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GIS-based genetic algorithmoptimization tool for supporting land use and land management restructuring

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For assisting agricultural planners in generating optimized land use and management allocation maps, the "Genetic Algorithms for Land use and Land management OPtimization" (GALLOP) tool was developed. The tool integrates multiobjective genetic algorithms, a geographic information system (GIS) and a database management system within the ArcGIS framework. The tool was applied to a case-study farm in Khorezm, a region in the west part of Uzbekistan. The results show that the combined optimization of multiple objectives is as a win-win strategy that achieved the best compromise between ecological and economic objectives. The GALLOP tool represents an innovative, fast and spatial planning tool for solving complex resource management optimization problems.

1. INTRODUCTION

More and more agro-ecosystems in dry areas have developed towards a critical environmental state. Farmers have received lower yields because practiced land use is not adjusted to ecological site conditions. As a consequence farm profits are often low. Furthermore, focusing on economical or ecological aspects separately may lead to completely different and often non-sustainable farm management policies. In search of viable alternatives, we tackled the questions how selected land-use-system indicators perform if the system is spatially optimized towards ecological, economic or a combination of both objectives. Aiming towards optimizing a set of objectives at the same time, we selected the multiobjective genetic algorithm (MOGA) based on the concepts of Pareto optimality and niche-techniques as analytical part of a spatial decision support tool (Malczewski, 2004). While the numerical optimization models are used in the decision support tool for problem solving, the geo-information component is used for spatial analysis and visualization of the spatial problem and solution domain, and both components may be integrated into a user interface to form a spatial decision system for supporting automated land use and land management planning.

The main goal of this paper is to present a spatial planning tool called "Genetic Algorithms for Land use and Land management OPtimization" (GALLOP) that allows one to optimize he spatial land use and land management allocation within a farm landscape based on meeting concurrently, economic and ecological objectives.

The specific research objectives were 1) to develop the system architecture of this tool with optimization routines for several single objectives and combinations of single objectives, 2) to program and design a user-friendly graphical interface that is flexible to read in data from different sources and allows users to select the land uses and land management combinations to be optimized, and 3) to demonstrate the application of this tool to a case study farm landscape.

2. REVIEW ON SELECTED GENETIC ALGORITHM APPLICATIONS FOR SPATIAL RESOURCE USE OPTIMIZATION

Since the invention of the genetic algorithm (GA) by John Holland (1975) it has been applied to many optimization problems such as in planning of afforestations, urban areas and land use allocation. For example, Ducheyne (2001) worked on the GA in forest management optimization. He proposed to use the GA based on the following statements: (1) GAs can handle conflicting objectives and do not combine multiobjectives prior to the optimization process; (2) GAs allow easy integration between the optimization module and GIS functionality; (3) GAs generate multiple alternatives in a single optimization run due to their population-based approach. In urban planning, Feng and Lin (1999) applied a GA to design several alternative urban plans for the city of Tanhai in Taipei. They concluded that the plans optimized by GA were better than those previously designed by urban planning experts. Moreover, they now had a choice of alternative plans, whereas before only one plan was devised. In land use planning, multiobjective GAs have been used by Matthews (2001). He argued that multiobjective GAs applied to rural land planning have significant potential for assisting land managers in tackling complex resource allocation problems with conflicting and non-commensurable objectives.

3. METHODS

GAs are search methods that are based on natural biological evolution theory. They differ from the conventional optimization techniques as they involve a search from a population of solutions. First, a population of possible solutions is generated. An objective function is evaluated and all solutions in current population are ranked. Next, based on competitive selection strategy, poor solutions are eliminated and the better solutions are selected as parents and recombined with each other to form some new solutions by implementation of genetic operator such as crossover, mutation or inversion. Finally, the new solutions are used to replace the poorer of the original solutions, according to ranking, and the process is repeated, ameliorating the situation from iteration to iteration and approaching the optimal decision.

3.1. Geo-spatial chromosome representation

We used the principle of land-block representation, adopted from Matthews (2001), where each polygon represents the boundary of the land parcel (field) to which a land use or management type is allocated. The part of the polygon data structure manipulated by the GA can be seen as non-spatial as each polygon is linked to a record in a relational database table with bio-physical and economic conditions on each land parcel. The integer representation is used for this problem. The fixed number of land parcels in a farm structure defines the length of the chromosome.

3.2. Genetic algorithms

The single objective algorithm (SOGA) is based on the classical approach offered by Goldberg (1989). The algorithm was adopted to allow an elitism strategy and used N-point crossover, depending on chromosome length. For bi-objective algorithms, the rank-based fitness assessment approach offered by Fonseca and Fleming (1995) was adopted. This approach was selected because it had a fast performance and was successfully applied in similar tasks, namely in land use (Matthews, 2001) and forest planning (Ducheyne, 2001). Table 1 shows the parameters and corresponding values used in the simulations.

4. RESULTS

4.1. The system architecture of the GALLOP tool

The developed GALLOP tool is based on the following components: spatial optimization routines by genetic algorithms, a geographic information system (GIS), data base management system and graphical user interface within the ESRI ArcGIS 9.2 environment. Visual Basic for Application (VBA) was integrated with ArcObjects development platform for elaborating a user friendly graphical interface and integrating the tool components. The ActiveX Data Objects (ADO) and Open Data Base Connectivity (ODBC) interfaces were used for accessing the MS Access and GIS data bases (Fig. 1).

Table 1. Optimization parameters for developed genetic single- and multiobjective algorithms

Parameters	Value
Selection strategy (optional)	Tournament selection
Probability of mutation	0.01
Probability of crossover	0.80
Elitism	One best chromosome is copied
Stop criteria	Number of iterations, goal function value
Population size	20 – fixed
Number of generation	~3000
Lengh of chromosome	227 – number of fields

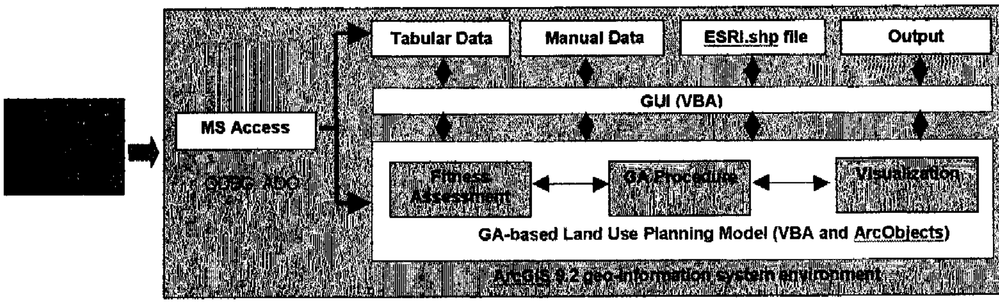

Fig. 1. Integrated component system architecture of GALLOP

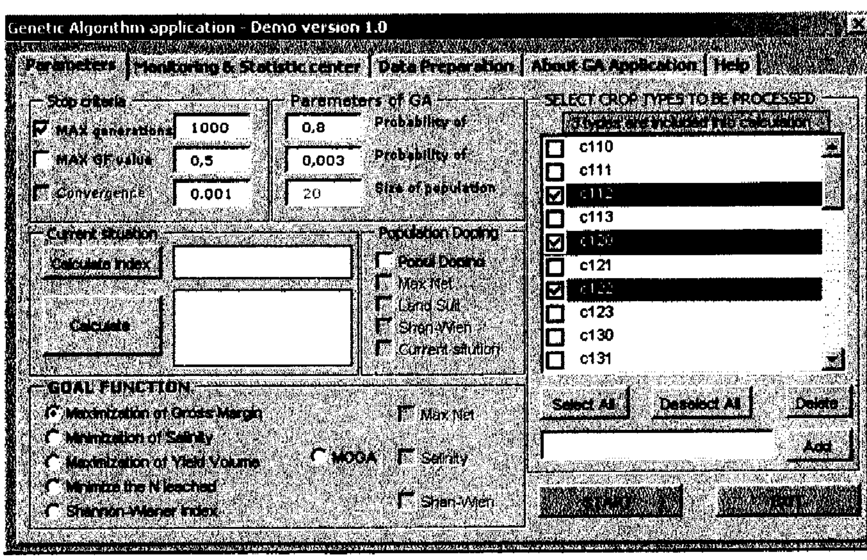

Fig. 2. Main page "Parameters" of the graphical user interface of GALLOP

The geo-information system provides all spatially distributed information to the tool. The specific ecological and economic optimization data used in this study were derived from external crop-soil simulation and non-linear programming models. The user has access to all the functions available in ArcMap for spatial data analyses. The fitness assessment component provides the means of analyzing for the GA module. The visualization procedure serves as decoder from GA-module to the real allocation parcels structure (converting the chromosome) and vice versa. The Genetic Algorithm Module is the core component of an iterative analytical tool. The user specifies a scenario, by choosing the objective functions, defining the management and GA-parameters or by limiting the planning to a subset of the land parcels.

4.2. The GUI of the GALLOP tool

A genetic application toolbar in ArcMap provides access to the specially developed graphical and interactive user forms of the GALLOP tool (Fig. 2).

The graphical user interface includes five pages to manage and monitor the process of optimization. The input parameters (single and multiobjective genetic algorithm parameters, objectives for optimization, etc.) are provided on the main page "Parameters". The possibility to monitor the optimization process, to track the changes in values of objective functions at each iteration during the whole optimization process, time calculation, changes in the process of algorithm (duplicates of individual, values of Elite individual) is provided on the "Monitoring & Statistical Centre" page. The "Data Preparation" page is used for

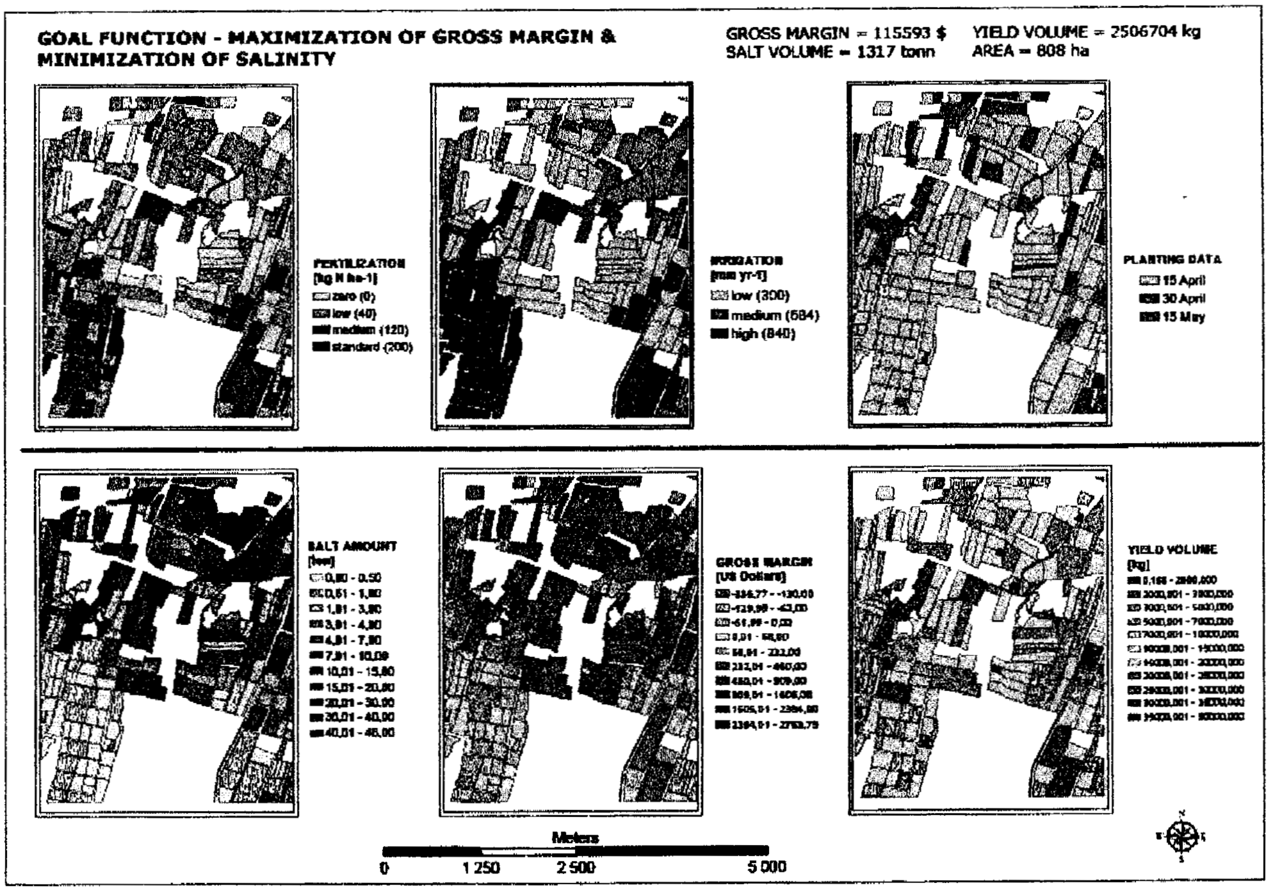

Fig. 3. Result of multiobjective genetic algorithm optimization: maximization of gross margins and minimization of soil salinity are selected as goal functions; white (empty) spots: on-agricultural sites

checking for necessary data for pre- and post-processing calculation of the results.

4.3. Case study: Land use and land management optimization in Uzbekistan

The GALLOP tool was tested in the Khorezm region, Uzbekistan, in the lower reaches of the Amu Darya River. A case-study landscape, the P. Mahmud Shirkat (PM-shirkat; nowadays a privatized farm), representing a typical situation and reflecting all problems of the region, was used as a pilot site for modelling different scenarios for development and reconstruction of the area. In sum, 227 agricultural fields of the PM-shirkat were included, which form the chromosome of corresponding length. Based on land user experts opinion and the current set of regional problems, maximization of the gross margin (GM) was identified as the economic objective. Minimization of soil salinization and Nitrate (N) leached into the groundwater was selected as main ecological objectives for optimization. Changes of yield volume (in the shown case: raw cotton yields only) were also interesting to us and were calculated in each scenario. The summarized optimization values for each objective are shown in Table 2.

One can see from Table 2 that optimization towards ecological criteria as a single objective (e.g., minimization of soil salinity or N leached) did not really pay off as indicated by gross margin ranging from negative values (for min. soil salinity) to lower values. It was also not profitable if only yields were maximized alone. OnAlternatively, maximization towards only economic issues (max. gross margins) led to a higher overall soil salinity. If both ecological and economic objectives were optimized (scenarios 5 and 6) a good compromise was achieved. The spatial representation of the best compromise result is shown in Fig. 3.

Compared to the single objective results, this

Table 2. Values of objective functions derived from genetic algorithm tool

Scenario No	Goal function	GM value [US $]	Soil salinity balance [t]	N leached [t]	Yield [ton]
1	Maximization of GM	158336	3117	64826	2600
2	Minimization of soil salinity	−38666	907	81442	1938
3	Maximization of yield	63636	1786	88745	2978
4	Minimization of N leaching	28343	4319	50733	1789
5	MOGA: combination of 1 and 4	124851	4717	54278	2278
6	MOGA: combination of 1 and 2	115593	1317	70607	2507

optimization really achieves high gross margin and low soil salinity at the same time. In a spatially explicit perspective, this requires higher fertilization and water amount in the marginal areas in the south and less fertilization and low irrigation amount in the more fertile area in the north.

5. CONCLUSIONS

A spatial planning tool called "Genetic Algorithms for Land use and Land management OPtimization" (GALLOP) was developed. The application of the tool to a study site showed that pursuing a single objective of land use restructuring such as maximization of gross margins had a major drawback on the ecology, e.g. by increased soil salinity and nitrogen leached. Similarly, only focusing on land management strategies that achieve high raw-cotton yields did not pay off. The combined optimization of multiobjectives was identified as a win-win strategy that achieved both, high profit and low environmental impact. The spatial explicit optimization reflected the necessary site-specific management for the respective optimized objectives. The GALLOP tool represents an innovative, fast, user friendly and spatially explicit planning tool for solving complex land use and land management optimization problems. Next steps will comprise the inclusion of crop-growth and yield of maize, rice, and wheat, as well as a systematic comparison of the GA performance with classical economic non-linear programming optimization.

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ГЕНЕТИЧНИЙ АЛГОРИТМ В ГЕОІНФОРМАЦІЙНОМУ СЕРЕДОВИЩІ ДЛЯ ПІДТРИМКИ РЕСТРУКТУРИЗАЦІЇ ЗЕМЛЕКОРИСТУВАННЯ ТА УПРАВЛІННЯ

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Для підтримки прийняття рішень щодо сільськогосподарського менеджменту та розробки оптимальних просторових планів реструктуризації земель було розроблено програмне забезпечення (ПЗ) "Genetic Algorithms for Land use and Land management Optimization" (GALLOP), яке інтегрує адаптований багатоцільовий генетичний алгоритм, гео-інформаційну систему та бази даних в ArcGIS середовищі. В якості тестової території була обрана ферма в Хорезмській області у західній частині Узбекистану. Результати тестування ПЗ показали, що багатоцільова оптимізація є безпрограшною стратегією, яка дозволяє досягти найкращого компромісу між екологічною та економічною складовими. Запропоноване ПЗ GALLOP є інноваційно зручним та швидким засобом вирішення комплексних просторових задач оптимізації та реструктуризації земельного менеджменту.