

Independent Project

Investigating Plant-Pollinator Network In a Tropical Urban Ecosystem

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ABSTRACT

Plant Pollinator Interactions are mutualistic in nature. Insect pollinators depend on nectar and pollen from plants for food while plants rely on the pollinators for reproduction via pollination. A plant-pollinator network (PPN) is a bipartite nested network composing many such plant-pollinator interactions. The interactions only exist between two distinct, non-overlapping sets i.e. the plants and the animals. For this study, we used the plant-bee network found in IIIT Delhi for the year 2019 and 2021 data separately. Our goal was to explore the consequences of random and targeted attacks (removal of hubs) on the network. We further analyzed the network by studying the change in network properties such as degree density, assortativity, nestedness, modularity etc. from the original network structure by removing plant nodes. We also performed simulations by adding and removing plant nodes from the network and analyzed the resulting network properties. Finally we studied the robustness and resilience of the PPN and found out which of the nodes affect it the most using simulations. All the analysis was done on 2019 and 2021 data and comparisons are drawn. We find that a small set of plant species are responsible for maintaining a large fraction of total bee species in the network. Our study will help in understanding the stability and resilience of this plant-pollinator network.

INTRODUCTION

Insect pollinators play a vital role in the sustainability of ecosystems by pollinating and regenerating flowering plants. However, insect pollinators are declining rapidly due to human-induced factors such as the use of pesticides and changes in land use. Our research investigates the interactions between plants and bees using a network analysis approach. Our findings can be used to design strategies for the conservation of the pollinator species and the plants they pollinate. Although a lot of studies have been done on analyzing plant-pollinator networks, very few studies have considered PPNs in urban tropical ecosystems, like (Stewart AB, Waitayachart P, 2020).

Underlying the functioning of biological systems is a complex network of interactions and exchange of energy, materials and information. Thus, analysis of the network structure of

ecological systems has emerged as a fundamental approach to gain better insights into community function, and as a simple way of dealing with complex, many-species systems.

We have seen that network theory is applied to analyze complex ecological interactions mainly food webs (Martinez 1992; Williams and Martinez 2000; Montoya and Sole´ 2003; Pascual and Dunne 2006) and they can be used as a tool to determine the structure and function as required in the specific network. Many researchers lately have also started to study the plant pollinated networks using network theory (Jordano 1987; Memmott 1999; Bascompte et al. 2003; Jordano et al. 2003; Bascompte and Jordano 2007).

Basically these plant pollinated networks comprises two sets of nodes i.e. one of plants and one of animals. It is a type of a bipartite graph which means these sets of nodes have connections among each other's set but not in their set itself. We can say that there is a connection between a bee and a plant if the bee sits on a particular plant as the bee depends on the plant for food and also the plant depends on the nectar from the bee for reproduction via pollination. So many such types of connections are formed in these networks.

We found various properties like assortativity, nestedness, robustness, modularity etc. Different sets of methods were used to analyze these sets of properties like removing nodes one by one, adding nodes one by one, removing modules, identifying specialist and generalist species etc. Also comparative analysis was done on two different datasets i.e. 2019-20 and 2020-21. The results were expected to differ a bit as the 2019 network was more denser than 2020.

Previously some researchers have tried to find out similar findings using different approaches. These networks are considered to have a structure more nested than expected by chance alone (Bascompte et al., 2003). It has been found that there has been an over-representation of shared mutualistic interactions between specialist (species with few interactions) and generalist (species with many interactions) when one tried to compare the observed networks against random networks where the interactions were shuffled randomly or arbitrarily mixed. Traditionally, this nested structure refers to the network topology (i.e., presence or absence of interactions). While quantitative measures of nestedness have been proposed (Almeida-Neto and Ulrich, 2011; Staniczenko et al., 2013), their application to observed networks is still limited for two main reasons: theoretically it has been shown that the topology and the interaction strength of mutualistic networks play a separate role in shaping species persistence (Saavedra et al., 2013; Rohr et al., 2014), and the frequency of interactions is not enough to parameterize interaction strengths (Schupp et al., 2017). These results have generated a rich research agenda on understanding the factors modulating the nested structure (topology) of mutualistic networks in general (Bascompte and Jordano, 2013).

We have also observed that when it comes to network stability it is not always the case that every species contributes the same amount to maintain community stability but only the species with particular topological attributes such as high connectivity are particularly very important in this case. For example, we have seen that when species with many connections to other species are lost then communities are heavily impacted compared to when species with few

connections are lost. The loss of species with many connections to other species often impacts communities more strongly than the loss of species with few connections^{3,4,5}.

Similarly, losing species that contribute more to nestedness in mutualistic networks leads to stronger impacts on community integrity⁶, while losing peripheral species (those with few connections within and between modules) in modular networks exerts only weak effects at the community level⁶. Very few developments have been towards understanding the importance of inherent biological attributes related to functional traits such as the span of life, body size, form of life, invasiveness or phenology^{7,8,9}. Arguably, to make progress in our understanding of the functioning of ecological networks we need an integrated evaluation of both purely topological attributes, which depend strongly on local community structure, and species' biological attributes.

We have also seen researchers studying the cascading effect which is when the extinction of a species leads to loss in interactions which can further lead to more species being lost. Models with ecological interaction networks constitute a useful tool to simulate coextinction cascades, with the ultimate goal of understanding community robustness to species loss and resilience^{10,11,12,13}. Topological coextinction models (TCMs) represented the first attempt to explore patterns of extinction in plant-pollinator networks¹⁰.

We assume static network structure to be the main basis for these models but it has very important constraints. For instance, they assume that a species can only become extinct when all its interacting partners are lost; however, the primary loss of a pollinator species in real plant-pollinator networks may cause the coextinction of a plant, leading in turn to the coextinction of other pollinators that strongly depended on that plant, and even to the indirect coextinction of other plants which rely on those pollinators. TCMs ignore that species vary greatly in their degree of functional dependence on mutualistic partners. For instance, in plant-pollinator networks, the plant breeding system is a key determinant of its dependence on pollinators to produce seeds and may modulate plant vulnerability to pollinator loss¹⁴. This dependence varies from high in plants with obligated cross-pollination to low in plants with autonomous self-pollination¹⁶. When modeling species vulnerability to coextinction, consideration of such dependencies is very important.

In our work we have collected images of plants and bees from IIIT D Campus and then identified them. After identification we created our own adjacency matrix through which we created our graph after detecting the connections.

MATERIALS AND METHODS

We collected over 500 images of plant-bee interactions (30 plants and 26 bee species) to create a bipartite plant-bee network in a tropical urban ecosystem. This data was collected from IIIT Delhi campus (28.5459° N, 77.2732° E, 215 meters above the sea level).

The campus consists of a variety of plants and bee species due to a variety of conditions.

To find out which plants and bee pollinators are present in IIT Delhi campus, regular monitoring was done and 2 image datasets were created in the year of 2019 and 2021 respectively. The images taken in the dataset consisted of a bee either sitting on a flower, or a bee attached to the stigma/anther of flowers.

By observing the connections in the image datasets, we created an adjacency matrix with plant species as rows and bee species as columns. We used a '1' to indicate an interaction between the species and a '0' to indicate no interaction.

Network Analysis:

We used Python modules - networkx and matplotlib to create a bipartite graph from the interactions in the adjacency matrix. We generated unique IDs for each plant and bee species and included a legend along with the graph mapping each of the IDs to the corresponding name of the plant/bee species name. For further analysis, we also used the Bipartite package in R.

Firstly, we performed targeted and random attacks on the plants in the PPN, as per given in Barabási et al, 2005 . The targeted attacks were performed based on descending order of degrees of the plant nodes.

Then we found out the following properties in the PPN:

Degree distribution: describes the frequency with which species with different numbers of links occur in any given network (Newman 2005).

Clustering Coefficient: measure of the degree to which nodes in a graph tend to cluster together.

Degree Density: the portion of the potential connections in a network that are actual connections.

Assortativity: If high degree nodes tend to attach to low degree nodes, the network is assortative else it is disassortative. In general biological networks tend to be disassortative.

Connectance: This value is a measurement used to determine the level of connectivity. It is the realized proportion of possible links (Dunne et al. 2002) i.e. sum of links divided by number of cells in the matrix.

Robustness: An index to represent what fraction of species we need to remove to eliminate half of all species in the web (via secondary/cascading extinctions). Higher value indicates greater ability to withstand changes or adverse conditions and maintain the network properties.

Modularity: indicates the presence of dense clusters of related nodes embedded within the network. In many systems, we can find a partition of nodes into specific communities or modules. Modularity occurs when certain groups of species within a network are much more

highly connected to each other than they are with the rest of the network, with weak interactions connecting different modules.

Resilience: The network resilience is an information theoretic measure that describes the extent to which random node removal deteriorates network structure. We have used modified Shannon's entropy to calculate resilience.

Nestedness: It is calculated using the matrix temperature (T), a perfectly nested network(value 0) implies that the more specialist species interact with species that are proper subsets of those species interacting with the more generalist ones (Bascompte et al. 2003), while a perfectly non-nested network(value 100) is just the opposite.

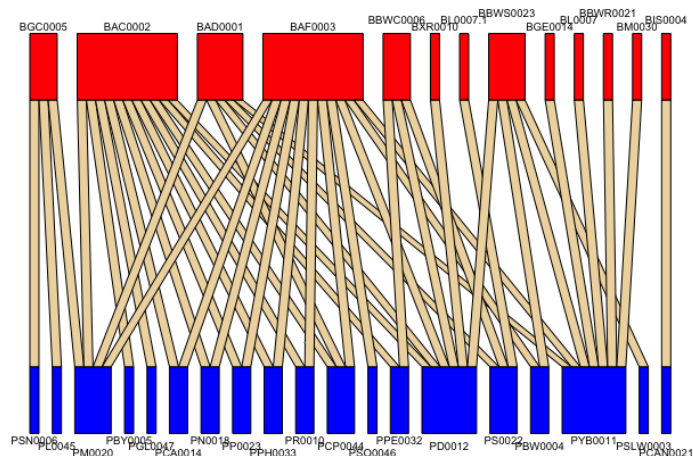
Vulnerability: mean effective number of HL species per LL species

Next, we found out the different modules in the network, removed modules and checked for variation in network properties.

We also conducted simulations where we added plant nodes one after another into the network and observed the variation in the analyzed network properties.

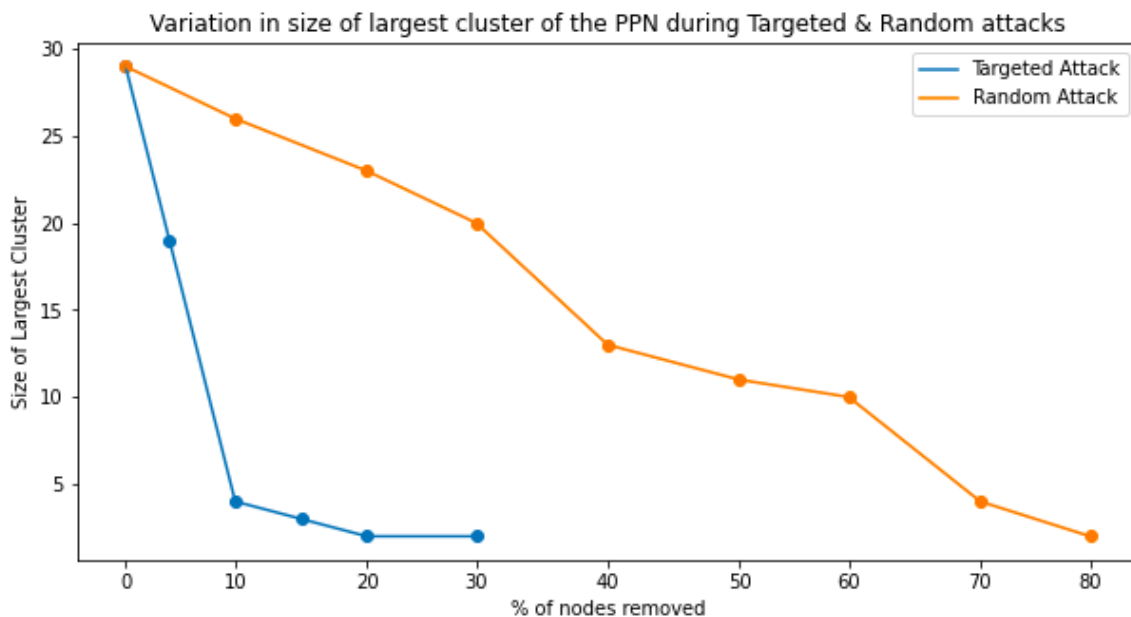
RESULTS

For 2021 Data:



Targeted and Random Attacks:

After performing targeted attacks and random attacks on PPN, we find that the network disintegrates much faster in case of targeted attacks, while it disintegrates a lot slower in case of random attacks. It takes just 10% of targeted node deletion for the PPN to disintegrate completely, while it requires over 80% of random node deletions to disintegrate the whole network.



All network properties:

Name	Value
connectance	0.1781377
web asymmetry	-0.1875
links per species	1.375
number of compartments	2
compartment diversity	1.263381
cluster coefficient	0.05263158
modularity Q	0.4602273
nestedness	13.88675
NODF	34.7992
weighted nestedness	0.4798943
weighted NODF	0
interaction strength asymmetry	0
specialisation asymmetry	0.007783594
linkage density	5.25
weighted connectance	0.1640625
Fisher alpha	8589934614
Shannon diversity	3.78419
interaction evenness	0.686862
Alatalo interaction evenness	1
H2	0
number.of.species.LL	19
mean.number.of.shared.partners.LL	0.7719298
cluster.coefficient.LL	0.1781377
weighted.cluster.coefficient.LL	0.3548387
niche.overlap.LL	0.3139038
togetherness.LL	0.1615149
C.score.LL	0.5095725
V.ratio.LL	1.875
discrepancy.LL	13
extinction.slope.LL	2.00349
robustness.LL	0.6615812
functional.complementarity.LL	21.1675
partner.diversity.LL	0.6406957
vulnerability.LL	2.315789

The assortativity coefficient of the network was found to be -0.47, which indicates that the network is disassortative. The nestedness was found to be 13.9 on a scale of 100. The connectance value is 0.17 . While robustness with respect to the plants is found to be 0.67. Vulnerability is found to be 3.4 .

Removing every plant node and then checking the properties:

	Removed_Node	Degree	AvgClusteringCoeff	Density	Largest_Clust_Size	Assortativity
0	None	None	0.205495	0.058355	29.000000	-0.470959
1	PYB0011	7	0.184356	0.050824	25.000000	-0.449382
2	PD0012	6	0.207515	0.052198	27.000000	-0.486994
3	PM0020	4	0.219597	0.054945	25.000000	-0.462629
4	PCP0044	3	0.202551	0.056319	28.000000	-0.462573
5	PS0022	3	0.217153	0.056319	28.000000	-0.492811
6	PPE0032	2	0.207526	0.057692	28.000000	-0.463599
7	PN0018	2	0.195690	0.057692	28.000000	-0.445010
8	PBW0004	2	0.205747	0.057692	28.000000	-0.467529
9	PCA0014	2	0.195690	0.057692	28.000000	-0.445010
10	PP0023	2	0.195690	0.057692	28.000000	-0.445010
11	PR0010	2	0.195690	0.057692	28.000000	-0.445010
12	PPH0033	2	0.195690	0.057692	28.000000	-0.445010
13	PSN0006	1	0.191216	0.059066	28.000000	-0.483046
14	PSLW0003	1	0.206730	0.059066	28.000000	-0.482357
15	PCAN0021	1	0.209300	0.059066	29.000000	-0.517767
16	PSO0046	1	0.203852	0.059066	28.000000	-0.456855
17	PBY0005	1	0.200942	0.059066	28.000000	-0.445474
18	PL0045	1	0.191216	0.059066	28.000000	-0.483046
19	PGL0047	1	0.200942	0.059066	28.000000	-0.445474
20	PMR0001	0	0.209300	0.060440	29.000000	-0.470959
21	PA0026	0	0.209300	0.060440	29.000000	-0.470959
22	PT0008	0	0.209300	0.060440	29.000000	-0.470959
23	PF0019	0	0.209300	0.060440	29.000000	-0.470959
24	PW0002	0	0.209300	0.060440	29.000000	-0.470959
25	PCM0015	0	0.209300	0.060440	29.000000	-0.470959
26	PCT0016	0	0.209300	0.060440	29.000000	-0.470959
27	PSU0007	0	0.209300	0.060440	29.000000	-0.470959
28	PCO0013	0	0.209300	0.060440	29.000000	-0.470959
29	PCH0009	0	0.209300	0.060440	29.000000	-0.470959
30	PCOR0017	0	0.209300	0.060440	29.000000	-0.470959

	plant_removed	connectance	robustness	vulnerability	nestedness
1	None	0.18859649122807	0.687215699853781	3.46511627906977	15.4266509035035
2	PSLW0003	0.194444444444444	0.667635115899337	3.52380952380952	15.3082813710168
3	PBW0004	0.189814814814815	0.659575247781653	3.53658536585366	14.5296403083207
4	PBY0005	0.194444444444444	0.670727940104669	3.52380952380952	17.437055676811
5	PSN0006	0.194444444444444	0.653557428745188	3.52380952380952	14.5865339114841
6	PR0010	0.189814814814815	0.666954595098668	3.53658536585366	15.0817816671524
7	PYB0011	0.25	0.749317036622424	2.77777777777778	25.6009517963022
8	PD0012	0.186868686868687	0.672459932062065	3.05405405405405	17.1516116227518
9	PCA0014	0.189814814814815	0.68554654443525	3.53658536585366	15.4464996375268
10	PN0018	0.189814814814815	0.662502754265742	3.53658536585366	15.5371196327964
11	PM0020	0.180555555555556	0.668399423813836	3.41025641025641	15.1693967084723
12	PCAN0021	0.212121212121212	0.693955592904329	3.52380952380952	15.3538125120691
13	PS0022	0.189814814814815	0.65203492290275	3.53658536585366	14.0396037171575
14	PP0023	0.189814814814815	0.670506191180742	3.53658536585366	15.0899094209856
15	PPH0033	0.189814814814815	0.670451378900427	3.53658536585366	15.0817816671524
16	PPE0032	0.189814814814815	0.664293031731163	3.53658536585366	14.7298519174765
17	PCP0044	0.185185185185185	0.680089199010726	3.5	15.0352538850639
18	PL0045	0.194444444444444	0.681953981207159	3.52380952380952	14.5312492153905
19	PSO0046	0.194444444444444	0.66337823073367	3.52380952380952	15.6673963595654
20	PGL0047	0.194444444444444	0.671803023968705	3.52380952380952	17.2499528855156
21	PMR0001	0.18859649122807	0.654299313454236	3.46511627906977	14.6999627853535
22	PW0002	0.18859649122807	0.691414265494736	3.46511627906977	14.8826484395629
23	PSU0007	0.18859649122807	0.669183359483683	3.46511627906977	15.2442045768916
24	PT0008	0.18859649122807	0.685925829318076	3.46511627906977	15.2442045768916
25	PCH0009	0.18859649122807	0.662959491180261	3.46511627906977	15.195858938122
26	PCO0013	0.18859649122807	0.676679864642901	3.46511627906977	14.6163089443529
27	PCM0015	0.18859649122807	0.687430652341558	3.46511627906977	14.7704880488359
28	PCT0016	0.18859649122807	0.684594641977388	3.46511627906977	15.0818827249987
29	PCOR0017	0.18859649122807	0.695303396892212	3.46511627906977	15.0836985473951
30	PF0019	0.18859649122807	0.668501339292737	3.46511627906977	15.1751309409344
31	PA0026	0.18859649122807	0.665740082932098	3.46511627906977	14.9969423551732

Firstly, we can see that PYB0011 is the node with the highest degree(i.e. 7). On removing this node, the degree density, largest cluster size and vulnerability becomes the minimum of all. While connectance robustness and nestedness become maximum when we remove this plant from the network as compared to removing any other node.

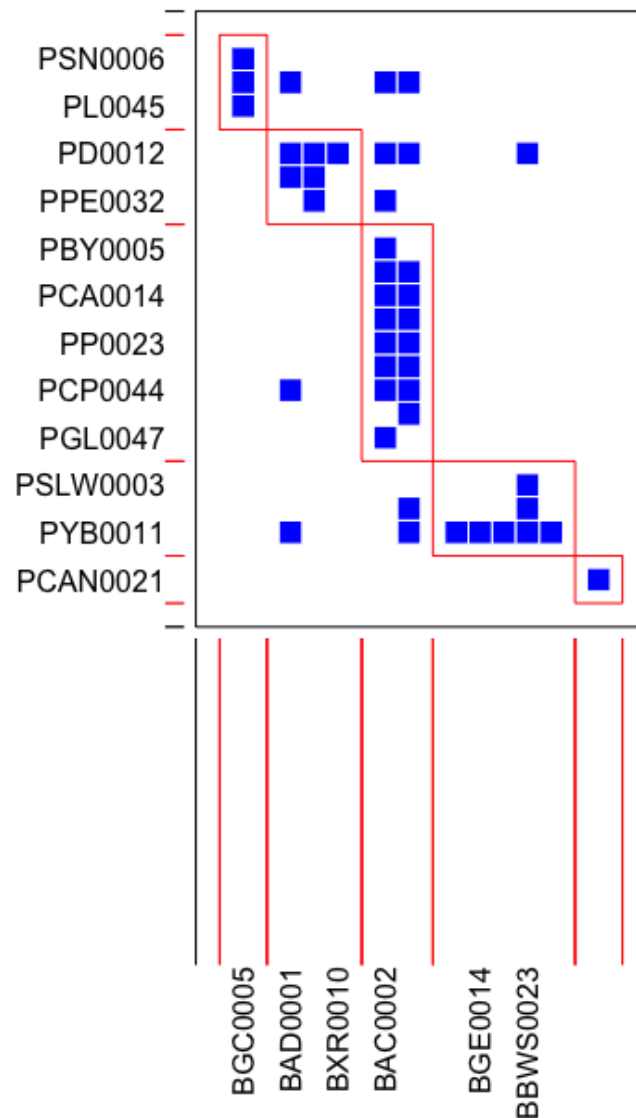
The highest change in assortativity is observed when node PCAN0021 is removed.

Also, removing PM0020(degree 1) reduces the largest cluster size to 25, the same as what was found after removing the hub node.

Overall PYB0011 is the node causing the most significant change in the properties of the network.

Finding modules in the network:

5 modules were found in the network as shown in the below figure.



Removing Modules one at a time:

	module_removed	connectance	robustness	Shannon_diversity	vulnerability	nestedness
1	None	0.1885965	0.6739629	3.761200	3.465116	14.99839
2	1	0.2031250	0.6700073	3.663562	3.666667	16.50615
3	2	0.2031250	0.6721340	3.663562	3.666667	17.14974
4	3	0.3166667	0.7344594	2.944439	2.368421	39.38960
5	4	0.2031250	0.6717374	3.663562	3.666667	16.72393
6	5	0.1944444	0.6769080	3.737670	3.523810	14.94249

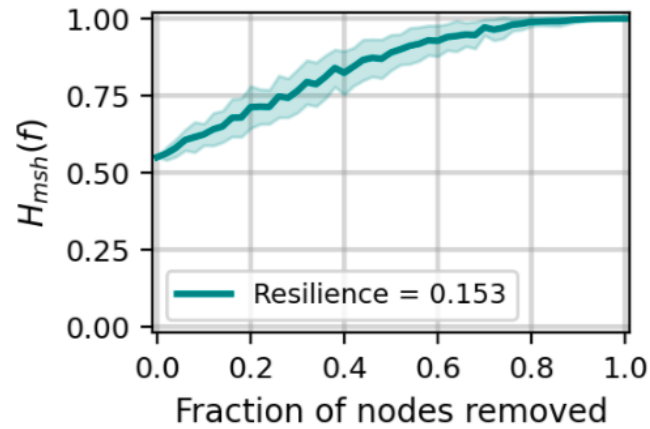
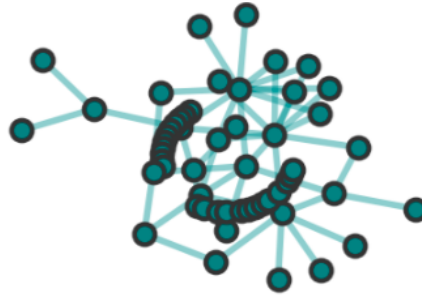
One removing modules one at a time we find that removal of module 3 causes the most significant change in properties, all the other modules don't change the overall network properties as such.

Adding nodes one at a time based on degree:

	plant_added	connectance	robustness	vulnerability	nestedness
1	None	0	0	0	0
2	PYB0011	1	NA	7	NA
3	PD0012	0.65	0.65	6.53846153846154	37.8236109178083
4	PM0020	0.515151515151515	0.590454545454545	5.94117647058823	31.7547126276718
5	PCP0044	0.454545454545455	0.637272727272727	5.5	26.2188893353381
6	PS0022	0.4	0.634913453396954	5.18181818181818	25.3310985076191
7	PPE0032	0.363636363636364	0.662663094318973	4.91666666666667	24.511503491008
8	PN0018	0.337662337662338	0.633733173961384	4.69230769230769	24.6173375725821

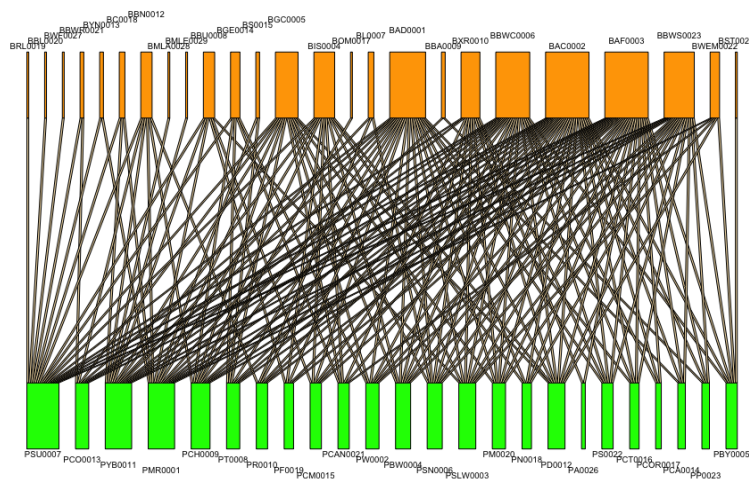
On adding ones one at a time by descending order of degree, it can be observed from the above table that on adding the first few nodes, the properties (other than robustness) calculated have high values which keep on decreasing with each new added node and then become almost stagnant when they're close to the actual network value.

Finding resilience of the network:



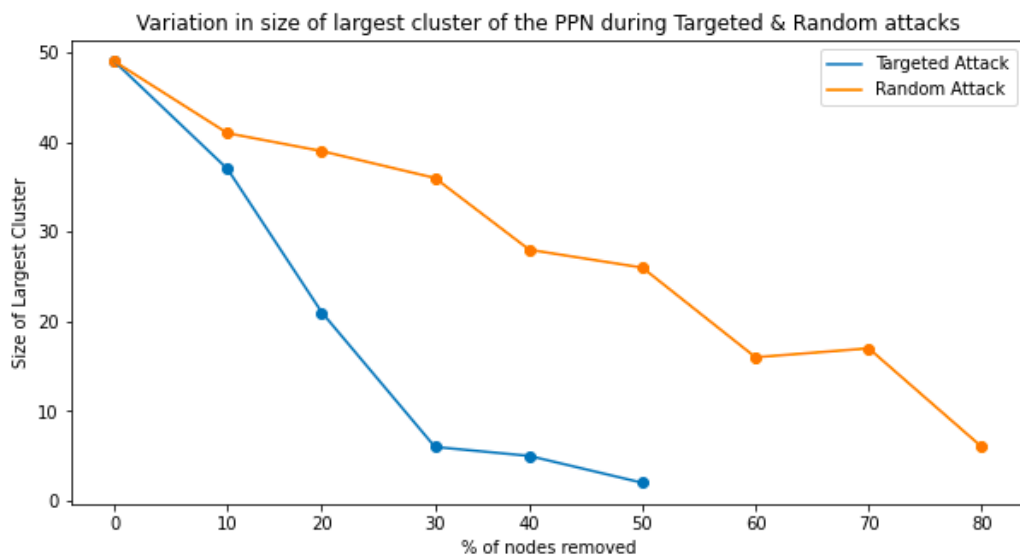
The resilience of this network is found to be 0.153, which is quite low.

For 2019 Data:



Network Simulations:

After performing targeted attacks and random attacks on PPN, we find that the network disintegrates faster in case of targeted attacks as compared to random attacks, but in this network the integrates at a lesser rate as compared to the 2021 PPN network. It takes 30% of targeted node deletion for the PPN to disintegrate completely, while it requires over 80% of random node deletions to disintegrate the whole network.



All network properties:

connectance	web asymmetry	links per species	number of compartments
0.29166667	0.02040816	3.57142857	1.00000000
compartment diversity	cluster coefficient	modularity Q	nestedness
NA	0.12500000	0.21642449	14.27891212
NODF	weighted nestedness	weighted NODF	interaction strength asymmetry
66.86924115	0.66300426	0.00000000	0.00000000
specialisation asymmetry	linkage density	weighted connectance	Fisher alpha
-0.32020180	11.69714286	0.23871720	17912043972496378.00000000
Shannon diversity	interaction evenness	Alatalo interaction evenness	H2
5.16478597	0.80738514	1.00000000	0.00000000

cluster.coefficient.LL	0.35817143	togetherness.LL	0.38243459
niche.overlap.LL	0.57705264	V.ratio.LL	4.17393903
C.score.LL	0.12420429	extinction.slope.LL	3.16163293
discrepancy.LL	37.00000000	functional.complementarity.LL	46.03766201
robustness.LL	0.74471622	vulnerability.LL	8.95428571
partner.diversity.LL	2.09175722		

The assortativity coefficient of the network was found to be -0.43, which indicates that the network is disassortative. The nestedness was found to be 15.5 on a scale of 100. The connectance value is 0.29 . While robustness with respect to the plants is found to be 0.74. Vulnerability is found to be 8.9 . Largest cluster size is 49.

As compared to the 2021 network, it can be observed that all of the calculated network properties show a greater value in the 2019 network.

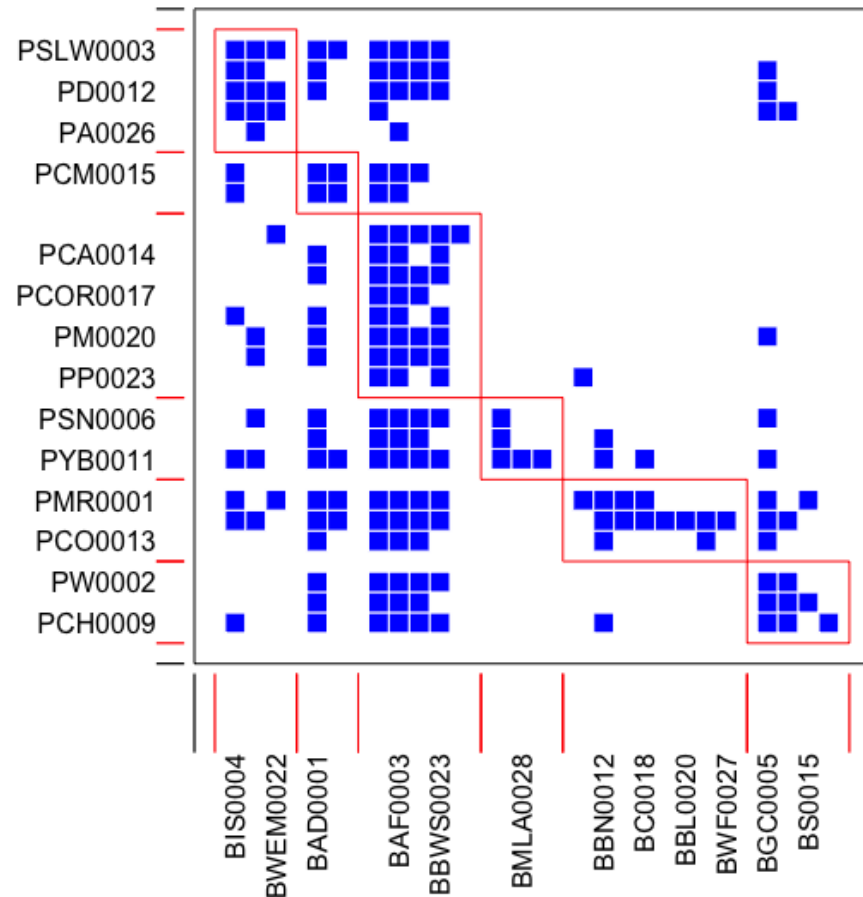
	Removed_Node	Degree	AvgClusteringCoeff	Density	Largest_Clust_Size	Assortativity
0	None	None	0.272176	0.208333	49.000000	-0.431871
1	PSU0007	17	0.257515	0.194581	45.000000	-0.419828
2	PMR0001	14	0.272892	0.198276	48.000000	-0.430766
3	PYB0011	14	0.265995	0.198276	46.000000	-0.430897
4	PCH0009	10	0.269451	0.203202	47.000000	-0.431027
5	PSLW0003	9	0.268248	0.204433	48.000000	-0.420861
6	PD0012	9	0.266585	0.204433	48.000000	-0.416960
7	PBW0004	8	0.265987	0.205665	48.000000	-0.412856
8	PSN0006	8	0.268083	0.205665	48.000000	-0.420995
9	PT0008	7	0.272364	0.206897	48.000000	-0.433150
10	PW0002	7	0.268186	0.206897	48.000000	-0.418683
11	PM0020	7	0.266384	0.206897	48.000000	-0.412003
12	PCO0013	7	0.275188	0.206897	48.000000	-0.433871
13	PCM0015	6	0.270569	0.208128	48.000000	-0.421322
14	PCAN0021	6	0.278656	0.208128	48.000000	-0.432837
15	PR0010	6	0.272959	0.208128	48.000000	-0.432847
16	PBY0005	6	0.272205	0.208128	47.000000	-0.435615
17	PS0022	6	0.266994	0.208128	48.000000	-0.410958
18	PN0018	5	0.269701	0.209360	48.000000	-0.413169
19	PF0019	5	0.273130	0.209360	48.000000	-0.424647
20	PCT0016	5	0.267073	0.209360	48.000000	-0.409504
21	PCA0014	4	0.269820	0.210591	48.000000	-0.411512
22	PP0023	4	0.275357	0.210591	48.000000	-0.432377
23	PCOR0017	3	0.272649	0.211823	48.000000	-0.414698
24	PA0026	2	0.279527	0.213054	48.000000	-0.426102
25	PCP0044	0	0.276951	0.215517	49.000000	-0.431871
26	PPE0032	0	0.276951	0.215517	49.000000	-0.431871

	plant_removed	connectance	robustness	vulnerability	nestedness
1	None	0.291666666666667	0.749037876944897	8.95428571428571	15.5826818178974
2	PMR0001	0.28	0.727597657460147	8.51552795031056	14.7507017562028
3	PW0002	0.292173913043478	0.740701548263126	9.03571428571428	14.1182036304298
4	PSLW0003	0.288695652173913	0.746511333625323	8.95180722891566	15.5977695163643
5	PBW0004	0.290434782608696	0.745911811362564	9	15.5201204468392
6	PBY0005	0.306159420289855	0.75591852935776	9.05917159763314	13.82631481579
7	PSN0006	0.290434782608696	0.751176388023872	9	15.3999059123712
8	PSU0007	0.312252964426877	0.764976408784644	8.08860759493671	16.2502968551908
9	PT0008	0.292173913043478	0.745925794542306	9.03571428571428	13.8512583434947
10	PCH0009	0.298913043478261	0.764632832184755	8.89090909090909	14.6127455221381
11	PR0010	0.293913043478261	0.741156499486081	9.05917159763314	13.7969121684562
12	PYB0011	0.304347826086957	0.763185231247595	8.51552795031056	16.7289421189119
13	PD0012	0.288695652173913	0.767378403206183	8.95180722891566	14.2940608957079
14	PCO0013	0.292173913043478	0.749216462922642	9.03571428571428	13.7956273165883
15	PCA0014	0.297391304347826	0.751866983590824	9.07017543859649	16.3596861311956
16	PCM0015	0.293913043478261	0.752218266671665	9.05917159763314	14.0673325001247
17	PCT0016	0.295652173913043	0.754232028448343	9.07058823529412	15.9019331701359
18	PCOR0017	0.299130434782609	0.754128823619061	9.05813953488372	15.6253774214564
19	PN0018	0.295652173913043	0.742463495717282	9.07058823529412	14.2997130021874
20	PF0019	0.295652173913043	0.751864651575364	9.07058823529412	15.4186306791158
21	PM0020	0.292173913043478	0.747175683944428	9.03571428571428	15.4888949941887
22	PCAN0021	0.293913043478261	0.751807528993715	9.05917159763314	13.4779559503732
23	PS0022	0.293913043478261	0.757747918671325	9.05917159763314	15.4992524835647
24	PP0023	0.297391304347826	0.755605101675229	9.07017543859649	13.6779778509238
25	PA0026	0.300869565217391	0.759124335806426	9.03468208092485	17.023963678721
26	PPH0033	0.291666666666667	0.74710611632167	8.95428571428571	14.2626740095709
27	PPE0032	0.291666666666667	0.757777007217004	8.95428571428571	14.2789121174323
28	PCP0044	0.291666666666667	0.755740320319273	8.95428571428571	15.5690459506711
29	PL0045	0.291666666666667	0.75069955467988	8.95428571428571	15.565492599782
30	PSO0046	0.291666666666667	0.755901835823428	8.95428571428571	15.5466522512854
31	PGL0047	0.291666666666667	0.752181588068196	8.95428571428571	14.2626740095709

On removing nodes one at a time, we find that no node is able to make a significant difference in any network property, even on removing the hub nodes like PSU0007 and PMR0001 no significant change was observed. This indicates that the network is not dependent on a higher degree plant node to maintain its properties.

Modularity of the network:

6 modules were found in the network.



Modules removed one at a time:

	module_removed	connectance	robustness	Shannon_diversity	vulnerability	nestedness
1	None	0.2916667	0.7569134	5.164786	8.954286	14.27631
2	1	0.2872807	0.7127767	4.875197	8.709924	15.33777
3	2	0.2800000	0.7099179	5.036953	8.584416	16.06508
4	3	0.3256579	0.7372412	4.595120	7.464646	16.15214
5	4	0.2761905	0.7203906	4.976734	8.558621	14.56688
6	5	0.2761905	0.7262747	4.976734	8.558621	16.02240
7	6	0.2761905	0.7287938	4.976734	8.558621	14.56551

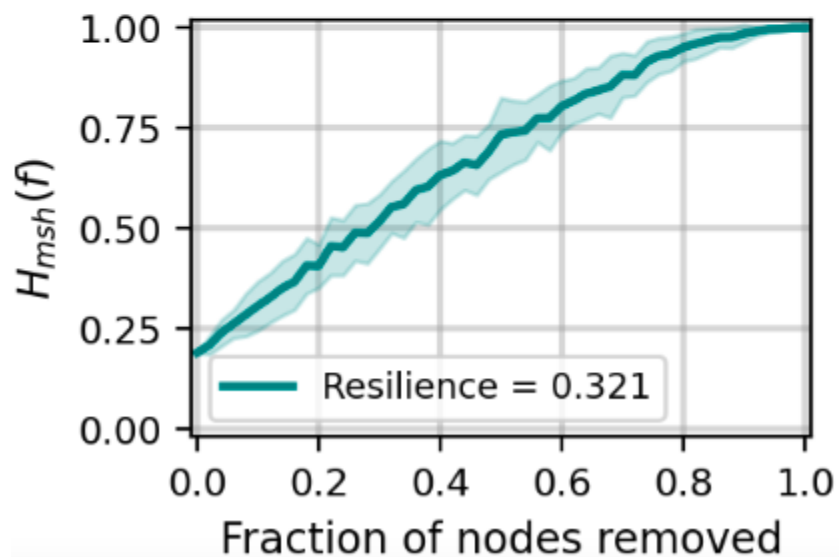
As observed during the node removal, removing modules one at a time does not change overall network properties much, the only noticeable difference was that when module 3 was removed, the vulnerability of the network fell from 8.95 to 7.46 .

Adding plant nodes one at a time:

	plant_added	connectance	robustness	vulnerability	nestedness
1	None	0	0	0	0
2	PSU0007	1	NA	17	NA
3	PMR0001	0.775	0.757	15.6451612903226	26.1183061170256
4	PYB0011	0.652173913043478	0.63	15.1333333333333	28.7871627093361
5	PCH0009	0.572916666666667	0.722222222222222	14.2	23.2032529272348
6	PSLW0003	0.533333333333333	0.702323298523716	13.46875	21.7496885380597
7	PD0012	0.506944444444444	0.713183304264059	12.9178082191781	21.1141053087776
8	PBW0004	0.482142857142857	0.717467835271278	12.4320987654321	19.6679901548549
9	PSN0006	0.463541666666667	0.723182934214354	12.0337078651685	21.1676474325066

On adding plants one by one, the network properties still remain close to the actual value so there's no significant change observed.

Resilience of the network:



The network resilience is 0.321, which is a fairly high value.

DISCUSSION

In the case of 2021 data, we can say that the PPN is highly vulnerable to targeted attacks, while it's quite robust to random attacks as the network disintegrated on removing 10% nodes. The network won't disintegrate easily unless we deliberately start removing the hub plants and bees. Whereas in the case of 2019 data, we can say that the PPN is less vulnerable to targeted attacks when compared to 2021 data, as the network disintegrated on removing 30% nodes. We also found 2019 data has more connectivity when compared to 2021 data so we can say that 2019 network is more densely connected. Vulnerability was found to be significantly higher in 2021 data as compared to 2019 data so we can conclude that there is a larger number of bee species per plant species in the 2019 network.

Rest of the discussion follows for both the years network as common.

The negative assortative coefficient explains that a new bee species when introduced in a network, would prefer interacting with a plant with lesser degree, rather than a plant already interacting with a large variety of bee types. This helps maintain the natural balance of the ecosystem. We can also say that nodes with the highest degree need not necessarily affect the network level properties the most. We plan to expand the network to include more species of plants and pollinators to create a more complex mutualistic network.

As our network is disassortative, if a high degree plant dies, it would most likely be connected to a low degree bees, and that bee will find it difficult to survive in the network as there will be no plant left.

The properties of assortativity are useful in the field of epidemiology, since they can help understand the spread of disease or cures. For instance, the removal of a portion of a network's vertices may correspond to curing, vaccinating, or quarantining individuals or cells. Since social networks demonstrate assortative mixing, diseases targeting high degree individuals are likely to spread to other high degree nodes. Alternatively, within the cellular network—which, as a biological network is likely disassortative—vaccination strategies that specifically target the high degree vertices may quickly destroy the epidemic network.

We have seen that if nestedness is high, even if specialist group of bees die, then also our plant pollinated by those bees could survive as it is being pollinated by generalist species. On the other hand, if it is low, if specialist group of bees die then chances of such plant to survive are very less due to it not being pollinated by generalists.

We can see in our table after removing or without removing the plant nodes, modules or adding nodes the nestedness is in the low range so we can say that in our network if certain specialist bees die then the plant pollinated by them has very less survival chances as it won't be pollinated by generalists.

Some other observations we see are If any plant is removed and if it shows high cascading effect, then the value to the extinct half network would be less so robustness would be low(0.1-0.2). But if it doesn't show a cascading effect, then the power to extinct half of the nodes would be high, so robustness would be high. In general we have seen in our original network and also after removing plant nodes,modules and adding nodes the robustness is moderately high so we can say our network even without removing or adding anything doesn't show any cascading effects that easily. Robustness is the tolerance of a network to the removal of a species (Memmott et al., 2004) and is a useful metric for network stability. A number of network metrics are associated with robustness. For example, modules in a network—groups of species that interact more with one another—can be the result of habitat heterogeneity, co-evolution or phylogenetic relatedness of the species, or species traits like phenology (Lewinsohn et al., 2006; Morente-López et al., 2018; Pimm & Lawton, 1980; Thompson, 2005), and modularity is associated with the stability of networks (Thébault & Fontaine, 2010, Stouffer & Bascompte, 2011). In seed dispersal networks for example, plant and animal trait values—body mass and seed mass—were associated with the modularity of individual species (Donatti et al., 2011, where species modularity describes whether species are peripheral or highly connected both within or among modules).

On comparing 2019 and 2021 data we found out that 2019 was a more densely connected network. Most of the network properties like degree density, nestedness, robustness, resilience etc. were found to be higher in the 2019 network. We also came to a conclusion that when nodes in the form of hub, modules etc. were removed in 2019 data not much change in properties was seen so we can say it is a stable network as compared to 2021 data in which the properties were getting affected on removing nodes again in the form of hubs,modules etc. Through this study we were able to show the basic nature of plant-pollinator networks in urban tropical ecosystem. The analysis done in this study can be compared to analysis done in other studies(for different regions across the world) and further insights can be drawn which can help in developing a better understanding for ecological conservation and sustainability.

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