Performance of Multicriteria Evaluation and Heuristic Methods in the Delineation of Green Infrastructure in Areas with Fragmented Landscapes

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Abstract. The EU Commission has established Green infrastructure as one of the tools to preserve biodiversity and grant the provision of ecosystem services that reduce impacts on natural values like those produced by climate change. Therefore, a European green infrastructure strategy has been created that commit member states to incorporate green infrastructure to their territorial planning. Yet, methodologies to delimit green infrastructure so as to facilitate its inclusion in territorial plans are still scarce. The available methods are mainly based in multicriteria evaluation and focus on zoning general green infrastructure areas taking into account the provision potential of just a few ecosystem services. Considering the provision of a wide range of ecosystem services to delimit green infrastructure elements is key to grant their multifunctionality and increase their efficiency mitigating climate change impacts in natural values and human population. However, the lack of data or the high cost to accurately map ecosystem services provision potential, leads most of the time to infer it from land cover data. This creates problems when using these maps to delimit green infrastructure in areas with fragmented landscapes; since identified green infrastructure areas may be irregular and scattered. There are heuristic methods like simulated annealing that have been used to identify ecosystem services hot spots which consider the regularity and size of the identified patches. These methods can be used to delimit green infrastructure in fragmented landscapes finding a balance between the regularity of the areas and their potential to provide multiple ecosystem services. In the current work, a comparison has been made between the performance of simulated annealing and current multicriteria evaluation methods to delimit green infrastructure multifunctional buffer zones in an area of north-western Spain with a very fragmented landscape. Results have shown that simulated annealing delimits more regular multifunctional buffer areas but with a less average potential for providing multiple ecosystem services. The conclusions of the paper indicate that simulated annealing is good produces more regular multifunctional areas but with a lower ESs provision potential. It was observed that in the case of ESs that were mapped considering factors at landscape scale, their provision potential did not vary too much between the multifunctional buffer areas delimited with each of the methods. This indicates that delineation methods may produce more regular GI elements if ESs provision potential is mapped considering the influence of biophysical factors at a wider landscape scale.
1. Introduction
The EU Biodiversity Strategy for 2030 [1] identifies climate change as one of the main drivers of biodiversity loss. In this sense, the document highlights that integrating green infrastructure (GI) into planning can help to mitigate climate change and other impacts on natural values by ensuring the provision of ecosystem services (ESs) that play an important role on climate change mitigation and human population wellbeing.

In line with the recommendations of the Biodiversity Strategy, the Communication of the European Commission "Green infrastructure: Enhancing Europe’s Natural Capital” [2], sets the basis for the creation of an European GI strategy, which commits member states of the European Union to incorporate GI to their planning. The communication of the commission defines the Green Infrastructure as a “strategically planned network of natural and semi-natural spaces and other environmental elements designed and managed to offer a wide range of ecosystems services”. Bearing in mind this definition, it is necessary to consider the provision potential of an area to provide ecosystem services (ES) in order to plan multifunctional GI elements that ensures the provision of multiple ecosystem services [3].

Despite the progressive incorporation of GI into planning [4], methodologies to delimit multifunctional GI elements and facilitate its inclusion in territorial plans are still scarce. The most widely used methods to delimit GI are based in Multicriteria Assessment Analysis. These methods frequently use weighted sums to aggregate data on ES provision potential together with other criteria so as to identify the areas with a higher potential to locate GI element. Methodologies such as the one developed by Lique et al., [5] combine the potential for the provision of different ecosystem services and ecological connectivity to delimit GI. Other methodologies to locate hotspots of ES provision potential can also be used to delimit GI like the one developed by Kopperoinen et al., [6]. This methodology assesses the provision potential of several ESs through the combination of GIS data with the participation of local and regional experts and actors. Others such as Aguilera Benavente et al., [7] define the elements of the GI by evaluating ecological connectivity, ecological status, multifunctionality and permeability obtaining an overall GI index. The aforementioned methods do not define elements of GI with specific functions such as mitigating the impacts of climate change, while taking into account their multifunctionality by ensuring that they provide a wide range of ESs.

The mapping of the provision potential of a wide range of ESs in order to delineate GI elements that provide a wide range of ESs, is costly due to the lack of data [8]. This limitation is frequently overcome by considering land cover maps as a proxy of ecosystems in order to estimate their potential to provide ESs [8]. However, when using the obtained maps in methods based in multicriteria assessment analysis to delimit multifunctional GI elements in areas with a high land cover fragmentation, the resulting delimited elements are irregular and scattered [9].

Heuristic methods, which have already been used to delimit ES hotspots [10] or GI areas in several scenarios [11], can address the problem of irregularity of the delimited GI elements. These methods allow incorporating criteria such as the size or compactness of the delimited areas or the proximity to other elements such as corridors or GI core zones [9]. This allows delimiting larger and more regular GI elements in areas with fragmented landscapes, that have a greater potential for the provision of ESs [10]. However, heuristic methods require more execution time and some knowledge on how to adjust their optimization criteria.

In the current work, a comparison has been made between the Multicriteria Assessment Analysis used in Garcia et al. [9] and a Heuristic method based on a simulated annealing. Both methods were used to delimit multifunctional buffer zones that contribute to mitigating the impacts of climate change.
on the natural values of the core areas of GI while granting the provision of many ESs. The methodologies are applied in the area of Lugo, in the region in Galicia (Spain). This area contains several Sites of Community Importance (SIC) that host high natural values which are proposed to be incorporated to the Natura 2000 biodiversity conservation network of the European Union. Most of the SIC are associated with riparian habitats and wetlands of the Miño River. The comparison between the two methodologies was made using spatial metrics to analyze the regularity of the multifunctional buffer areas delimited with each of the methods and zonal statistics to see which method produces areas with greatest higher average potential for providing multiple ESs. The results showed that although simulated annealing delimits larger and more regular areas, the resulting GI elements have a lower average potential for providing ESs than those delimited with Multicriteria Assessment Analysis.

2. Materials and Methods

2.1. Study area

The study area comprises the city of Lugo and other 7 limiting municipalities, which are located in the region Galicia, on the northwest of Spain (Figure 1). This area is in the edge of the inland flats of “A Terra Chá” and is crossed from north to south by the Miño River. There are important natural values associated with the river and its wetlands which have been delimited in SICs that have been included in. Lugo is the biggest city in the area with approximately 100,000 inhabitants. The city produces some pressure on river ecosystems due to its proximity. Likewise, the region is mainly agricultural with an important service sector due to the influence of Lugo.

Figure 1. Location study region of Lugo

Lugo area, as the rest of Galicia, has a rather fragmented landscape mainly due to the orography and the fragmentation of land property. 60% of the population of Galicia owns land and each land owner owns 7 plots on average resulting in an average plot size of 0.25 ha [12]. This heterogeneity of the landscape makes it difficult to define compact and regular multifunctional areas.

Taking into account the possible climate change impacts in Europe listed in the IPCC report [13] those which are more likely to affect the study area are increased extreme precipitation events with the consequent increase in erosive processes and floods. There may also be more frequent summer droughts that can increase water deficits due to increased evapotranspiration. Hottest, drier summers can increase the increase the risk of wildfires. Higher precipitation can also lead to the pollution of
aquifers and surface water due to nitrate leaching, as well as a decrease of soil fertility. Other impact in the area may be a higher incidence of agricultural and forest pests and diseases as well as the proliferation of invasive species which together with changes in ecosystems and compositions of animal and plant populations, can result in a loss of biodiversity or the displacement of some animal and plant population to higher latitudes and altitudes.

Climate change effects together with the impacts produced by agriculture and urban activities in the ecosystems of the river create the need of delimiting multifunctional buffer areas around SICs in the area that grant the provision of a wide range of ecosystem services involved in the mitigation of the aforementioned impacts.

2.2. Ecosystem services

The first step to delimit multifunctional buffer areas to mitigate climate change and other impacts in natural values is identifying those ESs which are more related to impact mitigation. Therefore, those ESs taken as a reference are the ones listed in the Common International Classification of Ecosystem Services (CICES) version 5.1 [14]. Bearing in mind the possible impacts associated to climate change and human activities in the area, the selected ESs were:

a. Filtration, sequestration, storage or accumulation of contaminants by microorganisms, algae, plants and animals.
b. Erosion control
c. Hydrological cycle regulation
d. Fire protection
e. Pollination
f. Maintenance of breeding populations and habitats (including protection of the genetic pool).
g. Pest control
h. Regulation of the climatic composition of the atmosphere and oceans: Carbon absorption, Short-term carbon capture, Long-term carbon capture.

These ESs were mapped. The methodologies that were used to map them were mainly based on land cover data and obtained with weighted sum models where several environmental and biophysical factors were considered. In the case of other ESs where more data were available like pest control and maintenance of breeding populations and habitats; they were obtained with regression models that relate the presence or absence of certain animal species with environmental and biophysical variables. In the case of pollination, the methodology used in InVEST software [15]. The variables and methodologies that were used are described in more detail in García et al., [9].

2.3. Methodology

The method based in multicriteria assessment analysis to be used for delimiting multifunctional buffer areas is the one described in García et al. [9]. This method calculates a map of the average provision potential of all the considered ESs. Then the 20% of the cells with the highest average potential are selected which result in a number of patches with the highest potential. The patches with an area less than 100 ha are eliminated because they are considered not to be big enough for making a proper management in them. Finally, only the remaining areas that are in contact with core areas and corridors of the GI are kept. The holes in the delimited areas and the gaps between buffer areas, corridors and core areas are filled if they have an area less than 5 ha were added to buffer areas if they corresponded with natural land covers.

The method based in the simulated annealing delimits areas that maximize both the criteria of having a high potential for providing several ESs and have a regular surface which is close to core areas and corridors of the GI. This is a multi-objective optimization problem which is tackled by an
iterative global optimization algorithm [16] [17] that generates random solutions (departing from an initial selection) with a known probability distribution of error that decreases over time. The process converges to the optimal solution after a sufficient number of attempts. It is defined by providing: an objective function that assigns a numerical value to each possible selection of spatial units, proportional to the distance with the ideal solution (optimal value); a process for the generation of new solutions from the current one; and various parameters for the management of the iterative process and the evaluation of solutions.

To adapt the algorithm to the current problem:

- We rasterize the study area. Each selection of cells is a possible solution, which will be evaluated by applying the objective function. The ideal solution will have the lowest possible value of this (that is, during the execution the cost is minimized).

- We define an objective function that is a compromise between spatial criteria relevant to the problem and its calculation time. The function seeks to maximize the ecosystem value of the solution (each cell takes a numerical value that represents the potential of all the ecosystem services present at that point, with a combination of weights selected by a process of public participation), to minimize the number of continuous fragments of selected cells and to maximize their compactness by minimizing their total perimeter. Those three criteria (value, number of fragments, and their perimeters) are combined using user-selected weights.

- We implement the process of generating new solutions by randomly changing the position of a selected cell. Thus, the total number of selected cells does not vary, but their spatial distribution does. A solution is accepted if the value of the objective function is reduced, or if the error is less than the Boltzmann probability distribution (which depends on a parameter that varies in time; a linear evolution). We start with a random initial solution.

- We establish a maximum execution time. It can be proved [18] that the Simulate Annealing converges at the limit to the optimal solution with probability 1. However, practical implementations alter this property by forcing it to terminate in a finite and predictable maximum time. In this case we establish a limit based on the number of solutions generated. And since it is a stochastic process, each execution can generate different solutions even with the same initial conditions.

As a result of running this algorithm, we obtain several continuous sets of cells in high potential zones. A second algorithm is used to reduce this number and prioritize the most valuable ones. In this case, since we are calculating buffer areas, they are those next to corridors. The end user can modify input parameters, weights, and limits to influence the result.

The Simulated Annealing that we have implemented differs from the traditional description in some basic aspects that seek to simplify its use and reduce the calculation time necessary to find good solutions:

- Each term of the objective function is automatically normalized, so that it is easier to understand and adjust the influence of the weights assigned to each term. To do this, the process is executed for a time, recording the change in value due to each term, and this information is used to calculate a normalization constant per term. The solutions obtained are discarded.

- The Boltzmann probability distribution is automatically scaled to force an initial user-supplied solution acceptance rate. To do this, the process is executed for a time, recording the acceptance rate, and this information is used to calculate a scaling constant. The solutions obtained are discarded.
The calculation process is automatically adjusted to extend the solution exploration phase of the Simulated annealing so that, if the probabilistic acceptances disappear too early, the parameter that controls the temporal evolution of the probabilistic acceptance rate is slightly reduced, they are discarded the solutions obtained, and the process is restarted with the new value.

During execution, the generation of solutions does not change the position of a completely random cell, but rather the target position is modulated by the ecosystem potential value of the cell, under the assumption that these cells are more likely to form part of the final solution.

The process does not generate a completely random initial solution, but rather the value of distance to corridors is used to modulate the probability of selection.

Core areas were considered to be the SICS mentioned above and corridors those delimited by the Institute of Agricultural Biodiversity and Rural Development of the University of Santiago de Compostela (IBADER) based on the river network of the region.

3. Results and discussions
Multifunctional buffer zones were delineated according to the two methods explained previously, producing the maps shown below (Figures 2 and 3).

![Figure 2. Core areas, corridors and multifunctional areas Simulated annealing](image-url)
Reviewing the obtained maps, it can be observed that less area is delimited with the methodology based on multicriteria assessment analysis. This is because the obtained areas are very small and scattered due to landscape fragmentation. Therefore, the smallest patches are eliminated. In addition, many of the large patches that are not connected to the core areas and corridors of the GI are also eliminated, causing a higher loss of delimited area.

In the case of the delineation obtained with the simulated annealing, the obtained areas are much bigger and regular.

The regularity of the multifunctional buffer areas delimited with each method was analyzed using spatial metrics. With this aim, it was considered the mean fractal dimension (FRAC_MN) of the delimited areas as a measure of their edge irregularity and the mean area (Area_MN) as a measure of their size (table 1). These metrics were calculated using the software FRAGSTATS.

| Method          | FRAC_MN   | Area_MN   |
|-----------------|-----------|-----------|
| Simulated annealing | 1.0909   | 348.3489  |
| MCA             | 1.1576    | 88.2542   |

The results in table 1 show that the methodology based in multicriteria assessment analysis produce smaller and more irregular patches.

As regards to the multifunctionality of the delimited areas. Zonal statistics were used to measure the average ESs provision potential of the areas delimited with each method. The average potential for the provision of ESs (Table 2) and the average number of ESs was analyzed with a high or very high provision potential of buffer zones (Table 3).
Table 2. Zonal statistics related to the average supply potential for ESs within buffer zones.

| Ecosystem services | Mean  | STD   |
|--------------------|-------|-------|
| S. Annealing       | 0.41905 | 0.125685 |
| MCA                | 0.541537 | 0.063199 |

Table 3. Zonal statistics related to the average number of ESs with high provision potential in buffer zones.

| Ecosystem services | Mean  | STD   |
|--------------------|-------|-------|
| S. Annealing       | 2.306472 | 1.947746 |
| MCA                | 4.392352 | 1.187145 |

Having a look at tables 2 and 3, it can be observed that the simulated annealing delimits areas with a lower average ESs provision potential and that produce a lower number of ESs. The standard deviation of the mean ESs provision potential and the number of ESs in the areas delimited with the simulated annealing is higher, indicating that there is a high variation of these values.

In order to have a deeper insight in the provision potential of each ES in the delimited areas we show in Table 4 the average potential for each of the ESs considered in the multifunctional buffer zones delimited with both methods.

Table 4. Zonal statistics related to average buffer potential for each ESs.

| Ecosystem services | S. Annealing | MCA |
|--------------------|--------------|-----|
| Filtration         | 0.294728     | 0.478543 |
| Erosion control    | 0.615044     | 0.870402 |
| Hydrological cycle regulation | 0.342128 | 0.44379 |
| Fire protection    | 0.479432     | 0.484431 |
| Pollination        | 0.372839     | 0.537227 |
| Breeding populations | 0.711233 | 0.729765 |
| Pest control       | 0.556464     | 0.564106 |
| Carbon absorption  | 0.139665     | 0.233248 |
| Short-term carbon capture | 0.399465 | 0.799849 |
| Long-term carbon capture | 0.292085 | 0.293154 |

Table 4 shows that in the case of ESs mapped combining land cover and other biophysical factor with and added weighted sum, the average provision potential is lower in multifunctional buffer areas delimited with simulated annealing. Only in the case of Maintenance of breeding populations and habitats and Pest control, the average provision values are similar in the areas delimited with both methods. The provision potential of these ESs was not directly estimated from land cover patches; it was inferred from landscape and biophysical variables present in an area. As a consequence, landscape fragmentation does not when the simulated annealing includes in the delimited area land cover patches which do not have a very high average provision potential in order to find a balance between the regularity of the delimited patch and its average ESs provision potential, the average provision potential for these two ESs is not significantly reduced. Even though there are ESs that are very influenced by land cover [19] [20] , some authors suggest considering wider landscape areas by the time of identifying spots with a high potential for providing several ESs in order to avoid fragmented patterns [21].
4. Conclusions
The simulated annealing has shown to delimit more regular and bigger multifunctional buffer areas. In addition, this method controls better the areas of the delimited multifunctional buffer zones. Yet, the average ESs provision potential for these zones is lower with respect to methods based multicriteria assessment analysis. On the other hand, analysing the individual provision potential of ESs, it has been observed that the provision potential of ESs which are mapped considering biophysical variables at landscape level do not vary too much in the areas delimited with each of the methods. This indicates that if the landscape structure is considered by the time of delimiting GI elements, land cover fragmentation will not have a high impact on the size and regularity of delimited areas. Therefore, if the influence of biophysical factors in mapping SE provision potential is considered on a broader landscape scale, delineation methods can produce more regular GI elements. In fact, some authors suggest to considering wider landscape areas to identify less fragmented ESs hot spots [21].

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