	5	0.219047619	-0.78431	0.0952381	0.13684211	-0.006015038
13	**Striped Bass Larvae**	**48**	**3**	**0.228571429**	3.529412	**0.0952381**	**0.14736842**	**0.004511278**
14	Striped Bass Juvenile	47	4	0.223809524	1.372549	0.0952381	0.14210526	-0.00075188
15	**Striped Bass**	**48**	**3**	**0.228571429**	3.529412	**0.0952381**	**0.14736842**	**0.004511278**
16	Shad	46	5	0.219047619	-0.78431	0.0952381	0.13684211	-0.006015038
17	**White Perch**	**50**	**1**	**0.238095238**	7.843137	**0.0952381**	**0.15789474**	**0.015037594**
18	**Catfish**	**48**	**3**	**0.228571429**	3.529412	**0.0952381**	**0.14736842**	**0.004511278**
19	**Largemout h Bass**	**49**	**2**	**0.233333333**	5.686274	**0.0952381**	**0.15263158**	**0.009774436**
20	Sturgeon	47	4	0.223809524	1.372549	0.0952381	0.14210526	-0.00075188
21	**Cormorant**	**48**	**3**	**0.228571429**	3.529412	**0.0952381**	**0.14736842**	**0.004511278**
22	People	46	5	0.219047619	-0.78431	0.0952381	0.13684211	-0.006015038

Table V

Fresh Water Shallows

	Removal of 1 Species	**links after removal**	**change in links**	**Connectance** $C_S = \frac{2L}{S(S-1)}$	**% Change in Connectance**	**Cmin**	**Cnorm** $C_{norm(S)} = \frac{C_S - C_{min(S)}}{1 - C_{min(S)}}$	**Change in Cnorm**
1	Algae	78	9	0.371428571	-1.37931	0.095238	0.305263	-0.0090
2	Detritus	76	11	0.361904762	-3.90805	0.095238	0.294737	-0.0195
3	Phytoplankton	76	11	0.361904762	-3.90805	0.095238	0.294737	-0.0195
4	Bacteria	76	11	0.361904762	-3.90805	0.095238	0.294737	-0.0195
5	**Water Celery**	**84**	**3**	**0.4**	**6.206896**	**0.095238**	**0.336842**	**0.0226**
6	Amphipods	78	9	0.371428571	-1.37931	0.095238	0.305263	-0.0090
7	Cladocerans	78	9	0.371428571	-1.37931	0.095238	0.305263	-0.0090
8	Midges	78	9	0.371428571	-1.37931	0.095238	0.305263	-0.0090
9	Damselfly	80	7	0.380952381	1.149425	0.095238	0.315789	0.0015

10	Snails	81	6	0.385714286	2.413793	0.095238	0.321053	0.0068
11	**Eel Larvae**	**83**	**4**	**0.395238095**	**4.942529**	**0.095238**	**0.331579**	**0.0173**
12	**Carp**	**73**	**14**	**0.347619048**	**-7.70115**	**0.095238**	**0.278947**	**-0.0353**
13	**Spottail Shiner**	**73**	**14**	**0.347619048**	**-7.70115**	**0.095238**	**0.278947**	**-0.0353**
14	**Redbreast Sunfish**	**73**	**14**	**0.347619048**	**-7.70115**	**0.095238**	**0.278947**	**-0.0353**
15	**Tessellated Darter**	**73**	**14**	**0.347619048**	**-7.70115**	**0.095238**	**0.278947**	**-0.0353**
16	American Eel	78	9	0.371428571	-1.37931	0.095238	0.305263	-0.0090
17	Largemouth Bass	82	5	0.39047619	3.678161	0.095238	0.326316	0.0120
18	**Mute Swan**	**86**	**1**	**0.40952381**	**8.735632**	**0.095238**	**0.347368**	**0.0330**
19	**Canvasback Duck**	**86**	**1**	**0.40952381**	**8.735632**	**0.095238**	**0.347368**	**0.0330**
20	Great Egret	83	4	0.395238095	4.942529	0.095238	0.331579	0.0173
21	Bald Eagle	83	4	0.395238095	4.942529	0.095238	0.331579	0.0173
22	People	82	5	0.39047619	3.678161	0.095238	0.326316	0.0120

We define most significant species as those whose removal from the food web lowers the value of the connectance dramatically and the weakest are those whose removal from the food web improves the connectance or has the least effects on food web. Based on this analysis we list the top two most significant species and the two least connected species from all four regions in Table VI.

Table VI

	Marsh (Links Lost)	**Brackish (Links Lost)**	**Fresh Water Channel (Links Lost)**	**Fresh Water Shallows (Links Lost)**
Significant Species	Spartina Alterniflora (10), Typha (10), Phragmites (10), Deltrius (9), Midges (9), Mud worms (9), Amphipods (9), Snails (9)	Striped Bass (14), Copepods (11), Crab Larvae(11), Rotifers (11)	Detritus (9), Zebra Mussels (8)	Carp (14), Spottail Shiner (14), Redbreast Sunfish (14), Tessellated Darter (14), Detritus (11), Phytoplankton (11), Bacteria (11)
Weak Species	Great Blue Heron (2), Snapping Turtle (2), Muskrat (3)	Cormorant (1), Sturgeon (5), Blue Crab (5)	White Perch (1), Largemouth Bass (2), Blue Crab (2)	Mute Swan (1), Canvasback Duck (1), Water Celery (3)

Note that losing the most important species from the food web significantly lowers the connectance of the food web, whereas, the loss of the insignificant species has trivial effects on the food web. affect the connectance Note that losing the most significant, the striped Bass, from the Brackish regions lowers the connectance by approximately 6% whereas losing the least important species, Cormorant, from the same regions increases the connectance by approximately by 8% (see Table III). Similar results are observed in the tables II, III, IV, and V.

Thus, loss of poorly connected species (i.e. species that have relatively fewer links to the other species in the food web) results in positive change in normalized connectance, whereas the loss of highly connected species results in a negative change. This is reflected in our results which show strong negative correlation between the change in normalized connectance and number of links lost (see figures 2, 3, 4, and 5).). The loss of highly connected species shows positive change in connectance whereas the loss of weakly connected species shows negative change in connectance. For example, in all of these figures, change in connectance becomes negative (lowers) if highly connected species are removed andhange in connectance takes positive values (improves) if poorly connected species are removed. Notice that (using this definition of connectance) the highly connected species are not always necessarily the intermediate species. Carp (links 14), Spottail Shiner (links 14), Redbreast Sunfish (links 14), Tessellated Darter (links 14), Detritus (links 11), Phytoplankton (links 11), Bacteria (links11) are found to be highly connected species in the Fresh Water Shallows food web. The species Detritus, Phytoplankton, and Bacteria are considered as basal species (traditionally called weak species) when the others are considered as intermediate species in this food web. Although trophic status of people is the highest in this foodweb (30) and it is also a top species in this food web, it is not considered as one of the important species based on the measure of connectance. Many other intermediate species in this food web are also not considered as important species, since these species do not share relatively larger number of feeding links with others. Similarly, in the same food web Mute Swan (links 1), Canvasback Duck (links 1), Water Celery (links3) are found to be the most weakly connected species. Water celery is a basal species (traditionally weak species) when canvasback duck and mute swan are considered as top species in this food web. Therefore, measure of connectance identifies the highly connected species and the poorly connected species based on the number of feeding links lost due to the species removal.

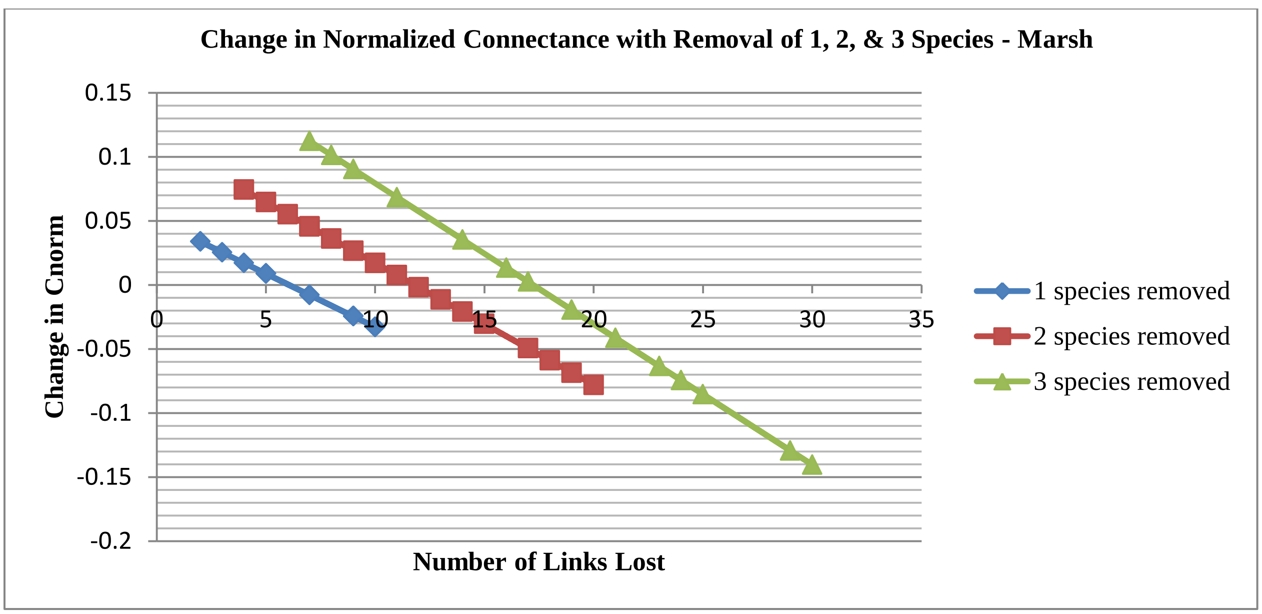

Figure. 2**:** The original network is made of 18 species and 60 links with a measure of initial connectance of approximately 0.39 (see **Eq. 1**) and with an initial normalized connectance value of ≈ .32 (see **Eq. 2**).

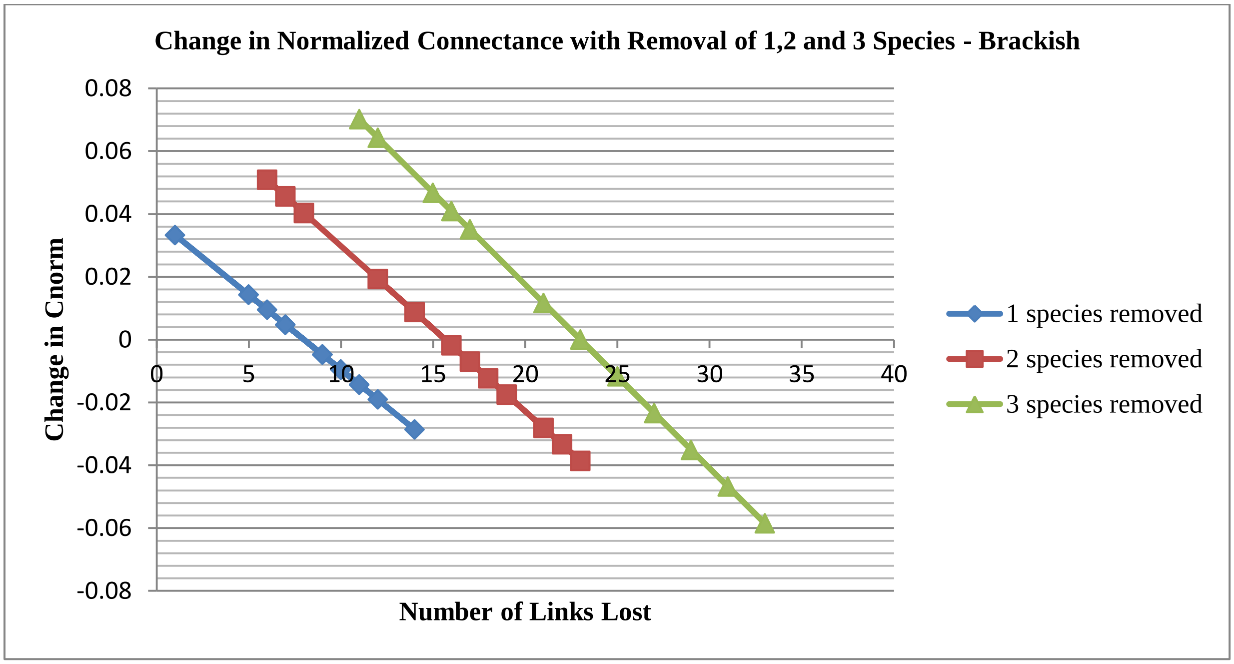

Figure. 3: The original network is made of 23 species and 99 links with a measure of initial connectance of approximately 0.39 (see **Eq. 1**) and with an initial normalized connectance value of ≈ .33 (see **Eq. 2**).

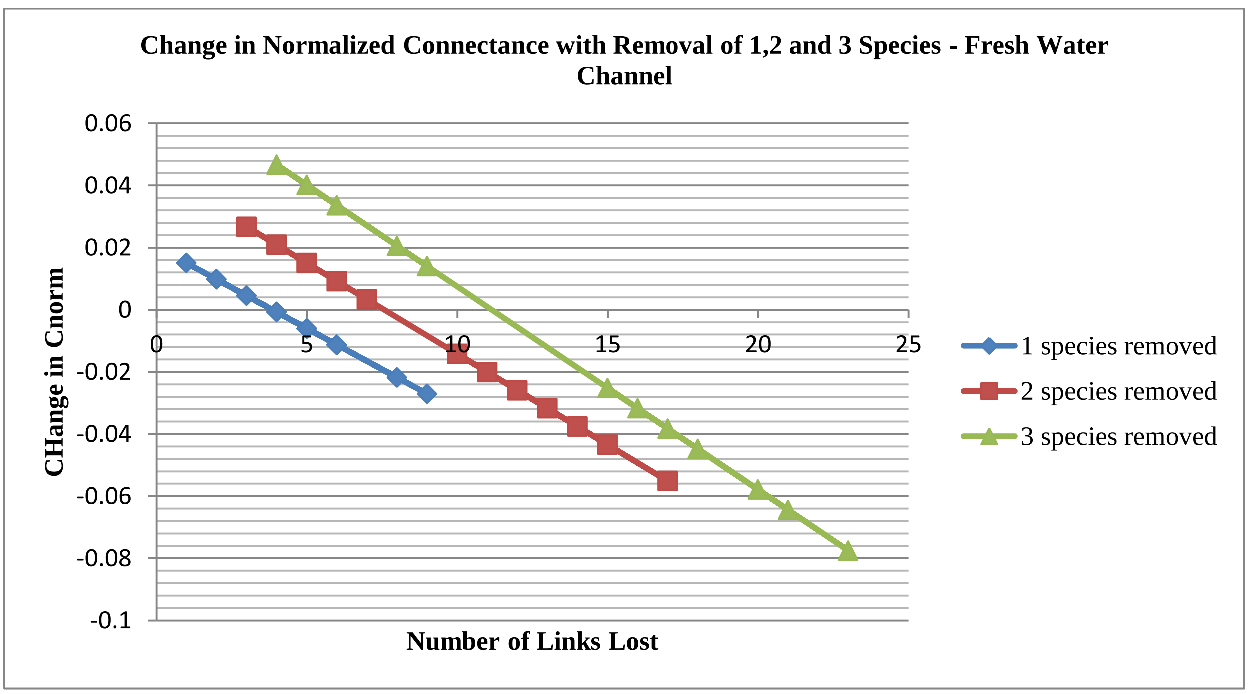

Figure. 4**:** The original network is made of 22 species and 51 links with a measure of initial connectance of approximately 0.22 (see **Eq. 1**) and with an initial normalized connectance value of ≈ .14 (see **Eq. 2**).

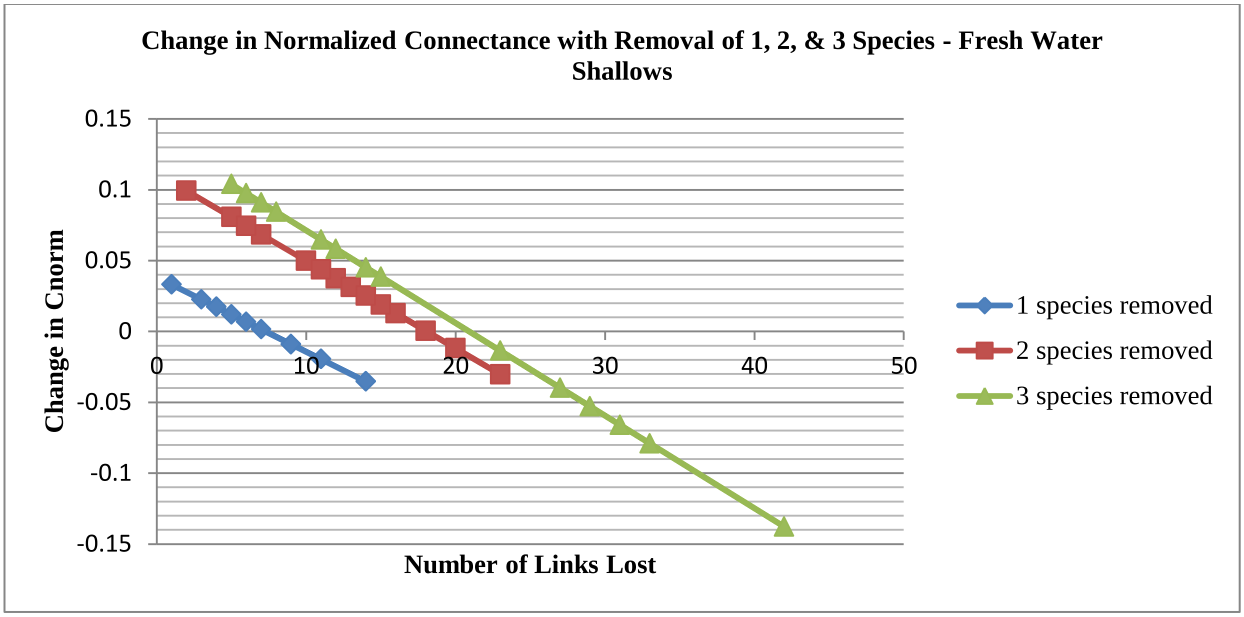

Figure 5**:** The original network is made of 22 species and 87 links with a measure of initial connectance of approximately 0.38 (see **Eq. 1**) and with an initial normalized connectance value of ≈ .31 (see **Eq. 2**).

Conclusions

We use a measure of connectance to study the robustness of each food web and identify the most connected species and least connected species from all four regions of the Hudson River food web. As noticed by Dunne et al [5] and Gilbert [8] we also observed removing species from ecosystem affects robustness of the food web. Strong negative correlations are observed between the change in normalized connectance and the number of links lost for all four regions that are being studied. Although we associate small negative changes and large negative changes to connectance, respectively with the least important and the most significant species in food webs, we need to take caution before generalizing any result. Further studies need to be used along with the measure of connectance to establish significance of species in a given food web. In general, a robust food web should show small changes in their connectance to less loss of species whereas; a non-robust food web should show more sensitivity in its connectance with species loss.

Acknowledgement: This work is supported by MAA NREUP grant, provided by the National Science Foundation's Division of Mathematical Sciences and the National Security Agency. The authors greatly acknowledge Dr. Margaret Cozzen for proofreading the documents and also providing valuable insights. Dr. Ghosh-Dastidar is also very grateful to DIMACS, Rutgers University for providing the opportunity to use all kinds of resources needed to support this work. Dr. Ghosh-Dastidar also acknowledges the support of NIMBioS and New York City College of Technology during the sabbatical period.

References

1. Cary Institute of Ecosystem Studies, Food Webs in the Hudson River, http://www.caryinstitute.org/sites/default/files/public/attachments/foodchains.swf (accessed on 4/12/14)

2. M. Cozzens, 2001. Food Webs, Competition Graphs, and Habitat Formation, Mathematical Modeling of Natural Phenomena, vol. 6, issue 6: 22 – 38.

3. M. Cozzens, Food Webs, Competition Graphs, and Habitat Formation, Margaret B. DIMACS module, Rutgers University.

4. Dunne, Williams, and Martinez, Network Structure and Network Theory: the Role of Connectance and Size, Proceedings of National Academy of Science USA, 99: 12917-22, 2002.

5. Dunne, Jennifer A., Williams, Richard J, and Martinez, Neo D. 2002. "Network Structure and Biodiversity Loss in food webs: robustness increases with connectance," Ecology Letters, 5: 558 – 567.

6. Dunne, Williams, and Martinez, *Network Structure and Robustness of Marine Food Webs*, www.santafe.edu/media/workingpapers/03-04-024.pdf

7. Gilbert, A. J. 2008. "Connectance indicates the robustness of food webs when subjected to species loss." Ecological Indicators 9: 72 – 80.

8. Department of Environmental Conservation, *Hudson River Estuary, Wildlife and Habitat Conservation Framework*, http://www.dec.ny.gov/lands/5096.html (accessed on 4/14/14)

9. D. B. West, Introduction to Graph Theory (Edition 2), Pearson (2000).

10. Junker and Schreiber, *Analysis of Biological Networks, Wiley Series in Bioinformatics*, Wiley-Interscience, 2008.

11. Cozzens, M. B. 2011. *Food Webs, Competition Graphs, and Habitat Formation*. Mathematical Modeling of Natural Phenomena John. R. Jungck and Elsa Schaefer (eds.).

12. Martinez, N.D., 1991. Artifacts or attributes? Effects of resolution on the Little Rock Lake Food Web. Ecol. Monogr. 61, 367 – 392.