ESTABLISHING LIMITS TO AGRICULTURE AND AFFORESTATION: A GIS BASED MULTI-OBJECTIVE APPROACH TO PREVENT ALGAL BLOOMS IN A COASTAL LAGOON

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Abstract. Biodiversity conservation and ecosystem services provision can compete with other land uses due to its incompatibility with many productive activities. The need for multifunctional landscapes that simultaneously provide food security, maintenance of ecological functions and fulfill welfare requirements is evident. Multi-objective optimization procedures can select between different land uses in each parcel of the territory, simultaneously satisfying contrasting objectives. Each solution (a map) represents a spatial configuration of land uses, generating spatial alternatives and offering flexibility to conduct discussions among social actors. In order to prevent eutrophication we developed a methodological approach for planning land-use transformations in productive territories, considering ecological processes from the beginning. A two-objective approach was used to allocate different land uses in the most suitable sites (objective one) that simultaneously minimize nutrients exportation (objective two). The land uses allocation was Pareto optimal and was conducted by integer linear programming. According to the relative importance given to each objective, two types of land use allocation were obtained, one dominated by agriculture but where a threshold of phosphorus load was exceeded, and another one where conservation and livestock ranching on natural

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1. Introduction. Productive activities and natural ecosystems usually coexist in the territory as a result of the history of land uses in the zone, but generally not responding to any integral planning process. Both of them are of primary importance to social welfare and biodiversity conservation, but many times compete between them for available land, promoting tensions and conflicts among social and institutional actors. Conflicts among land use sectors occur when sector activities jeopardize or reduce the capacity of other sectors to exploit a specific area, i.e., when competing land uses overlap in space [6, 7]. Conflicts usually drive to environmental and social impacts, as well as to a great inefficiency in the system which in turn reduces its capacity to maintain productivity, biodiversity and human welfare. A major challenge of humanity is to learn how to organize itself to reverse the negative trends in the environment and to effectively deal with the common pool character of natural resources [45]. It is recognized that food production and production efficiency need to be increased to satisfy the increasing world demand and to increase human welfare, but there is no doubt that this increase must be sustainable [27]. In this context, the need for multifunctional landscapes that simultaneously provide food security, livelihood opportunities, maintenance of species and ecological functions, and fulfill cultural, economic, aesthetic and recreational needs is now recognized [34, 44].

Therefore, in complex situations where multiple combinations of land uses are possible at different areas, planners need novel tools that can overcome complexity to feed land planning processes. Under such situations, a systematic process of both analysis and synthesis is needed to choose among all options of configuration of land uses allocation in the territory, which must indeed be spatially explicit. Combinatorial optimization [47] is a suitable tool for tackling this complexity, given its ability for optimizing a given measure, which depends on the way of combining many elements from a given discrete domain. In addition, when several contrasting objectives are present, multi-objective optimization procedures select between different land uses in each parcel of the territory, simultaneously satisfying contrasting objectives and achieving Pareto optimal solutions [20]. Each solution (a map) represents a spatial configuration of land covers and uses. These procedures may generate a high diversity of alternatives and bring ways of analyzing synergies and tradeoffs among objectives [14], offering a great flexibility to conduct discussions among different social actors and for the decision making step [29]. During the process and from the very beginning, decision makers can be integrated during different stages [13], as well as stakeholders, promoting deliberative [33] and knowledge broken [48] processes.

Multi-objective optimization may be conducted through exact methods with mathematical programming or by heuristic optimization techniques. Multi-objective linear programming (eventually including integer variables) requires two or more objective functions that cannot be improved for one objective without compromising any of the other objectives involved, or a single-objective function which is optimized subject to a number of mathematical constraints. Algorithms are available to find the values of the decision variables that maximize or minimize the objective function/s while satisfying the constraints. These techniques find the optimal solution, although in practice the inherent complexity of the spatial problems or its
sizes can impede the calculation or it is too time consuming. In these cases, genetics algorithms \cite{30, 62} or simulated annealing \cite{57}, can be alternative methods, among others \cite{39}, but optimality of solutions cannot be guaranteed and algorithm programming, calibration and validation can be out of the capacities and time frame of the planning process.

Eutrophication is the main cause of degradation of aquatic ecosystems \cite{46}. Despite it is caused by multiple factors and it is accelerated by climatic change \cite{32}, in rural zones land uses are among the main sources of nitrogen and phosphorus \cite{12, 41, 60}. Generally, natural cover supplies less amount of nitrogen and phosphorus than agriculture and animal farming activities \cite{31, 56, 60} which is mainly caused by fertilization and farm management practices. In many soils and regions fertilization is unavoidable to increase crops productivity, due to the low natural levels of nutrients \cite{65}. Despite the aquatic ecosystems are resilient to the nutrient load increase, a shift from a clear water state to one dominated by harmful phytoplankton is a major risk if loads continuous to increase \cite{58, 64}, jeopardizing the social benefits obtained from these ecosystems \cite{9}. Natural mechanisms exist in the catchment area, as well as in the aquatic ecosystems to overcome the impacts of the increase of nutrients. Buffer strips, littoral wetlands and fluvial forests offer the ecosystem service of nutrients load retention and reduction \cite{1, 42}, attenuating the impacts of land use intensification.

Eutrophication prevention is the kind of problem that may have an approach of multifunctional landscapes. Under this perspective some ecosystems may be destined to food production, while others should be maintained natural or even be restored, in order to retain the functions that mitigate impacts and sustain productivity and other social benefits. To do so, spatial explicit approaches are needed to allocate different and competing land uses in the territory.

The aim of this study is to present a methodological approach when planning for land-use transformations in productive territories, preventing eutrophication from the beginning. The approach was applied to a case study in a basin that is undergoing an accelerated process of land-use change in Uruguay, South America. Specifically, we build a multi-objective approach to allocate different land uses in the most suitable sites that simultaneously minimize nutrients exportation to avoid eutrophication. The land use allocation was Pareto optimal and was conducted by integer linear programming, based on maps of land suitability for different land use sectors (obtained from \cite{53}).

2. Study area and problem description. Laguna de Rocha (Uruguay; $34^\circ35'S - 54^\circ17'W$) is a subtropical choked lagoon located in Uruguay (South America); it has a surface area of 73 km$^2$ and an average depth of 0.6 m (Fig. 1), with a catchment surface area of 121.433 ha. The lagoon periodically connects with the Atlantic Ocean through a channel that opens through the sand bar, one to several times a year \cite{15}, determining a steep salinity gradient. Hydrology is the driving force for the functioning of the entire ecosystem \cite{8, 16, 36, 54, 59}. Due to its outstanding biodiversity, multiple protection categories have been declared for the area. It belongs to a Biosphere Reserve (MAB-UNESCO Program), a Ramsar Site and to the National System of Protected Areas.

Native grasslands are the predominant ecosystem \cite{53} which sustains the most important land use, livestock ranching (Fig. 1). Urban use represents a small percentage of the total area and includes the departmental capital with 25.422 inhabitants (\url{http://www.ine.gub.uy/web/guest/censos-2011}, visited on April
As in other regions of Uruguay, this watershed has undergone an increase in the area occupied by intensive agriculture and afforestation. Agriculture surface area doubled, while afforestation quadrupled between 1997 and 2011 [42]. This trend is expected to increase given the existence of large areas suitable for these rural economic activities, and the increasing global demand for these products [26].

Figure 1. Laguna de Rocha watershed. Land cover in 2011 and the protected area boundary are indicated.

Laguna de Rocha is still in a healthy state, but warning is arising because several symptoms of water quality deterioration were observed, indicating the beginning of
an eutrophication process \cite{4} and recent episodes of potentially toxic cyanobacteria have been noticed (V. Hein and D. Calliari, pers. comm). Also, episodes of proliferation of submersed aquatic vegetation and macroalgae were observed \cite{52, 54}. Land use changes in the catchment area may be explaining the nutrients increase in the lagoon \cite{55}. However, other factors may be operating as well, as the artificial opening of the sand barrier that separates the lagoon from the ocean or the water temperature increase related to climate change.

Previous works showed that phosphorus (P) is the nutrient that has increased the most \cite{4} while phosphorus in the sediments was related to the annual P load from the watershed and to the surface area of soils suitable for agriculture \cite{55}. Therefore, phosphorus in Laguna de Rocha is an appropriate indicator of the eutrophication process. If nutrients increase due to land use exports, cyanobacterial blooms and submersed aquatic vegetation (including macroalgae) may increase in frequency and duration \cite{54}, threatening biodiversity, fisheries and other human activities.

3. Methods. The methodology was organized in three stages. The first one consisted of establishing a conceptual model to allocate land uses in the watershed considering sustainability issues. Second, a multi-objective integer linear model was developed and implemented to maximize the area under agriculture and afforestation and simultaneously minimize the export of phosphorus from the watershed. Finally, the phosphorus load currently being exported by the land covers of the watershed was estimated and compared with the phosphorus threshold load that promotes the growth of cyanobacteria in Laguna de Rocha. Below is the description of the three steps.

3.1. Stage 1: Conceptual model to allocate land uses in the watershed. The watershed of Laguna de Rocha has diverse land covers that support different land uses. Land covers can be natural or be the product of human modifications made to increase production. The natural covers are: dunes, native forests, flooded grasslands, wetlands and grasslands. The artificial covers are agriculture and afforestation. Table 1 describes each of them. The land uses in the watershed are determined by the type of cover. Afforestation and agriculture are carried out only in the lands with such cover, while livestock ranching is carried out in all covers, including afforestation, artificial pastures, stover and all types of grasslands. However, land uses can take place according to a suitability value for each parcel of land (pixel), which depends on slope, soil type, and other. The suitability values for the three land uses were obtained from the multi-attribute modeling carried out in \cite{53} in this same watershed. The suitability values for afforestation and agriculture were directly obtained from these authors, while for livestock ranching and conservation an average from both uses was calculated, since they were estimated separately in such work. Biodiversity is found mostly in natural land covers, where extensive livestock ranching is a traditional use, generally compatible with conservation \cite{53}. Therefore, for the purposes of this work livestock ranching and biodiversity conservation uses were pooled.

The land cover that exports the greater amount of phosphorus is agriculture, for any crop, followed by afforestation, while natural covers have the lowest phosphorus export coefficients. The most suitable nutrient export coefficients for Uruguay were taken from international and national scientific sources and were selected by the Soil and Water Department of the Faculty of Agronomy - Universidad de la República (C. Perdomo, pers. comm.). The most likely values were used for calculations
| **Land cover**          | **Description**                                                                 | **Land use**                          | **Land use that pixels can take after modeling** |
|-------------------------|---------------------------------------------------------------------------------|---------------------------------------|-----------------------------------------------|
| Grasslands              | Soils covered by natural grasslands (Fig. 1)                                    | Livestock ranching & conservation (G+C) | A,F,G+C                                       |
| Flooded grasslands and wetlands | Areas near by water bodies that are flooded frequently (Fig. 1) | G+C                                   | G+C                                           |
| Dunes                   | Dunes and sand deposits, mostly in the coastal zone (Fig. 1)                    | G+C                                   | G+C                                           |
| Natural forests         | Native trees and shrub vegetation (Fig. 1)                                      | G+C                                   | G+C                                           |
| Agriculture             | Agriculture in 2011 image (taken from [42]), it includes mainly cereals crops and artificial prairies, and also oversowing, tiled lands, stovers, forage crops and horticulture (Fig. 1). | Mainly agriculture and artificial prairies (A) | A,F,G+C                                       |
| Afforestation           | Afforested lands in 2011 image with exotic species to supply industry (Fig. 1) | Afforestation F                       | F                                             |
| Buffer strip            | Lands adjacent to the streams, the width is variable and proportional to the order of the streams (Fig. 1) | G+C or A or F                         | G+C                                           |

**Table 1.** Description of land covers of Laguna de Rocha watershed from a 2011 Landsat image (obtained from [42]). The table indicates the land use that is currently carried out in each cover, and the land use that each land cover can take after optimization. A: agriculture, F: afforestation, G + C: livestock ranching and conservation. The pixels with land covers that cannot change during modeling were not included for the optimization procedure.

(Table 2). On the other hand, natural land covers have the highest provision of the ecosystem service of prevention of eutrophication (sensu Nin et al. 2016), especially the different types of wetlands and native forests [18]. These land covers have outstanding landscape and biodiversity values, being specially protected by the management plan of Laguna de Rocha protected area, as well as by other national regulations.
Based on this, a conceptual model to guide the land use optimization procedure in the watershed of Laguna de Rocha was developed. The model established that certain land covers (mainly the natural covers, excepting grasslands) cannot be modified and land uses other than livestock ranching cannot be conducted (Table 1). This helps simplifying the optimization model, reducing the number of decisions that must be made, while at the same time guarantees the conservation of biodiversity and ecosystem services in poorly suitable sites for productive uses [53]. Therefore, only grasslands and agriculture can be transformed into other land covers, to take other uses. Grasslands can become agriculture or afforestation, while agriculture can transform into afforestation or re-establish a grassland cover. The restoratation of grasslands from agriculture can occur under certain conditions and management with acceptable costs and time periods. On the contrary, once afforestation is established, it cannot be replaced by agriculture or grasslands, at least not at reasonable restoration costs and time periods. In addition, a so-called “buffer strip” cover was also generated by overlaying procedures in GIS. This strip has an increasing size, proportional to the order of water courses to comprise their floodplains (Fig. 1). The surface area of the buffer strip was removed from the optimization procedure, to maintain or restore the original land cover (mainly forests, wetlands and flooded grasslands) and to assure the provision of diverse ecosystem services including the prevention of eutrophication, also complying with the recent regulations for some watersheds in Uruguay (http://www.mvotma.gub.uy/ambiente/prevencion-y-control-para-el-cuido-del-ambiente/estado-del-ambiente/plan-santa-lucia).

The GIS was built based on the land covers and land uses obtained from a Landsat satellite image of 2011 [42]. The watershed contour was converted into a vector grid with cells (pixels) of half a hectare. Each pixel of the grid took the value of the land cover that was mostly represented in that cell, by overlying procedures. Therefore, in each pixel only one land cover was represented. For the purposes of this work, the lagoon and the urban area were removed from the analysis, so the surface of the study area was 111,235.5 ha (222,471 pixels). Of these, only 95,939 pixels, less than a half, were used in the multi-objective model, representing those that can change of land cover to support use changes (Table 2). The decision to change land cover in the pixels depends both on the value of the P export coefficient of such cover and to the suitability of the land cover to support any of the three land uses: afforestation, agriculture or livestock ranching and conservation. Fig. 2 shows the suitability maps for all land uses.

3.2. Stage 2: Integer linear programming model. In order to state the multi-objective optimization model, we consider the following notation:

- $I$ is the set of pixels of equal size, organized as a grid which constitutes a partition of the study region, in our case it comprises 95,939 pixels.
- $J$ is the set of possible land uses for each pixel, namely, agriculture, afforestation and livestock ranching & conservation.
- $s_{ij} \in [0, 1]$ is the suitability value of pixel $i \in I$ for land use $j \in J$.
- $S_{\text{min}}$ is the minimum suitability value in the dataset.
- $p_j \geq 0$ is the phosphorous produced by a pixel with land use $j \in J$.
- $x_{ij}$ is a binary variable which takes value 1 if land use $j \in J$ is allocated to pixel $i \in I$, and 0 otherwise.
Figure 2. Land suitability maps for a) agriculture, b) afforestation and c) livestock ranching and biodiversity conservation, obtained from [53]. Detailed explanation of each map construction is presented in Methods.

The constraints of the model are the following:

\[
\sum_{j \in J} x_{ij} = 1 \quad \forall i \in I
\]

\[
x_{ij} \leq x_{ij} - S_{\min} \quad \forall i \in I, j \in J
\]

\[
x_{ij} \in \{0, 1\} \quad \forall i \in I, j \in J
\]

where the first one imposes that only one land use can be allocated to each pixel, the second one imposes allocations allowable by suitability values and the third one imposes the binary nature of the variables.

In order to maximize the total suitability of the system (that is to allocate the different land uses in the most suitable sites) while minimizing the export of phosphorus from the watershed, the following multi-objective model was designed as (Eq. 1):

\[
\min(\alpha \text{Obj P} + (1 - \alpha) \text{Obj suitability})
\]

where \(\alpha\) gives a relative weight to one objective with respect to the other.

The objective of phosphorus reduction (Eq. 2) seeks to minimize the P export from the watershed by selecting for each pixel between the possible land covers according to its export coefficients. This objective minimizes the sum of the product of the pixels involved in the optimization by the export coefficient of the land cover that these pixels take.

The objective of suitability improvement (Eq. 3) seeks to maximize the fitness in the watershed, selecting for each pixel among the possible land covers with the highest suitability for each land use. Land suitability is defined as the fitness of a particular area for a specific use relative to the needs and potential of social factors [6]. This objective maximizes the sum of the product of the pixels that intervene in the optimization by the suitability value for the land uses that can take place in the land covers. For technical reasons, we transform this maximization problem into a minimization one (compatible with the minimization of P), by considering its opposite value.

\[
\text{Obj P} = \sum_{i \in I} \sum_{j \in J} x_{ij} p_i
\]
### Table 2

| Land cover                  | Number of Pixels | P Export Coefficient (kgP/ha/y) | P load exported by each land cover (kg P/y) |
|-----------------------------|------------------|---------------------------------|------------------------------------------|
| Dunes and sand deposits     | 495              | 0.01                            | 2.5                                      |
| Natural forests             | 17545            | 0.01 [22]                       | 87.7                                     |
| Buffer strips               | 74799            | 0.01 (the same as wetlands)     | 374.0                                    |
| Afforestation               | 7611             | 0.29 [5]                        | 1104.0                                   |
| Wetlands and flooded grasslands | 26082       | 0.01 [31]                       | 130.4                                    |
| Grasslands                  | 83073            | 0.24 (Adapted from [19])        | 9968.8                                   |
| Agriculture                 | 12866            | 2.0 (average between values for cereals [35] and artificial praires [51]) | 16725.8 |

**TOTAL** 22471 28392.8

This table shows the number of pixels occupied by each land cover in 2011, the export coefficients and the TP load that each cover exports. Each pixel has a surface area of half a hectare.

\[
Obj\text{ Suitability} = -\left(\sum_{i \in I} \sum_{j \in J} x_{ij} s_{ij}\right)
\]  

Several computational experiments were performed with the multi-objective model, in which the value of \(\alpha\) was modified. Experiments with a small \(\alpha\) are expected to maximize suitability but increase P export, while the opposite is expected with higher values of \(\alpha\) (Table 2). Finally, the load of P exported by the watershed for each model was compared with the load that can be tolerated by the lagoon without promoting cyanobacterial growth, which is the sum of the load exported by the pixels that enter and that do not enter into the optimization model.

#### 3.3 Stage 3: P export from the watershed and P threshold for cyanobacterial growth

The phosphorus load exported from the watershed was obtained from the sum of the products of the export coefficient of each land cover by its surface area (Table 2, Fig. 3a), according to [55]. To estimate how much of this phosphorus load reaches the lagoon as total phosphorus (TP), a conversion was used based on the LOICZ model (Land Ocean Interactions in the Coastal Zone [28]). This factor estimates the efficiency in the retention of nutrients or particles in soils, based on calculations made in large basins [66]. For our region it is indicated that the soils retain 79.8% of the nutrients, so only 20.2% of the TP that the watershed may be exporting would reach the lagoon [66]. It was assumed no additional phosphorus losses in the lagoon (retention in the sediments or due to the discharge of water to the sea, among other processes), due to the lack of estimates.
To estimate how much of the TP that reaches the lagoon represents soluble reactive phosphorus (SRP), which is directly assimilable by phytoplankton, the historical proportion of SRP / TP obtained from a series of 19 years data for this lagoon was used (Section Limnology of Faculty of Sciences / CURE, unpublished data). According to these data, 28.8% of the TP is in the form of SRP (Fig. 3a).

Finally, the SRP load exported by the watershed was compared with the SRP load sufficient to promote the growth of cyanobacteria in the lagoon. To estimate the SRP threshold for cyanobacterial growth we used the estimates made in [11], based on the DELFT3D model. This is a spatially explicit hydrodynamic model coupled with a water quality model [17]. The hydrodynamic module was run first, using data from bathymetric and meteorological variables of Laguna de Rocha, with a resolution of one day. These results were coupled to the water quality module that simulated the orthophosphate concentration and the biovolume of the phytoplankton groups present in Laguna de Rocha [11]. The threshold of SRP for cyanobacterial growth in this lagoon was compared with experimental data of cultures of cyanobacteria under comparable conditions of salinity and temperature, obtained from a literature search [10], as well as with [59] modeling results for this lagoon. The concentration value obtained was in the range of 25 to 45 µg l⁻¹. For the purposes of this work, the most permissive value of the SRP range was used, 45 µg l⁻¹, which was extrapolated to the water volume of the lagoon in order to obtain the total SRP load (Fig. 3b). The volume of water was 4.38 × 10⁷ m³ and was obtained by the product between the surface of the lagoon (73040000 m²) and its average depth (0.6 m), according to [55].

4. Results. According to our estimations, the soils of Laguna de Rocha watershed are currently exporting a load of TP (28,451 kg TP) slightly lower than the threshold value (33,872 kg TP) that promotes the growth of potentially harmful cyanobacteria (Fig. 3).

The optimization model was implemented in the AMPL language [25] and solved using the CPLEX solver (https://www.ibm.com/analytics/cplex-optimizer). The optimization procedure to allocate land uses obtained a series of maps with different surface areas of A and G+C, depending on the weight assigned to each objective, while F was kept constant along all trials consuming all the suitable pixels (Fig. 4). In the maps were suitability maximization was favored (lower α values) the TP load exported from the catchment area almost doubled the threshold for cyanobacteria growth (Table 3). On the contrary, when the minimization of TP exportation was favored (higher α values), A were almost removed and G+C expanded even into cropped lands, decreasing the TP loads to very low values (Table 3).

The optimization procedure selected two contrasting types of land use allocation maps, one which favored agriculture but almost doubled the acceptable threshold of TP load for cyanobacteria growth or one which almost discards agriculture with TP loads even lower than the established threshold. The shift from one type of land use allocation to the other occurred at a values around 0.235, and very low differences in α can make the system to change abruptly (Fig. 5).

When maximization of land suitability is favored (lower α values) G+C is affected, converting high suitability grasslands pixels (= 0.5) for this use to A. This potential impact is mainly located in the middle of the watershed, at lands with slopes lower than 0.6 with high agriculture suitability (Fig. 6a and 2a), surrounding
Figure 3. Steps followed for the determination of: a) the phosphorus load exported by the watershed and b) the phosphorus load that the lagoon can receive without promoting the growth of cyanobacteria, over a year.

| α   | Agriculture (ha) | Livestock ranching and conservation (ha) | Afforestation area not included in the model (ha) | P load (kg - year) |
|-----|------------------|----------------------------------------|--------------------------------------------------|-------------------|
| 0.01| 25,487.5         | 13,100                                 | 9,382                                            | 73,830.5          |
| 0.1 | 17,707           | 20,880.5                               | 9,382                                            | 55,468.5          |
| 0.235| 16,792           | 21,795.5                               | 9,382                                            | 53,309.1          |
| 0.240| 1,351            | 37,236.5                               | 9,382                                            | 16,868.3          |

Table 3. Surface area of the different land uses of the optimization trials shown in Fig. 4. The value of α and the load of TP is indicated.

the city of Rocha. This potential conflict among land uses decreases as α gets closer to 0.1. Analyzing this potential conflict the other way around, when minimization of TP load is favored (higher α values) agriculture is affected (Fig. 7), converting high suitability pixels (= 0.5) to conservation and livestock ranching. The conflicting pixels (Fig. 7a) are almost the same as in Fig. 6a for α=0.1, but increases dramatically as α increases (Fig. 7b).
5. Discussion. The two-objective optimization model was able to allocate different land uses in the watershed of Laguna de Rocha protected area, accomplishing with both productive and environmental restrictions. According to the relative weight ($\alpha$) given to each objective, two types of land use allocation were obtained, one dominated by agriculture but where the threshold of phosphorus load was exceeded, and another one where conservation and livestock ranching prevailed and the phosphorus load decreased dramatically. In both cases afforestation was selected for all its suitable pixels. A value that slightly favors agriculture ($\alpha$ around 0.235) seems the most appropriate tradeoff for land use allocation in this watershed. Higher $\alpha$ values almost eliminate this important economic activity, favoring conservation and livestock ranching, while on the contrary, lower values obtain totally unacceptable TP loads.
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Figure 5. Shows the number of pixels assigned to each land cover for the different levels of $\alpha$. The P threshold for cyanobacteria growth is located between $\alpha$ values of 0.234 and 0.24.

Figure 6. In black are shown the pixels were the optimization procedure allocated agriculture and also have high conservation and livestock ranching suitability (values = 0.5) in the catchment area of Laguna de Rocha. Left figure: $\alpha = 0.0001$ to 0.1 and right figure: $\alpha = 0.1$. For higher $\alpha$ values the model stops allocating agriculture in suitable pixels for G+C. The number of pixels selected (in black) in both cases are 13,038 (6,519 ha) and 893 (446.5 ha), respectively.

The model allocates land uses in the pixels with the highest suitability for such uses and the lowest phosphorus export coefficient. As a result, the optimum spatial configuration for all land uses was reasonable for all $\alpha$ levels, occupying the most suitable soils and land covers. Afforestation was allocated in all its suitable pixels due to legislation that establishes which soils can be and cannot be afforested. The soils that can be afforested obtained the highest suitability value, which also have a quite low phosphorus exportation coefficient, explaining the preference of the model by this land use. In all optimal maps agriculture area surrounds the city, occupying suitable and low slope soils, far from the sierra and the wetlands, while
conservation and livestock ranching occupied the most biodiverse zones, mainly the flooded grasslands, forests and wetlands. The allocation of all land uses was similar to the results obtained by [42] whom applied a prioritization scheme with the Zonation software [40], indicating that the results obtained by this model are realistic and consistent with previous work, as well as with the current allocation of crops (see Fig. 1).

The improvement of the performance of any of the two objectives will inevitably increase the number of pixels under potential conflicts among land uses, and it will in one side exceed the phosphorus threshold or at the other side get values very below the threshold, unnecessary affecting one land use sector. However, the model failed to find optimum maps with intermediate values of agriculture surface area and acceptable P loads. This could be related to a limitation of the weighted-sum method used to address the multi-objective nature of the problem.

The conjecture was also supported by (not shown) trials with an $\epsilon$-restricted procedure [21], i.e., an optimization model with just one objective (suitability maximization) subject to a restriction (P threshold). These trials obtained optimal maps with higher surface areas of agriculture but well within the P threshold. Nevertheless, the spatial configuration of land uses was totally unrealistic, showing a barred allocation of agriculture in different zones of the watershed. This reveals a limitation of the optimization model (not related to its resolution procedure), which lacks of explicit spatial terms on its formulation. This can be an important restriction for its application to other cases, even though for this case the model generated acceptable results in terms of land uses surface area. To incorporate spatial terms into the model it will be necessary to move toward heuristic methods.

But, even these methods have disadvantages as they cannot assure exact optimal outputs and have higher programming complexity; they offer the possibility to represent a more realistic picture, combining several objective functions, restrictions, and to introduce vicinity analyses [57], and can also be used in bigger problems (number of pixels) [29, 37, 39]. It is worth mentioning that our proposed model is static, in the sense that it does not represent the evolution of the system according...
to time. However, it considers explicitly the interaction among its components (pixels), which produce different levels of total suitability and total phosphorous export. This feature, jointly with the multi-attribute modelling for the calculation of the model parameters, gives the expressiveness to the whole model. Moreover, the size of the instance relative to the case study (more than 95,000 pixels) determines in principle its complexity, in the sense of the computational effort required to find the optimal solution. However, due to the structure of the underlying mathematical problem and the available state of the art optimization methodologies and software, the problem can be solved to optimality. Adding compactness constraints turns the problem much more difficult to model and solve, requiring heuristic approaches. We are working right now in this line of research.

It is being discussed which is the most appropriate model approach to this kind of spatial allocation problems. Many are defenders of exact linear programming methods and other of heuristic ones, among others. In [39], the author states that the most important issue is how suitable is the model to the environmental problem, instead of which are the algorithms used. In real problems, many times the choice of the “best” model involves the available skills and know how of practitioners of governmental agencies for agriculture, forestry, land and environmental protection planning, as well as the software’s availability, complexity and costs. Efforts must continue to design accurate spatial allocation models, but friendly to land use planners, at the same time as capable to offer flexibility to adapt to each case problem. This can only be achieved by the joint effort of planners and researchers. The model used in this article is computationally tractable and sensitive enough to produce different compromises between suitability and phosphorus.

This kind of modeling approach helps explore the “what if” inevitable questions in sustainable planning. The compromise $\alpha$ of up to 0.235 represents the optimum land use distribution accomplishing with both productive and environmental restrictions. Under this land use alternative, the number of pixels with potential conflicts among land uses (agriculture vs livestock ranching and conservation) has a surface area of 6,638 ha, representing almost 9% of the watershed of this lagoon. In [53], it is found that a similar proportion of surface area under potential conflicts, in the watershed of four coastal lagoons, with a multi-attribute model coupled with a simple linear programming in an Excel Solver. Conflicts according to this model may arise between agriculture and biodiversity conservation sectors, because livestock ranching can be conducted in all land covers and afforestation was always selected for all alpha values. Nevertheless, other environmental impacts of afforestation as natural habitat substitution and reduction of annual runoff that intensify water shortages [23, 63, 65] were not considered. Even though this model found no tradeoffs to allocate afforestation, this is a social resisted use that causes conflicts among stakeholders in Uruguay [2]. Additional objectives or restrictions should be included into the model formulation to address afforestation environmental impacts.

A special point that needs to be highlighted is the urban export of phosphorus, which was not considered in this exercise. However, [55] estimated that this load can be comparable to the agriculture load in this watershed, due to the allocation of Rocha city. This implies that if urban investment does not improve waste waters management other economic activities can be affected, as agriculture, whose growth will be limited by a phosphorus quote that is being consumed by the urban wastewater effluents. Furthermore, this kind of analytical approaches shows that implementing a system of phosphorus quotes to decide if a land use can be
conducted or not is at least a possibility in phosphorus loaded catchments, where spatial explicit models as this one may help decision makers.

For this two-objective model, the expansion of the two land uses that are expanding the most in Uruguay, afforestation and agriculture, are restricted by a threshold of phosphorus exportation to keep healthy aquatic ecosystems. This triggers the discussion of how to increase the surface area and productivity of these land uses without exceeding that threshold, which is matter of debate worldwide. Best agriculture practices [61], precision agriculture [67], agroecological alternatives [3], livestock ranching over natural grasslands [50], buffer strips [43], among many other alternatives are now under discussion. To contribute to this discussion we need to improve phosphorus loads estimations from watersheds for different crops and management practices, as well as better estimation of safe phosphorus thresholds in aquatic ecosystems. This information will help to overcome the assumptions that need to be made during modeling, to answer many of the questions for sustainability planning. Disposing of more accurate data will help overcome some of the gross assumptions taken during this modelling exercise, and possibly different pictures of land use configurations and surface areas will be obtained.

To choose among different land uses in the territory there exist several technical and policy tools, as Land Planning Instruments and Environmental Impact Assessments [49], while Strategic Environmental Assessments are gaining recognition [24]. Additionally, each country has its own legislation, many of which determines the permissions to conduct or not several activities in the territory. For example in Uruguay the novel Soils Law, reformulated in 2009, makes farmers design a crop rotation system that keeps soil erosion under a certain level, consulting a software (without spatial terms) developed by the government in a joint effort with the university (http://www.mgap.gub.uy/unidad-organizativa/direccion-general-de-recursos-naturales/suelos/planes-de-uso-y-manejo-de-suelos/herramientas). Spatial explicit models, as the one shown in this article, can help planners to include spatial criteria to design multifunctional landscapes, with a mosaic of cropped and natural ecosystems, offering diverse ecosystem services other than food and fiber production. Furthermore, since the input and output information are very intuitive (maps, legislation, land covers, agronomic criteria), it can promote social discussion with the participation of stakeholders from the very beginning of the planning process. This article describes the first steps of the development of a spatial explicit tool to help decision makers and planners to integrate conflicting objectives to guide sustainable development decisions, as are needed in real problems.

6. Conclusions. The two-objective optimization model allocated agriculture, afforestation and livestock ranching and biodiversity conservation in the watershed of Laguna de Rocha protected area, accomplishing with both productive and environmental restrictions. Two types of land use allocation were obtained, depending on the relative weight given to each objective. The one dominated by agriculture exceeded the threshold of phosphorus that promotes cyanobacteria growth. In the other one, conservation and livestock ranching prevailed and the phosphorus load decreased dramatically. Afforestation was selected for all its suitable pixels in all cases due to its high suitability and low phosphorus exportation coefficient. The tradeoff output where the phosphorus load is close to acceptable values had similar agriculture surface area than in the current situation, but with a quite different
spatial allocation. Future work is needed before the model can be applied in decision support. It must be improved the vicinity analyses, mainly compactness of productive lands to accomplish with minimal yields needs, as well as a more detailed description of agriculture types and rotation systems. Also, additional objectives and restrictions must be incorporated, as other environmental impacts to be avoided (e.g. biodiversity loss) and yields or social goals to be achieved. Moving to metaheuristics approaches is the next step to obtain more realistic modeling for the challenging work of allocating land uses in multifunctional landscapes for sustainable development.

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