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An approach of Complex Infrastructure Networks in Ecological Landscape

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Abstract

In recent years, complex networks have become more and more tools of interest to study dynamics related to land analysis. A further step forward was made studying ecological corridors, useful sets of land patches that connect areas of interest otherwise disjointed and independent. Ecological corridors have proven themselves as particularly useful in order to allow animals, mostly land animals, to migrate in case of adversity taking place in the area of origin, or starvation. It is now established that take care of single areas of interest, like those of the "Natura 2000" project, has shown its limits. Ecological corridors are therefore crucial for better preservation of fauna. However, it is not easy to understand what are the critical issues that lead to critical or unusable ecological corridors. This paper analyzes how patches of ecological corridors can quickly jeopardize the usefulness of the corridor itself and of the entire network which it belongs, even if from a first analysis they do not seem particularly important.

Keywords: *Complex Networks; Ecological Networks; Ecological Corridors; Connectivity*.

1. Introduction

Territory management is not a trivial task. The increasingly widespread presence of human infrastructures and technologies has increasingly reduced natural habitats [20] [14], vital areas to preserve and protect biodiversity on the territory. Now more than ever the idea of having to preserve areas and resources of various native animal species require is widespread.
However, it is unthinkable to stop technological progress, but is instead considered a useful tool to return to protecting biodiversity. There were surely innovations in landscape analysis through computer vision techniques and diffusion of satellite technologies [24] [26], but what was really required was a classification of areas and species to be examined.
This led to the creation of the Natura 2000 project.
European areas currently considered to be at risk have been brought together and standardized by the Natura 2000 project [7] [18]. Natura 2000 project has the main purpose of preserving the biodiversity present on European territory. This has been done to ensure the long-term maintenance of natural habitats and species of flora and fauna in danger.
However, the creation of the project was a useful improvement in the situation previously discussed, but the animal migration issue remains.
As has been explained extensively in previous studies [3] [9], the mere limitation of studying and managing single protected areas of reference now has little, if any, room for improvement. This has led the scientific community to become increasingly interested in other approaches, such as considering larger areas, with more varied and ambitious goals, rather than focusing on the specific one.
Despite, this leads to problems never encountered before.
Applying the use of complex networks in studied territories has led to new interesting considerations [22] [32] [5] [8] [31] and it also brought to observe the results on a much larger scale. The development of an adequate tool to monitor and apply conceptual analysis was essential.
QGIS is an open source geographic information system (GIS) [21] [12]. It is widely used for analyzing and editing geo-referenced files. These can be of various kinds, such as raster and vector formats. The files also may contain information related to the attributes of the map itself, allowing the user to perform some operations useful for statistical analysis and the study of the territory. Through simple geometric operations, it is possible to aggregate similar patches united by proximity or by attribute, making this an incredibly useful tool for most of the analysis of the territory that an environmental engineer may want to perform. Furthermore, the support for Python 3 and the existence of a dedicated QGIS library also makes it possible to execute scripts on individual layers of the project, allowing some operations to be automated.
Still, although valid tools such as QGIS exist for land studies, some problems remain unsolved. In this regard, in recent years the effectiveness of ecological corridors has begun to discuss.

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Ecological corridors have been designed to connect distant and non-communicating protected areas [23] [13] [11].
The presence of these corridors consequently allows the animal species to migrate if necessary. Ecological corridor, like areas of Nature 2000 project, is designed to coexist with human infrastructures already in the territory. It is a complex goal to obtain sometimes.
Previous papers [15] [10] [19] [1] try to give a valuable evaluation criterion of critical patches in an ecological corridor. Some proposes a process to create a classification of patches of land that make up the ecological corridor, considering them as nodes of a graph. The evaluation of the patches is then performed starting from the removal of nodes one at a time and studying the results in the complex network. In a nutshell, by removing one node at a time, it is possible to detect a cut node.
A cut node is a node of the graph which, if removed, divides the original graph into several subgraphs. In ecological corridors, the main goal is to continue to join two or more protected areas even in case of the removal of a cut node. Therefore, it is logical to deduce that the most problematic cut nodes are precisely those that separate the ecological corridor.
Some paper [10] also focuses on multiple metrics on evaluating a cut node, such as the magnitude of the second graph produced by the removal of the cut node, or such as the distance between the cut node and the nearest protected area. However, these considerations are partial if we consider a practical case.
Let's take for example variety of terrain, slope, presence and spread of water, climate and weather, presence of flora, presence of different animal species and their nutrients [17] [25].
It is not uncommon for two non-neighboring patches to have some similar, if not equal, properties. It is also necessary to consider local legislation, sometimes valid on some patches and not on others. These considerations lead to the realization that there can be various reasons why it is possible to unite patches, even if distant. The sudden removal of multiple patches, virtually not considered harmful, could leave a situation not previously contemplated, even harmful.
So the study of several patches of terrain considered as a cut node is therefore unexplored. Given the analysis made so far, it might be thought that the patches of land other than cut nodes are at least reliable, but depending on the graph examined, it is not easy to determine.
This paper proposes a study on the problem posed, and an approach to find pairs of nodes that can be defined as cut nodes. It was decided to call these nodes "second-degree virtual cut nodes", but for simplicity, the rest of the paper will refer to them just as virtual cut nodes.
Although the Natura 2000 project specifies distinct areas of biodiversity interest, it has not yet provided a standard for ecological corridors. Consequently, in the absence of official shapefiles, we will use those proposed by papers that have previously examined the metropolitan area of Cagliari, located in Sardinia, Italy [6].

Protected areas and ecological corridors who are located in Sardinia are actually particularly suitable to reflect the considerations previously made. That is because Sardinia hosts different types of landscapes, and some areas, even some of those that will be considered, are at serious hydrogeological risk [4]. Some studies also show how the chosen environment can aggravate with reckless human intervention on the environment [29]. In order to have a clearer idea of the network structure, the case study will be analyzed according to metrics that take into account the territory and the network in its completeness and complexity [30].

2. Case Study

As we saw, a useful approach to highlight cut nodes has been analyzed by combining various metrics, among the quantity, the size of the graphs resulting from the removal of cut node and the distance of this from the nearest Natura 2000 area.
However, the study [10] did not consider the close correlation that can exist between neighboring territories. Although it is objective that cut nodes are crucial points of the ecological network, in practical cases events that interest landscape is rarely limited to a precise patch.
It is easy to think about periods of drought, which can drastically affect the presence of the resources essential for animals to survive, or even floods, which happens frequently in some areas of Sardinia, like in Capoterra [2].
Despite Capoterra being part of the Metropolitan area of Cagliari, it is surrounded by protected areas and even crossed by some ecological corridors. For our studies, we will mainly focus on the Metropolitan area of Cagliari, in south Sardinia.
This makes the considerations made previously nevertheless scientifically valid and useful, but partial and not suitable in a practical and concrete case if used alone.
There may indeed be groups of nodes considered unrelated or non-dangerous if taken individually, but if taken together they may cause the same effects as a removal of a single cut node from the network, or even worse.
The work presented in this paper generalizes the idea, allowing us to understand which patches of land are linked and providing a basic ranking of which are the most dangerous nodes if taken collectively, focusing on second-degree virtual cut nodes.
This makes it unprecedented not only for the consideration and application of the ecological corridors on the landscape, a tool that has not yet reached its maximum potential and which can become increasingly more useful, but also for a practical and objective reading of the corridor itself.
Simply considering the corridor as an immutable reality represents an obstacle to understanding its function in the territory and for the fauna, and this paper brings the research one step to a higher stage by focusing on the profound connection that the single patches can have between them, in their various combinations. This allows not only to identify critical patches, but with a careful analysis also to use this information to acquire data on new connections in the territory, whether they are about environmental risks, fauna migration or plant conservation.
Additional consideration of their application to find breakpoints in ecological corridors will be analyzed in further studies. It's possible to suppose that this is more likely by increasing the degree of virtual cut nodes, still, it has not been studied how it is related.
It is also necessary to specify that the properties of a pair of nodes involved in a virtual cut node are transitive. In fact, if the order of removal of the nodes from the considered graph is inverted, the creation of a new virtual cut node is still guaranteed. Nevertheless, for the sake of simplicity, we will refer to the node removed first as a parent virtual cut node, and to all the nodes with which it could join in a virtual cut node as child virtual cut nodes.

3. Research of second-degree Virtual Cut Nodes

Libraries of the QGIS API Documentation were used for graph building.
Graph *G* will represent from now on the network of ecological corridors.

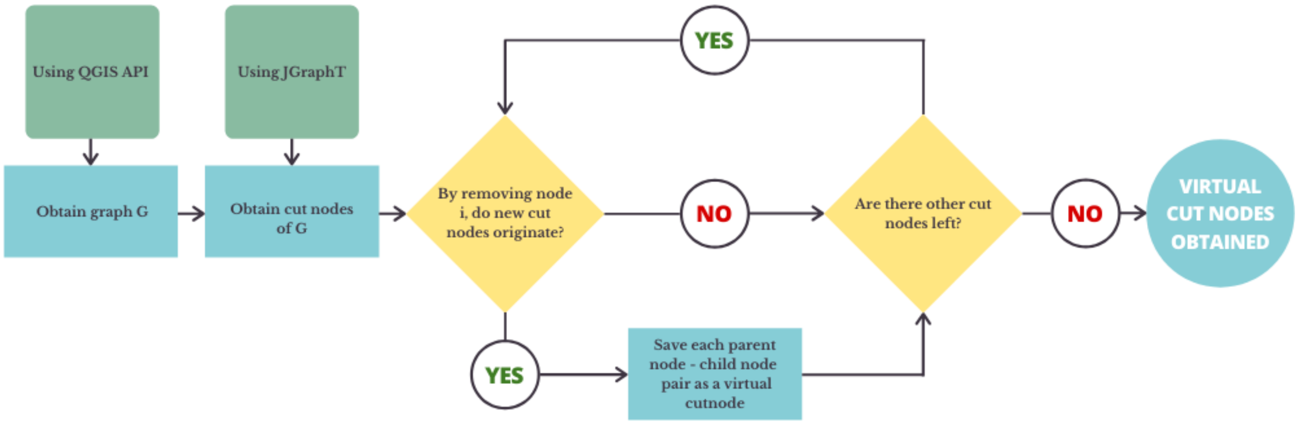

Fig. 1. Algorithm flow required to find Virtual Cut Nodes

It indicates single patches as nodes and the reachable pairs of nodes as edges.

A custom Python script was developed for this purpose and it was then executed on QGIS shell and applied to the corridor layer mentioned above.

The analyzes regarding the identification of cut nodes were instead implemented in Java, with open source library JGraphT [16]. By sequentially executing these codes we can already collect the first information on graph *G*, which includes:

- Nodes = 6995
- Edges = 17464
- Cut Nodes = 569

From this first estimation, is possible to see that about 8.13% of nodes are cut nodes. It is important to reiterate that these cut nodes do not necessarily break the ecological corridor. However, they create subgraphs, sometimes even formed of single patches, no longer connected to the main ecological corridor.

```
#with open source library QGIS
graph = Graph.get_graph_from_layer(path_to_ecological_corridor)

#implemented in Java, with open source library JGraphT
graph.compute_cut_nodes()

print(graph.count_nodes)      #6995
print(graph.count_edges)      #17464
print(graph.count_cut_nodes)  #569

virtual_cut_nodes = dict()

for parent_node in graph.nodes:
    graph_i = Graph.get_graph_without_node(graph, parent_node)
    graph_i.compute_cut_nodes()

    if graph_i.count_cut_nodes > graph.count_cut_nodes:
        set_a = graph_i.cut_nodes
        set_b = graph.cut_nodes

        #save in dictionary the parent node and his children
        virtual_cut_nodes[parent_node] = set_a.difference(set_b)

print(virtual_cut_nodes)
```

Fig. 2. Example code needed to perform Virtual Cut Nodes research

To highlight the response of the network from the removal of an extra cut node, it is necessary to re-execute the Java code for the cut node search.

Starting from graph *G* obtained from the layer it is now possible to produce n G_i graphs, with n equal to the number of nodes of the graph *G*. Graphs G_i will be different from graph *G* due to the absence of one of his original nodes and the consequent edges that involve it. The missing node will be a candidate parent node of the virtual cut node. Applying one more time the cut node search on graph G_i and comparing it with the original cut nodes list, is now possible to recognize which are the children of the virtual cut node. The whole process can be easily understood by the flowchart in Figure 1 or by simple pseudo-code on Figure 2.

Table 1. Count of detected second-degree Virtual Cut Nodes, divided by pairs of nodes that can also include an old Cut node or completely new ones. The count is also determined by grouping child virtual Cut nodes with parent virtual Cut nodes

	Virtual Cut Nodes	Parent Nodes
All	1610	1021
Without Original Cut Nodes	887	751

Table 1 shows that the number of virtual cut nodes is far superior to the original cut nodes. If the removal of a virtual cut node is considered as a normal cut node, 23% of nodes are potentially dangerous. Removing original cut nodes from virtual cut nodes found, the percentage drops to 12.68%.

So the analysis showed that also original cut nodes are involved in some virtual cut nodes, but they are not involved in all cases. Removing the original cut nodes from the list of virtual cut nodes it is possible to observe that the number of brand new virtual cut nodes is higher compared to the number of original cut nodes.

Another not trivial property to understand without graphic support is that the pair of nodes that compose the virtual cut node are not always adjacent, but they can also be quite far away depending on the conformation of the graph.

Figure 3 shows an increasingly detailed zoom of a portion of the ecological corridor used as an example. In the ecological corridor shown we can see a cut node and several virtual cut nodes, one for each parent-son pair. In the presented case, it is clear that the parent node is much more dangerous than its children, as these, if removed, do not generate a number of children greater than or equal to the parent.

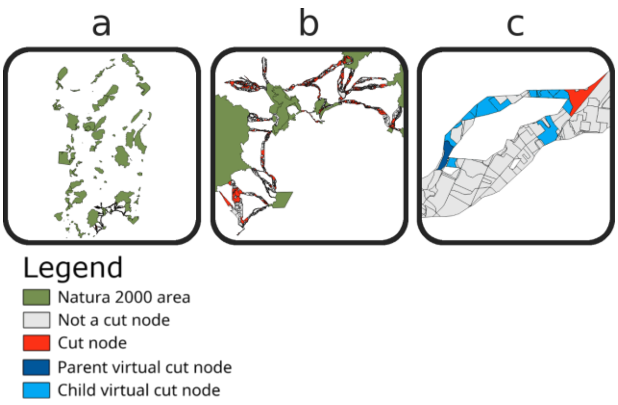

Fig. 3. (a) Natura 2000 areas in Sardinia; (b) Ecological Corridors; (c) Cut node and Virtual Cut nodes

Finally, the approach used proved to be adequate in order to highlight the vulnerabilities that cannot be considered in a superficial or local study of the landscape. The impressive number of virtual cut nodes shows that the study of single cut nodes and their peculiarities remains, although detailed, partial. Even if dangerous, a single cut node could be more difficult to remove than other virtual cut nodes, perhaps linked by temporary food shortages, or disrupted by weather agents that are especially violent in those patches.

4. Further Theoretical Iteration

We analyzed and established how the cut nodes single considered as stand-alone criteria can lead to superficial consideration.
In fact, the examination of this variable alone does not take into consideration the study of the entire network as a more complex reality, which is not limited to the simple composition of nodes and edges.
The mathematical approach to the network without further information on the structure of the territory, the species that live there, and the atmospheric conditions that rage and the multitude of actual cause-effect relationships that come into play are almost limited.
The information gathered about migrations in the first place would bring the value of the analysis to a whole new level, especially if united with the ubiquitous computing and effective monitoring of the single specimen [27], obviously if well-integrated for this specific task.
However, it is an established reality that there are local and administrative situations that make it complex, if not completely impossible, to access to valuable and crucial information about the land, which would make the difference between a quality analysis of the territory and the composition of the network from a mediocre one.
Once established, let's focus on the algorithm itself. From a purely mathematical point of view, or rather in absence of any additional information on the ecological corridors taken into consideration if not the conformation of the graph resulting from their analysis, it is possible to affirm that if we compare virtual cut nodes of various degrees that generate analogs subgraphs for numbers and dimensions, the most dangerous ones are those of lower grade.
By accepting this consideration, it is possible to assign to the network a score calculating the greatest possible degree of virtual cut nodes that can be found. The idea behind it is that an ecological corridor composed only of cut nodes or low degree virtual cut nodes will obviously be more fragile than a network that offers more nodes that can be lost without affect dramatically the practicability of the ecological corridor.
It is now possible to define an algorithm that iterates the search for virtual cut nodes of increasing degree by excluding discovered nodes belonging to lower degrees from subsequent iterations.
As explained in the previous chapter, single nodes can in fact be part of different virtual cut nodes with different degrees, but for this analysis, we will consider those of a lower degree more critical, so that the analyzed nodes will be cataloged in the first degree in which they will be discovered to be part of.
The recursive algorithm will exit from the loop if there are no more nodes to match. The loop is defined as follows:

- List *m* of matched nodes (originally empty) contains virtual cut nodes already spotted. List *m* so contains the virtual cut nodes of degree $< k$ with $k >= 1$. *k* represents the number of iterations of the loop;
- Calculate virtual cut nodes of *k* degree from original graph *G*. The nodes that must be analyzed are those which are not listed in *m*;
- Store the virtual cut nodes of *k* grade found in list *m*. For further in-depth analysis, is useful to keep track of their grade and composition.

The highest degree *k* achievable with this algorithm can be another criterion for testing the solidity of the network structure. The examination of virtual cut nodes compared to the size of the corridor analyzed and the number of nodes that compose it can give an additional useful measurement grade.
This is vital from a genuinely mathematical point of view when there is no further data, however, it can also be a modest but meaningful extra value in the case was desired to calculate a potential overall score given by the union of the various considerations made so far on the various classification scales.
A wide distribution of virtual cut nodes of different degrees means little dependence on single nodes or single groups of nodes, and therefore the possibility of accessibility of the corridor even if weakened by numerous critical issues.

5. Data and Considerations

The study showed that even between second-degree virtual cut nodes there are significant variations in quality. In fact, some parent nodes generated an impressive amount of children, as shown in Tables 2 and 3.
This way to evaluate nodes is so solid that in larger projects could be an essential metric for evaluation.
Like all considerations previously made, however, it must be remembered that this depends profoundly on the ecological landscape, and therefore on the graph generated and taken into consideration. In most cases, initial analysis is applied on a healthy network.
For further studies, subgraphs or paths specifically optimized to walk across the network [28] could be considered in case of specific events that put the network itself or the species that live there in danger. These optimized sub corridors will have to be designed in order to be well suited with the behavior of the species in case of emergency and lead them in a secure area in a relatively small period of time. Therefore other specialized expertise will be required for their realization.
The data also showed that the nodes that constitute a second-degree virtual cut node necessarily become cut node if their partner is removed from the graph. However, if it is true that the removal of the parent node causes the creation of a cut node corresponding to the child node and vice versa, it is not necessarily true that the removal of the child alone generates as many children.

It is also important to note that the approach to creating the necessary data is computationally onerous. This approach performs exponential complexity in data collection only, because of the need to recalculate every cut node present in each graph G_i generated for the study. It can be noted that the generation of a different structure of the graph or the addition of a new point requires a calculation of the cut nodes starting from the beginning. It is probably possible to better design the process by better analyzing the problem at the code level.

Table 2. All Parent Cut Node and Child Cut Node, original Cut Nodes included

Parent Cut Node	605	159	73	53	28	23	17	13	7	13	20	3	1	2	1	1	1	1
Child Cut Node	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	25	28	37

Table 3. Only brand new Parent Cut Node and Child Cut Node

Parent Cut Node	474	107	47	31	15	17	10	7	6	12	18	3	2	1	1
Child Cut Node	1	2	3	4	5	6	7	8	10	11	12	13	15	16	25

6. Conclusions and Future Works

The study and analysis of second-degree virtual cut nodes have shown that the use of complex networks in the ecological landscape analysis as a useful tool is still largely unexplored. It has been seen that, considering all virtual cut nodes, 23% of the nodes could be potentially dangerous.

This is not a negligible result when something that can affect different and distant patches such as floods could append. The use of virtual cut nodes as a method of further analysis is useful to pursue a more comprehensive view of the interconnection of patches, impossible to ignore in this field. Certainly, the theory behind virtual cut nodes can be generalized to offer additional value to rank nodes in the study of the landscape.

A factor that would make the difference and drastically improving the analysis of complex networks would be the presence of historical data concerning animals or plants already in the various territories.

Even have additional meteorological and natural risks data would be essential for more accurate analyses. In this way it could be even more evident the affinity between territories and ad hoc design solutions could be designed.

For future developments, these and other types of scores could also be automated, such as the number of minimum steps required for a node to become a cut node, or the number of minimum steps required to reach a secure area.

Ultimately, it would be very beneficial to have an accessible dataset of ecological corridor shapefiles. The creation of non-standardized corridors may in the long run or in large projects lead to problems of conflicts, and their absence forces the study of network aspects only on a low scale.

Nomenclature

Notations

G — Graph composed by the analysis of the ecological corridor, formed by nodes, that represent the individual patches of land, and by edges, that represent the relationships between neighboring patches

n — Number of nodes contained in the graph G

G_i — Subgraph obtained by removing one of the n nodes from graph G

m — List of nodes classified as part of virtual cut nodes in the recursive algorithm used to spot the maximum virtual cut node degree foundable

k — Number of iterations of the recursive algorithm used to spot the maximum virtual cut node degree foundable, and also maximum degree found

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