SOTER-PA 2.0: A COMPUTATIONAL SYSTEM
FOR FAIR LAND ALLOCATION AND ENVIRONMENTAL PLANNING

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ABSTRACT. In Brazil, the National Institute of Colonization and Agrarian Reform (INCRA) encounters difficulties in agricultural land parceling. Manual methods often prioritize the geometric regularity of lots instead of a fair subdivision concerning soil quality and expected crop output. The problem of finding fair land subdivisions regarding the soil's agricultural aptitude has been named the Territorial Organization in Agrarian Reform Projects and Environmental Planning Problem (PROTERRA). Besides soil quality, PRO-TERRA requires that subdivisions exclude permanent preservation areas and native reserves, and imposes constraints on minimal access to water bodies and roads and a maximal area assigned to each lot. This study presents the new version of the Territorial Organization of Agrarian Reform and Environmental Planning System (SOTER-PA), which leverages combinatorial optimization algorithms to solve PROTERRA. We present its features and resources taking the most known geographic information systems. This system can also be used for other problems in a land subdivision and environmental planning context.

Keywords: land allocation, environmental planning, geographic information system.

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1 INTRODUCTION

Agrarian reform projects are fundamental for the sustainable development of countries, presenting economic, social, and environmental impacts (Clements, 2012; Moura et al., 2011b,a; Reis, 2012). Despite its relevance, part of the rural settlements planned by the National Institute of Colonization and Agrarian Reform fit into the technique known as "dumb square", in which lots are assigned rectangular areas, while overlooking the different agricultural aptitudes, relief, and hydrography present in the land (Ferreira Neto et al., 2011).

Ferreira Neto et al. (2010) introduced a study of computational tools to solve the "Problem of Territorial Organization for Agrarian Reform Projects and Environmental Planning" (PROTERRA, acronym in Portuguese). They proposed combinatorial optimization algorithms to support agricultural technicians and researchers in determining the number of lots for families regarding soil quality, environmental constraints, and land area limits. Moreira et al. (2011) then proposed the Territorial Organization of Agrarian Reform and Environmental Planning System (SOTER_PA, acronym in Portuguese) as a computational system that uses efficient optimization methods to solve PROTERRA.

SOTER_PA uses empirical procedures to add, during its solution, environmental planning components that exclude land parcels related to permanent preservation areas, legal reserves, and water resources. The first version of SOTER_PA implemented an adaptation of the meta-heuristic Genetic Algorithm (GA) (Ferreira Neto et al., 2011). This GA was tested on a specific terrain in Minas Gerais state, Brazil, and obtained better results than the layout proposed in the actual context, showing that it can divide lots more equally to the families. This fact motivates the use of such a tool.

The effectiveness of SOTER_PA was clear in its first version. However, the system was developed with a specific terrain in mind. Moreira et al. (2011) presented the second version of this program, which used tabu search as a solution method and that could handle any kind of terrain.

Despite presenting positive responses in the territorial subdivision, Ferreira (2015) reports that SOTER_PA has weaknesses. The user interface is via a command-line terminal, a way of interacting that is more difficult to use. Moreover, some of the parameters of the software require pre-processing. As the system does not have the resources to carry out such a task, the user is forced to use other programs, usually Geographic Information Systems (GIS). The generation of the final result is carried out in a separate module of SOTER_PA. The result consists of an image of the territory divided into lots and makes interpretation difficult due to three factors: (*i*) as it is an image file, it is not as accurate as a georeferenced file[1]; (*ii*) it does not present information about the generated batches (such as area and soil conditions); (*iii*) batches are differentiated based on colors that often have similar shades, compromising identification.

With the problem of managing territorial organization in agrarian reform projects in mind, the main goal of this article is to fill this gap by proposing a new version of SOTER_PA that ad-

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[1]A georeferenced file is a digital image representing a map, linked to a geographic coordinate system. It determines the location of each point on the map on the Earth's surface.

dresses the issues above. The new system is divided into three modules: (*i*) pre-processing of geospatial data; (*ii*) optimization; (*iii*) statistics and visualization. The results of one module are fed into the next. The remainder of this paper is organized as follows. In Section 2, we formally describe PROTERRA. Section 3 presents a brief description of correlated works to land-use allocation systems. Section 4 presents the architecture implemented for SOTER_PA, while Section 5 considers a detailed description of the system module. We conclude in Section 6.

2 PROBLEM DESCRIPTION

In the following, we provide a formal definition of PROTERRA. Although land subdivision is inherently a geometrical problem, we frame PROTERRA as a discrete problem to accommodate the usage of discrete optimization algorithms. To achieve this, terrains are discretized into regular grids. Typically, the team responsible for the subdivisions determines the cell size based on the desired trade-off between precision and difficulty of solution.

Let $A = [m] \times [n]$ be a regular grid of $m \times n$ cells representing a parcel of land to be divided, and $k \in \mathbb{N}$ the number of desired lots. Some cells $R \subseteq A$ and $P \subseteq A$ represent water bodies and permanent preservation areas or legal reserves, respectively, and cannot be allocated. We define the productivity index of land cell $l \in L$ by $i_l \in \mathbb{R}_+$, where $L = A \setminus (R \cup P)$. Concerning lot sizes, two constraints are imposed. First, lots must have a minimum area of $\alpha \in \mathbb{Z}_+$, in terms of number of cells. Second, the ratio of the largest area of a lot and the smallest area of a lot must be less than $\beta \in \mathbb{Z}_+$. For cell $l \in L$ at coordinates (x_l, y_l), we define its neighbor set as $N(l) = \{(x_l+1, y_l), (x_l, y_l+1), (x_l-1, y_l), (x_l, y_l-1)\} \cap L$. Finally, let $fr(A_i) = [\{N(l) \cap R \mid l \in A\} \neq \emptyset]$, be a Boolean function that returns 1 if lot A_i contains at least one cell adjacent to a water body, and 0, otherwise.

A valid solution to PROTERRA consists of a partition $L = A_1 \cup A_2 \cup \cdots \cup A_k$, subject to:

$$fr(A_i) = 1 \implies |A_i| \leq |A_j|, \qquad\qquad i,j = 1,\ldots,k, i \neq j, fr(A_j) = 0, \qquad (1)$$

$$\alpha \leq |A_i|, \qquad\qquad\qquad\qquad\qquad\qquad i = 1,\ldots,k, \qquad (2)$$

$$\frac{\max_{i=1,\ldots,k} |A_i|}{\min_{j=1,\ldots,k} |A_j|} \leq \beta, \qquad\qquad\qquad\qquad (3)$$

$$A_i \text{ is connected wrt. } N \qquad\qquad\qquad\qquad i = 1,\ldots,k. \qquad (4)$$

Constraints (1) establish that if lot A_i is adjacent to a water body, then every lot that is not adjacent to a water body must have larger area than A_i. Such a constraint is justified as a way to equalize for a lack of immediate access to water resources in some land parcels, since the presence of water results in a higher productive capacity. Constraints (2) enforce that each lot must have a minimum area α, and constraints (3) state that the ratio between the largest and smallest area planned for a lot must be less than a maximum value β, to avoid possible conflicts because of lot size inequality. Finally, constraints (4) ensure that lots are 4-connected with respect to grid A, which facilitates the delimitation and traversal of lots.

For a given lot $A_i \subseteq L$, let its productivity index be represented by $q(A_i) = \sum_{l \in A_i} i_l$, and define the average productivity index for all lots as $\overline{q} = \sum_{i=1}^{k} q(A_i)/k$. Among all valid solutions, PROTERRA seeks the one minimizing the standard deviation of the productive indices across all lots:

$$\sigma = \left(\frac{\sum_{i=1}^{k} (\overline{q} - q(A_i))^2}{k-1} \right)^{1/2}. \tag{5}$$

Although we consider land aptitude as a quality criterion of land parceling, by modifying the objective function above we can view the problem through other objectives which might have more environmental significance, such as land-use capacity, vegetation cover, or any other quantifiable measure derived from the weights on the terrain map.

3   PREVIOUS WORK

The manipulation of resources such as maps, images, and georeferenced data makes GIS excellent instruments for studies in the field of agriculture. Studies that used such a computational system achieved relevant results in the literature. Despite being numerous, however, none is known to address issues of territorial organization involved in the PROTERRA. In the following, we present examples of such systems that are similar to SOTER_PA, but which do not address the specific requirements of PROTERRA.

Liu et al. (2007) developed the Integrated GIS-Based Analysis System (IGAS) as an urban land-use management tool. IGAS operates to support decisions concerning urban growth and lake preservation. The authors performed a case study in Wuhan city, in the region of Hanyang Lake, in China. The system analysis considered many factors, such as population, economic structure, public policy, and goals for ecological conservation. As a result, the study provides alternatives for soil usage in the region from 2006 to 2020.

The following two papers consider the Terra Chá region (Galicia, Spain). Santé & Crecente (2007) developed LUSE, a software that solves land allocation problems using multi-objective optimization algorithms. The objective functions considered are the maximization of gross margin, employment in agriculture, land use naturalness, and traditional rural landscape while minimizing production costs and agrochemical usage. Land planning must reach adequate levels considering the existent demand for those uses or their products. Besides, the land parcels assigned to maize and fodder must be sufficient to maintain dairy farm production. LUSE shows a satisfactory level of convergence regarding the Pareto set of solutions and demonstrates the ease of applying it to other case studies. Santé-Riveira et al. (2008) propose a system named RULES (RUral Land-use Exploration System) that implements three main phases in an agricultural land-use model: (*i*) evaluation of parameters; (*ii*) optimization of land-use; (*iii*) spacial allocation of land parcels. The authors emphasize the strength of these tools o guide and support decisions in all land-use planning.

Another two studies consider the Galicia region. Porta et al. (2013b) considered a parallel genetic algorithm for a land-use allocation problem optimizing land suitability and the shape-regularity

of the resulting land-use patches. The problem is subject to current local and national legal rules and experts' criteria. Computational tests showed that the proposed multi-core algorithm could reach an almost linear speedup with an accurate solution. Porta et al. (2013a) present a population-based greedy algorithm for the problem of delimitation and zoning of agricultural settlements. Computational tests were carried out, considering different morphological aspects of the land and legislative aspects of the land division in this region. Through the results, it can be concluded that this tool has great potential. Another example of applying the population-based algorithm to solve the land-use allocation problem can be seen in Liu et al. (2015).

Demetriou et al. (2013) implement a module called LandParcelS (LandParcelling System), which is part of a more complex land planning and decision support system. The authors present a methodology that integrates geographical information and a genetic algorithm for a case study area in Cyprus. The study considers two approaches. The first one has a single objective function, that optimizes parcel shape index (PSI), a metric composed of six shape parameters: length of sides, acute angles, reflex angles, boundary points, compactness and regularity. The second approach creates a multi-objective weighted function considering three criteria: PSI, desired area, and the desired value of parcel shape. The results show improvements in the quality of current solutions, for both single and multi-objective cases.

Santé et al. (2016) extended RULES system of Santé-Riveira et al. (2008) through the Open Rules, a Planning Support System (PSS) free and open source, applies to all land use types, including rural and urban. The Open Rules was developed in Java, and its implementation is part of a module of the free GIS software gvSIG. It comprises multicriteria evaluation, multi-objective linear programming, and heuristic techniques. The authors tested its performance in instances from the region of La Troncal, Ecuador, and the results are suitable compared with current practical solutions.

Li & Parrott (2016) implemented an interactive system for land use planning. They deal with a multi-land decision problem, where more than one land use type (Agricultural, Commercial, Forest, Industrial, Park, Grass, or Residential) can be assigned to different spatial units. Through economic and environmental objectives, the authors propose a goal-programming approach to manage trade-offs among multiple objectives and a genetic algorithm to optimize the allocation of land units. Experiments conducted with an instance from the Regional District of Central Okanagan (RDCO), a province of British Columbia (Canada), showed robust solutions and at least one optimal solution according to scenarios planned by stakeholders.

We can affirm that Souza et al. (2023) is the more recent paper to study PROTERRA. The authors correlate PROTERRA with cutting and packing problem. The recurring criticism concerning the most prominent PROTERRA studies, such as Ferreira Neto et al. (2010, 2011); Gliesch et al. (2017), is that the lots produced have many angles, and they are irregular. This characteristic makes their installation expensive, which is not practical in this context. For this reason, Souza et al. (2023) see the land as a board, and lots as regular/rectangular pieces, resulting in a new instance of cutting and packing problem. Through a mathematical formulation, the authors attest

that the new approach can cover up to 90% of the land, with more distributed land concerning land aptitude, "rationalizing the dumb square".

As we can see, except the last paper explained, none of them consider the specific combination of PROTERRA's constraints and objective functions, presented in the previous section. This justifies the need to develop SOTER_PA.

4   SYSTEM ARCHITECTURE

SOTER_PA is a desktop system with different technologies applied to its development. To deal with geospatial data, we use QGIS (QGIS, 2023) for conversion and processing of maps and GeoTools framework (OS Geo Project, 2023) for spacial queries and map plots. Since GeoTools is a Java Toolkit, we implemented of the graphical interface of SOTER_PA in Java. This choice also allows the system to be executed in multiple platforms, such as Windows, Linux, and MacOS. We used the Eclipse IDE for Java development, and Maven as a build automation tool (Eclipse Foundation, 2023). To ensure maximum efficiency of the optimization algorithms, they were coded as a separate application in C++. Both applications interface through scripts. Figure 1 presents the SOTER_PA system architecture.
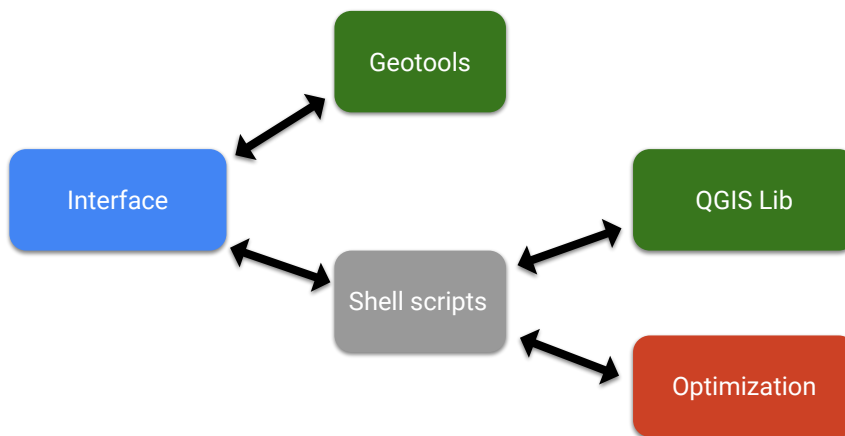

Figure 1 – Architecture scheme of SOTER_PA.

Note that the GeoTools module only has access to the graphical interface. The exchanging messages between processes are performed by shell scripts that call QGIS functions to handle geodata, and the optimization algorithm, to solve PROTERRA. The output of PROTERRA is sent from the solving module to the graphical interface by another script, and then, the map is visualized through a GeoTools procedure.

For the development of the main screen, we used the JMapFrame class from Geotools. It extends Java's JFrame class to create a window that works with geographic components. The JMapPanel (panel for the graphical display of maps) and the MapLayerTable (bar for displaying active layers) are examples of components. In addition to the geographic components, the main screen presents the implementations of JMenuBar (a Java component used to produce the top menu) and JPanel (a component used to create the toolbar). See Ferreira et al. (2023) to download SOTER_PA and obtain more information about its installation.

5   SYSTEM DESCRIPTION

This section explains in details of the SOTER_PA architecture. We divide the system in three modules: (*i*) input data (Section 5.1); (*ii*) optimization (Section 5.2); (*iii*) output data and visualization (Section 5.3). Each one will be presented as follows.

5.1   Input data module

The description of the input data modules gathers elements of graphical interface, QGIS procedures and GeoTools framework. Figure 2 presents the start screen of SOTER_PA.
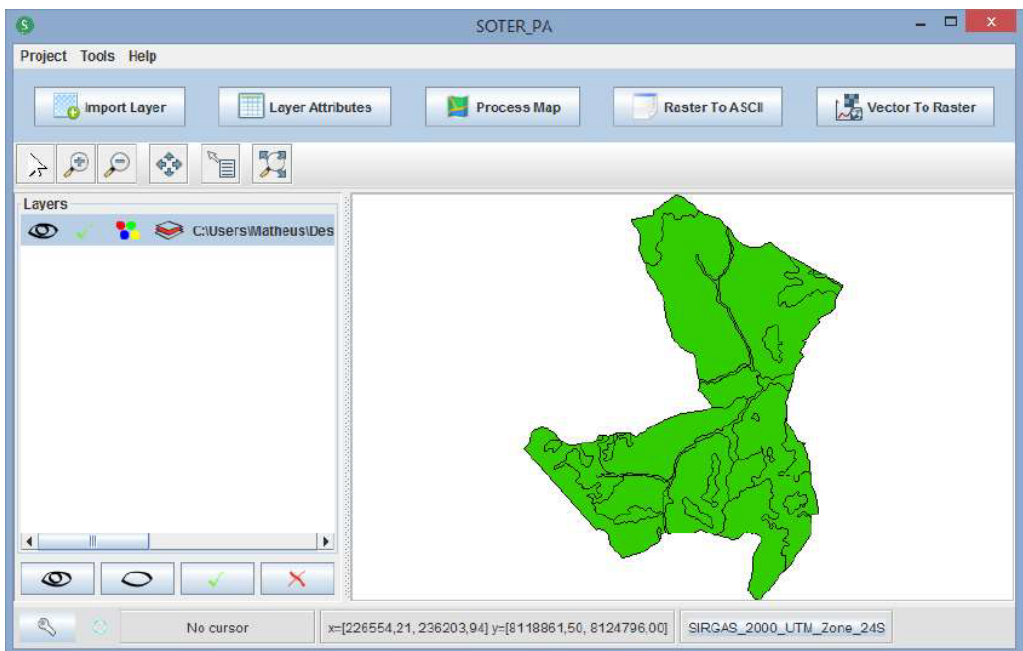

Figure 2 – Start screen of SOTER_PA.

When accessing the top menu (option "tools"), it is possible to see resources that may be convenient as:

- View maps ("import layer" button): when it is activated, a dialog box of JFileDataStore-Chooser type (Geotools component that extends class JFileChooser, from Java) opens. Then, it is possible to select a georeferenced file to be read by the system. The file is added to the MapContent component of the main screen (JMapFrame). With this, the MapLayerTable displays the selected file path, and the JMapPanel displays the map graphically. We considered raster (.tif) and vector (.shp) georeferenced files. We have added a vector file in Figure 3.

- Query data and filter map attributes ("layer attributes" button): when selecting this tool, a window is opened (JTable component, from Java) with all attributes and alphanumeric data of an added layer. Such attributes are obtained through the SimpleFeature component and can be filtered using the Filter feature (both come from Geotools). The user types a query in which he/she informs the map's features that he/she wants to visualize. The query results are seen in the table and highlighted in blue on the main screen's JMapPanel. A query illustrated in the Figure 3 shows the results for a filter applied on the field "Aptdao" on a vector map.
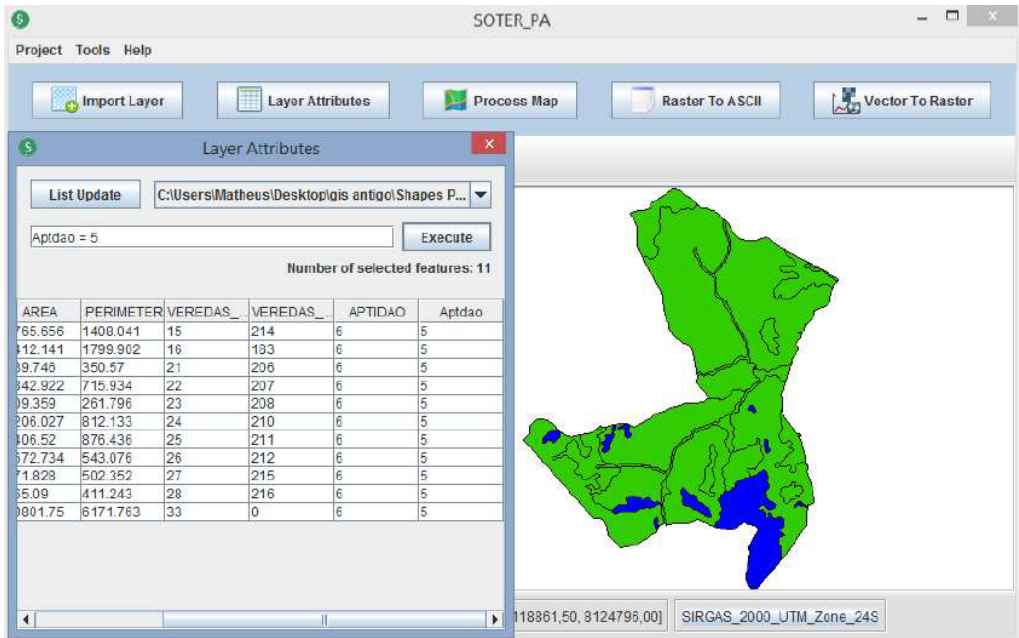

Figure 3 – Visualization of a vector file.

- Perform conversions between vector and raster files ("raster to ASCII" and "vector to raster"): to convert files, we need to use mechanisms offered by QGIS. To obtain an ".asc" (ASCII) file from a ".tif" file, for example, we need to use the "gdal translate" feature. One way to use it is via the command line. We aim to make the process transparent to the user. So, when the user triggers the conversion task, we instantiate a new thread using the Thread class from Java. This thread receives an instance of the Process class as a child process, which executes a shell script containing the command "gdal translate". So we send the command to the operating system console. After the completion of the conversion process, the thread receives an end notification, and the user is notified that the task has been executed.

The processes described using Geotools and QGIS resources are repeated whenever the system requires these libraries. That way, we instantiate its components through Java code and create a thread in Java to trigger a shell script that will execute the command from the library.
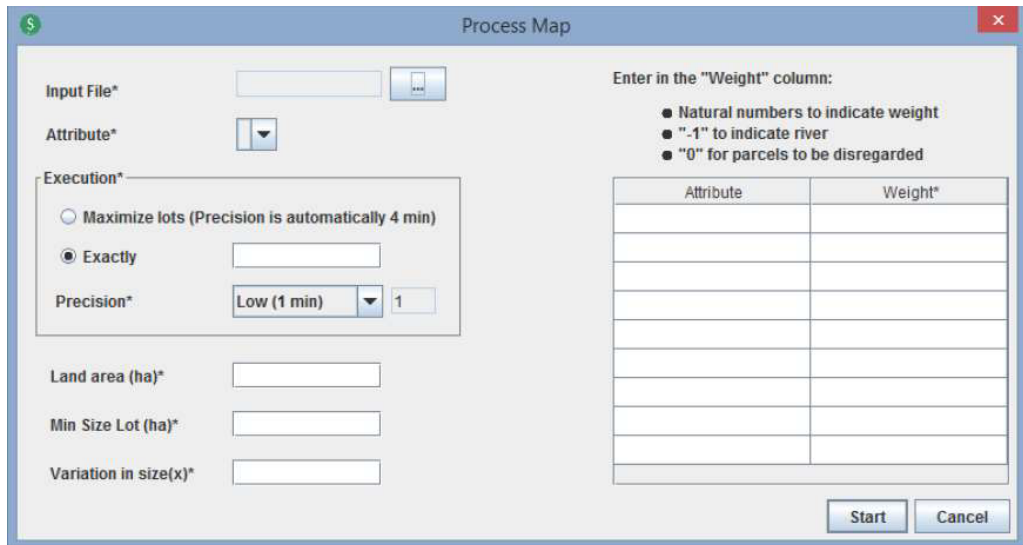

Figure 4 – Process map screen.

To process a map and get land parceled, one needs to click on "Process Map" (Figure 4) and follows these steps:

1. Select the directory of a ".shp" file. Such a file must be a georeferenced map representing the land to be parceled.

2. Select the attribute that will be used to place the identifiers representing the optimization function. Users can select agricultural aptitude and use it as a reference to define the scores in Step 4 (parameter i_l defined in Section 2). The selected attribute will occupy the first column of the configuration table. As the user can choose the attribute of the input file,

it is possible to parcel the land based on agricultural aptitude and any other convenient parameter (as long as it is contained in the input file).

3. Inform execution preferences: number of lots desired (field "Exactly"), algorithm precision (the greater the precision, the longer will be the processing time), area of the tested land (field "Land area (ha)"), lower bound (in ha) of the area of a lot (field "Min Size Lot (ha)"), and the maximum ratio between the largest and the smallest area of lots (field "Variation in size(x)". In this version of SOTER_PA, we disabled the option "Maximize lots (Precision is automatically 4 min)" due to the need for more tests to validate such an option.

4. Configure the optimization function in the table: one must place the identifiers (second column) and scores (third column) according to some terrain attribute. The scores defined by the user directly influence the result since they indicate the quality of the terrain regions. Note that the higher the quality parameter score, the better it represents in practice.

5. Start processing: after clicking "start", SOTER_PA starts processing the map. The execution status is displayed on the waiting screen. The processing consists of converting the ".shp" file into ".txt" (using the QGIS procedures). Then the run preferences are added to the algorithm parameter. This is called by opening a new thread that runs a shell script, just like accessing QGIS resources. The algorithm ends the thread and returns a file ".txt" (matrix with the layout of the generated lots) and a ".json" file (solution information and run logs) that are processed to create the final vector map (using QGIS resources). This phase also creates the matrix map in the ".tif" format. Note that for the tests carried out so far, the scores was based on the articulation between specialists in the area of soils who, when jointly analyzing the physical, agronomic, and social factors of the parceled areas, distributed 100 points among the different attributes.

5.2 Optimization module

The optimization module in SOTER_PA is based on genetic algorithms, a kind of meta-heuristic inspired by Darwinian evolution, first introduced by Holland (1973). Genetic algorithms evolve an initial population by applying a set of crossover and mutation operators to individual solutions, guided by a fitness value which indicates the solution quality. In our implementation, we use a fitness function that takes into account constraint violations from constraints (1), (2), and (3), as well the objective function (5), evaluated lexicographically in the specified order. As a result, the fitness value of a solution is equal to its objective function only if that solution is feasible.

The initial population is generated by a greedy stochastic constructive heuristic. First, a set of k seed cells, each representing a singleton lot, are generated by a k-means algorithm where the assignment phase consists of computing Voronoi regions weighted by productivity indices $i_l, l \in L$. Then, a greedy algorithm iteratively assigns cells to an adjacent lot, in the order of minimal increase to the fitness function. For efficiency, this assignment is done in batches of 256 cells at a time.

Through automated parameter tuning techniques we have fixed the population size to 15. Solutions are selected for crossover and mutation through a 3-tournament. The crossover operator recombines two parent solutions to produce a child solution, which is then reinserted into the population. The recombination procedure aims to maintain the common structure of the two parents as much as possible. To establish a correspondence between the lots of the two solutions, we use compute a maximum weight matching on a bipartite graph where each part corresponds to the lots of a parent, and the weight of an edge is equal to the area of intersection between the lots corresponding to its endpoints. The intersections of the matched lots are kept as new lots in the child solution, and the remaining, unassigned cells are then assigned using the same greedy algorithm used for solution construction. A similar idea is used for the mutation operator, where a percentage of the border of each lot is deleted and reconstructed by greedy construction. The genetic algorithm has a stopping criterion of 30 minutes. More details about its implementation can be found in (Gliesch et al., 2017).

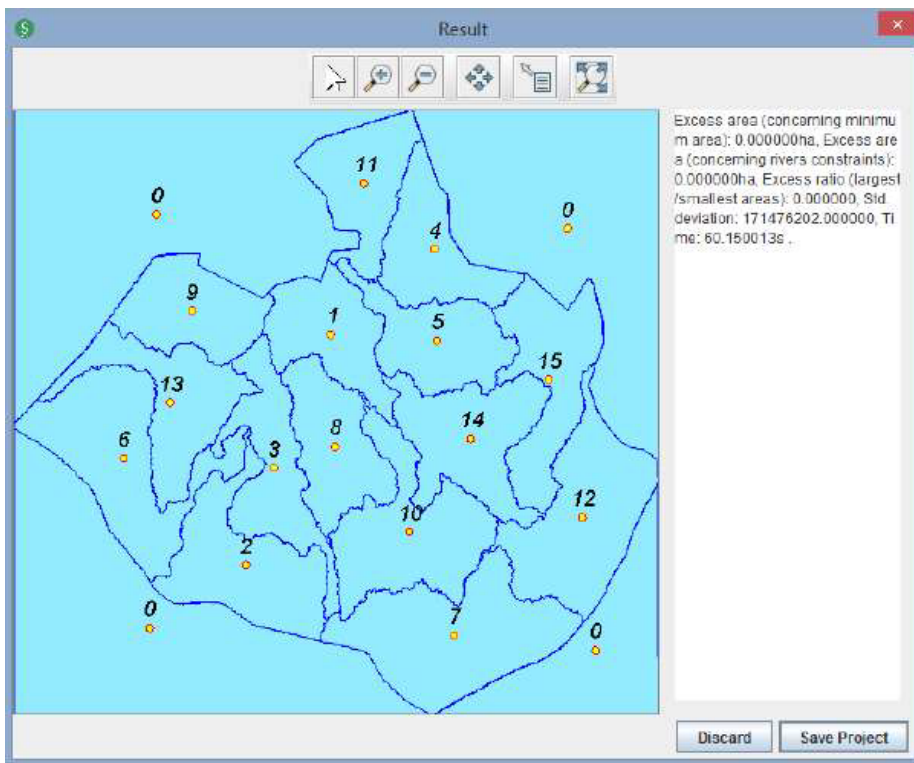## 5.3   Output data module and visualization

Figure 5 – Output data and visualization screen.

Figure 5 presents the output data and image visualization of the land parceling generated by the Genetic Algorithm described in Section 5.2. The user can access the image by clicking on

the "Save Project" button when the project is saved in ".shp" and ".png" formats. In the text field placed beside the image, one can see information about the solution regarding violations of Constraints (2), (1), and (3), the objective function and also the computational time (in seconds) spent by the algorithm. The executable file for SOTER_PA is freely available upon request.

6 CONCLUSIONS

In certain rural settlements designed by INCRA, the Brazilian National Institute for Coloniza-tion and Agrarian Reform, the way lots are established causes significant disparity in production between settled families. The lack of environmental criteria in defining plots in some INCRA-designed rural settlements has resulted in significant productive inequality among resident fam-ilies. To mitigate this issue, a combinatorial optimization problem named PROTERRA was de-fined. To solve PROTERRA, a computational tool called SOTER_PA uses a genetic algorithm to determine lots for families to respect soil quality, environmental restrictions, and number of land boundaries.

Older versions demonstrated weaknesses in the software regarding user interface, the need to re-sort to GIS to process input data from optimization algorithms, and the inefficient representation of the final result. To fill this gap, a new version of SOTER_PA was developed. The final product was a system with a graphical interface and geographic processing power from the QGIS and Geotools libraries.

As next steps, the suggestions obtained in the testing phase can be taken into account, as well as how to incorporate more advanced algorithms into PROTERRA resolution. In addition, more tests with users can be performed to validate the system usability.

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