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A Spatial Decision Support System for Agricultural Land Management in Maros Region, Indonesia

Samsu Arif
Department of Physics, Hasanuddin University, Makassar, South Sulawesi, Indonesia

D. A. Suriamihardja
Department of Physics, Hasanuddin University, Makassar, South Sulawesi, Indonesia

Sumbangan Baja
Department of Soil Science, Hasanuddin University, Makassar, South Sulawesi, Indonesia
Center for Regional Development and Spatial Information (WITARIS), Hasanuddin University, Indonesia

Hazairin Zubair
Department of Soil Science, Hasanuddin University, Makassar, South Sulawesi, Indonesia

Abstract

Land management which is increasingly complex from time to time, land convertion due to increasing population have caused conflicting various interests. Land management models developed to date are less able to answer the problems quickly and dynamically. Maros regency is one of the biggest producers of rice in South Sulawesi Indonesia. Its variability is fairly complex, consisting of coast, low land, and high land. Having a border with Makassar, its population pressure causes a bigger change of land function. It thus needs a model that can provide an optimal solution of land use and land management. The purpose of this research is to develop a model of Spatial Decision Support System (SDSS), which can help spatial decisions for the best land management of food crops, and to test the validity and sensitivity of the models. In this study, SDSS development methods integrate fuzzy set, Analytic Hierarchy Process (AHP), and Compromise Programming modules, to produce spatial information on land management. SDSS design utilizes some knowledge input in the operation, including experts who understand the mechanism of the SDSS and its applications. The results of study are in form of spatial distribution of Land Suitability Index (LSI) resulting from land quality assessment. The results can be used to simulate food land management models in various scenarios. Compromised situation between biophysical and non-biophysical parameters provide distribution pattern of values of land management for food crops.

Keywords: Spatial Decision Support System, fuzzy set, Analytical Hierarchy Process and Compromise Programming

1. Introduction

Human activity and the environment that interact will affect the dynamics of land use (Brinkman and Smith, 1973; FAO, 1976). The availability of land for agriculture is getting narrower with increasingly rapid population growth makes land management becomes complex, causing conflicting interest between sectors. This situation is worsened by the lack of information about the potential of land which results in land management model that is not relevant to the suitability and socio-economic conditions of society (FAO, 2011; Thuo, 2013).

Various concepts of land management models have been developed to solve the complex problems as above, ranging from classical methods introduced by Christian in 1958 (Baja, 2012), to the quantitative parametric approach that developed into a simulation modeling with an emphasis on the use of computer-based analysis system such as an expert system (Johnson, 1991). Such assessment procedures where then developed into land suitability evaluation with fuzzy sets methodology (Burrough, 1992; Nurmiaty and Baja, 2014; Tang and Van Ranst, 1992; Wang, 1990; Zabel et. al., 2014), Multiple Criteria Decision Making (MCDM) (Pereira and Duckstein, 1993), and Analytic Hierarchy Process (AHP) (Banai-Kashani, 1989; Yedage. et al., 2013; Vasiljevic et. al,2011). Integration of AHP, Fuzzy Set in Compromise Programming-based on Geographic Information System (GIS) in the evaluation of land will generate spatial based expert system as a model that can simulate optimal food crop land management. (Baja, 2012; Mardani, 2015), has integrated modules between AHP and GIS known as 'tight coupling integration' in the development of GIS and MCDM. The existence of geospatial based expert system (Spatial Decision Support System) in the field of food crop management can help various parties in making decisions about their land (Wai, 2005). Decision suppport System is a computer-based technology that can be used to support decision-making is complex and based on the specific problem (Rosa, 2011; Shim, 2002; Kucukvar et. al., 2014).

The purpose of this research is develop a Spatial Decision Support System model using Multi-Criteria Decision Making (MCDM) - Fuzzy Sets, AHP and Compromise Programming with Eucledian Dinstance formulations. Fuzzy sets approach using Semantic Import Model (SIM) was implemented. Criteria of weighting using the multilevel weighted average procedure or ordered weighted linear combination (OWA) was used. Analytic Hierarchy Process (AHP) is used to assist in the process of weighting, and Compromise Programming models were used to assess two important approaches in the rating of conformity: the evaluation of non-compensated and compensated. The whole process of GIS based decision making will simulate food land management optimization, from different scenarios.

1. Methods

2.1 Research Area

The research was conducted in Maros Regency, Province of South Sulawesi. Geographically this region is located at 4^{o} 43' 7.8" to 5^{o} 12' 43.0" latitude and 119^{o} 27' 58,4" up to 119^{o} 58' 21,3" longitude (Figure 1).

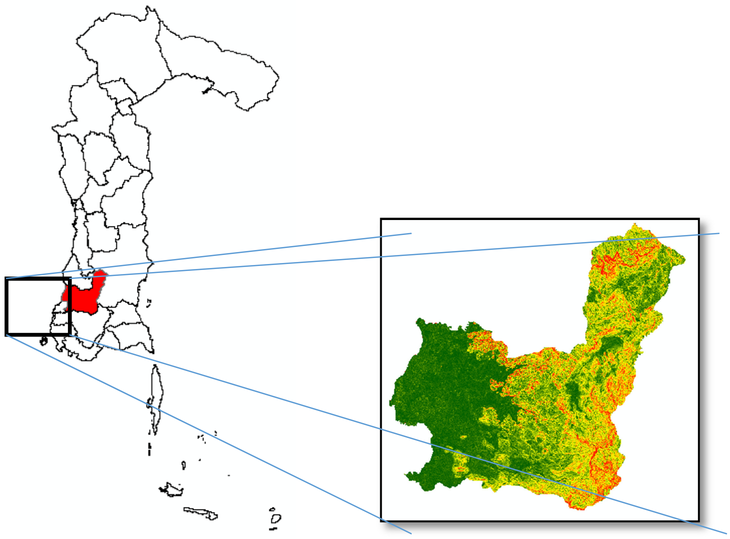


Figure 1. Location of the research area, in the box is Maros Regency

2.2 Databases

Spatial data used in this research is a raster model structure obtained from survey and three-dimensional images of earth surface. Raster data were used to represent the criteria values of land and evaluation on a continuous basis (Baja, 2012). Climate data were derived from the Global Weather, calculated on average for 30 years at any point, then be interpolated for the entire area of research.

There are fifteen main tables required by the system, and five table relate to each other. The tables include: (i) commodities, (ii) decision parameters, (iii) weighting mechanism, (iv) fuzzy sets, and (v) land suitability index (LSI)**.**

2.3 Components of Spatial Decision Support System (SDSS)

SIG-based Decision Support System called SDSS is a relevant tool used in sustainable development for decision makers. SDSS gives valuable information for land resource management. SDSS is flexible, can accommodate various preferences of share-holders and it enables an interaction with users effectively and repetitively in solving problems (Sugumaran, 2011; Yatsalo, et. al., 2010). SDSS is built based on synthetic-dynamic thinking system, where every component involved in SDSS does not work independently but inter-dependently to produce information (Muadz, 2013). Output of SDSS produces information that can become a basis to improve input and is used again by system if the person practicing and running it considers it not optimal by using some parameters (dynamic system). SDSS module is a component that can be seen as a unity and is a machine that processes data input. The output produced is then interpreted by an expert to determine whether or not the scenario made has produced optimal land management model (Figure 2).

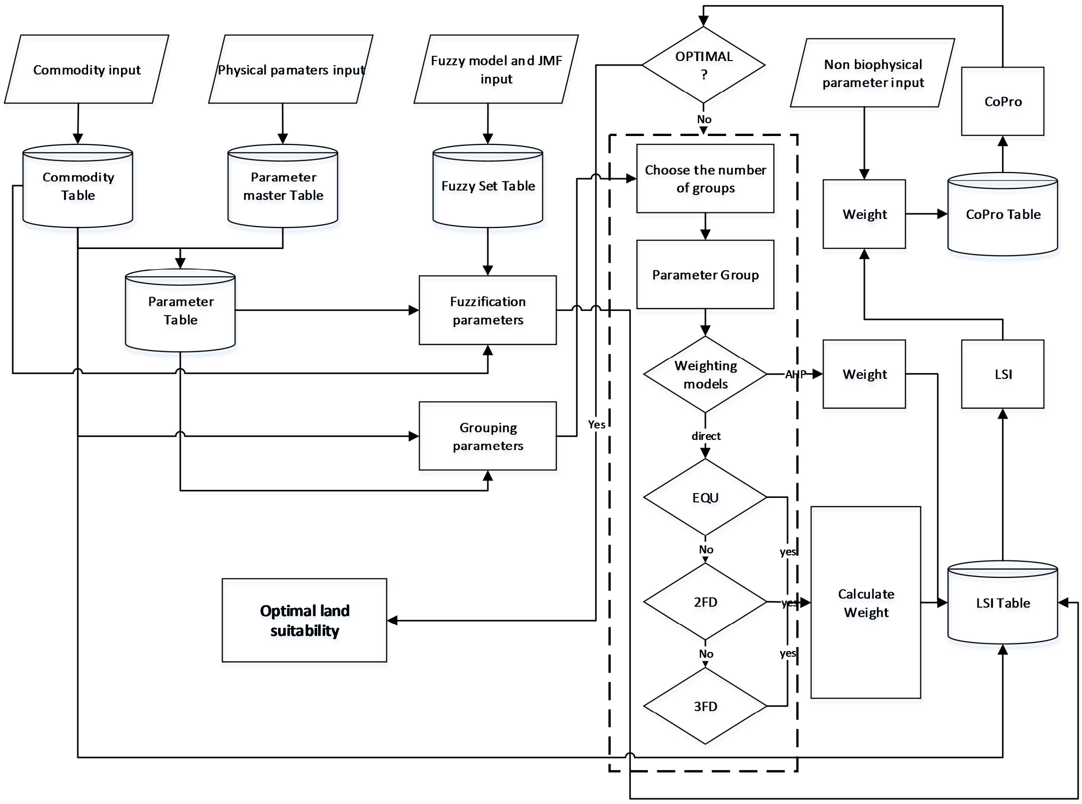


Figure 2. SDSS logarithm flowchart

2.3.1 Interaction Between SDSS Components

Land characteristic attribute values have different nominal values (soil depth: 0-172 cm, pH: 4.70-6.81, Organic C: 0-4.19(%), precipitation: 3237.15-3529.89 mm/year) therefore they need to be standardized in order that they have equality in the calculation of JMF (Joint Membership Function) and LSI. To standardize the land characteristic attribute values, 4 models of fuzzy set are used (Figure 3) and the following equation is to be followed (Baja et al., 2002; Burrough et al., 1992; Davidson et al., 1994):

$MF(x_i) = 1$ if $(b_1+d_1) \le x_i \le (b_1 - d_2)$ ………………………………...(1)

$MF(x_i) = [1/(1 + \{(x_i-b_1-d_1)/d_1\}\ 2)]$ if $x_i < (b_1+d_1)$ …………….……..(2)

$MF(x_i) = [1/(1 + \{(x_i-b_2+d_2) / d_2\}\ 2)]$ if $x_i > (b_2-d_2)$……..………..……(3)

Where:

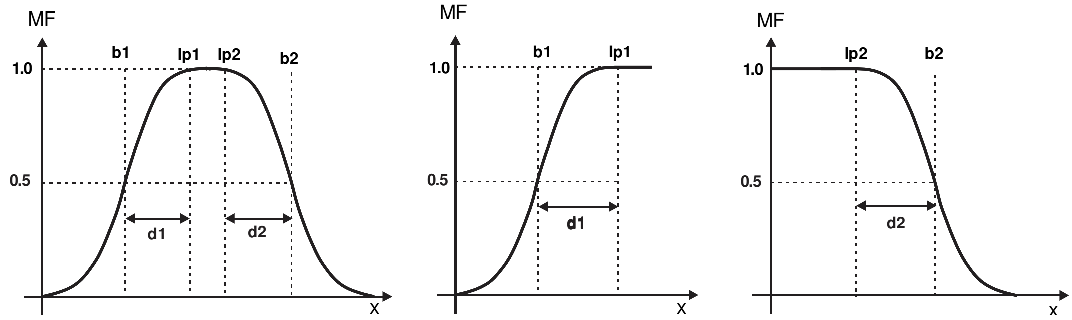
$MF(x_i)$ = Parameter x membership value
$x_i = i^{th}$ Parameter attribute value

Determination of fuzzy model variable value such as b_1, b_2 (ideal point or central concept), LCP (lower crossover point), UPC (upper crossover point), and d_1, d_2 (transition zone width) is an important stage for the procedure of modeling, including optimum point, lower limit, upper limit, lower base, and top of base (Glover et al., 2000; Harris et al., 1996; Karlen and Stott, 1994). Fuzzy variable value is stored in fuzzy database to become a reference in spatial data fuzzification.

Land characteristics are grouped into 3 (three) namely soil (JMF_S), topography (JMF_T) and climate (JMF_c). JMF_S (Cation Substitution Capacity, pH, Organic C, drainage, flood hazard, surface rock, erosion hazard, effective depth, salinity and texture), JMF_T (slope), and JMF_C (precipitation, temperature, and humidity). Contribution of each land characteristic in determining land suitability index has a different weight. From weighting result, a combination is made between land attribute values using combination function in equation 4 (Baja, 2012a). As an illustration, table 1 shows a model of Fuzzy Set and Membership Function (MF) of plants in irrigated rice-field. Parameter of precipitation is not used with an assumption that for rice-field the water availability is not a hindrance.

$JMF(x) = \sum_{i=1}^{n} \lambda_i MF(x_i)$ ……………………………..………..……(4)

where JMF is calculated based on the groups that compensate one another, namely: JMF_S for soil groups, JMF_T for topography, JMF_C for climate.



(a) Symmetrical models (b) Asymmetrical left models (c) Asymmetrical right models
Figure 3. Model of S Curve in the theory of Fuzzy Sets (adapted from Baja et. al., 2002)

Table 1. Model of Fuzzy Sets and Membership Function (MF) of plants in irrigated rice-field

No	Parameter	Type of Data	Model of Fuzzy	b1	Ip1	Ip2	b2	d1	d2
1	Average Temperature	C	1	20	24	29	33.5	4	4.5
2	Humidity (%)	C	1	30	33	90	91	3	1
3	Drainage	O,5	3	0	0	2	4	0	2
4	Texture	O,5	3	0	0	3	4	0	1
5	Soil Depth (cm)	C	2	32.5	50	0	0	17.5	0
6	Clay CEC (cmol)	C	2	15	16	0	0	1	0
7	pH H2O	C	1	5	5.5	8.2	8.5	0.50	0.30
8	Organic C (%)	C	2	0.80	1.5	0	0	0.70	0
9	Salinity (dS/m)	C	3	0	0	2	5	0	3
10	Slope (%)	O,3	3	0	0	3	6.5	0	3.5
11	Erosion Hazard	O,5	3	0	0	1	3	0	2
12	Flood Hazard	O,5	3	0	0	1	4	0	3
13	Surface Rock (%)	C	3	0	0	5	27.5	0	22.5

The use of Analytical Hierarchy Process (AHP) by comparing in pairs the land suitability index and nonbiophysical parameter involving expert judgement to avoid subjectivity in making decisions. AHP was first developed by Saaty (1990), and is very popularly used in designing land especially in land use allocation (Baja, 2012). The approach of AHP – Fuzzy is a reliable method and is used to combine data from various domains and sources (Elaalem, 2013).

Land suitability index with nonbiophysical data is then compromised to determine the correct model of land management by using the approach of compromise programming. Before compromised, weight of every parameter is calculated using AHP. Land suitability index reflects fertility of land (Mohammadrezaei et al., 2013).

Compromise programming is a mathematical programming technique used to find compromise solution in a set of purposes that contradict one another. Compromise programming can be considered as a natural and logical complement of multi-objective programming (Romero, 2003). Compromise programming applies principles of distance function, so it is suitable to be used in land suitability evaluation with raster-based GIS. Compromise programming is also a technique that can be used in a context of continuous compound purposes (Zeleny, 1973). Compromise Programming algorithm is made based on the formulation (Romero, C.R., 2003):

$$L_p = \left[\sum_{j=1}^{n} \alpha_j \left|Z_j^* - Z_j\right|^p\right]^{1/p} \quad \text{...(5)}$$

Where:

L_p = Distance from ideal point, $0 \le L_p \le 1$
Z^*_j = Ideal point
Z_j = considered point
p = parameter that regulates geometrical distance between Z^*_j and Z_j, and
α_j = criterion weight.

The smaller the L_p value is, the closer it is to ideal point, so optimalization of food-crop land management can be seen from the result of L_p value spatial distribution. In order for L_p value to be parallel with the value of IKL from 0 (not suitable) to 1 (very suitable), then the new L_p value (L_p^*) is formulated:

$$L_p^* = 1 - L_p \qquad (6)$$

2.4 Expert System

The operator who runs SDSS is an expert in the field of land management so the input knowledge given into the system can be accepted by SDSS in line with the thinking flow that has been built. The knowledge input meant here is: the type of data used; weighting model; MCDM scenario with compromise programming. Output of SDSS is a plant optimal land spatial distribution. The value of 0 shows the land that is not optimal, whereas the value of 1 is considered as the most optimal land by accommodating various interests that are given by the expert.

3. Result and Discussion

3.1 User interface skenario pembobotan dan pengelompokan JMF

Based on the frame made in the form of modules which interact mutually in SDSS, then this system can be used easily to stimulate food-crop land management model in various scenarios. Simulation model with weighting scenario toward biophysiscal parameter and nonbiophysival parameter use RTRW (spatial planning), and accessibility can be executed with SDSS user interface as shown in Figure 4.

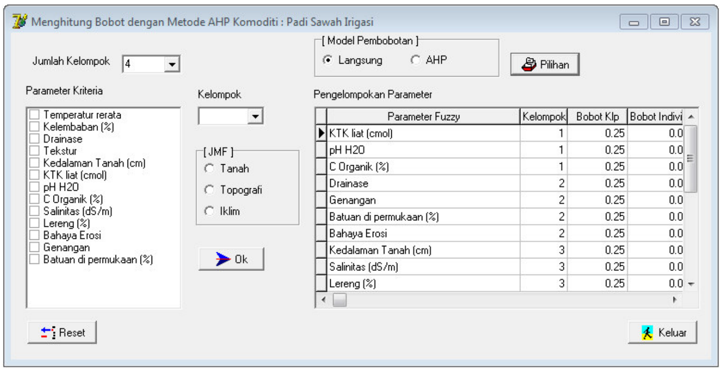


Figure 4. User interface Weighting scenario and JMF grouping

Scenario of weighting and grouping the JMF can be done easily (user friendly) by using user interface that is based on Graphical User Interface (GUI). There are two types of weightings, namely: direct weighting and weighting with AHP. In this user interface there are 4 main components: (i) components that determine the total of groups, (ii) parameter list, (iii) parameter grouping choice, and (iv) type of weighting. The total of groups gives choices of which parameters are to be grouped together based on difficulty level in management. Parameter list is provided to choose the parameter in the same grouping. The choices of parameter grouping (JMF) are provided to group the parameters based on characteristic group: soil, topography, or climate. Type of weighting gives choices: direct type or with AHP. If direct type is chosen, weighting scenario provides 3 choices: EQU (each group is given the same weight), 2FD (the group is twice as high as previous weight), 3FD (the group is three times as high as previous weight). If AHP type is chosen, the user gives paired comparison weighting.

3.2 Land Suitability index (LSI)

Calculating LSI in line with grouping and weighting of JMF is done by using LSI user interface (Figure 5). There are 4 main components, namely: (i) choose the commodity, (ii) file name to be stored, (iii) parameter list, and (iv) fuzzification parameter file name list. In the LSI calculation process, SDSS automatically stores the parameter names used in the calculation. Then the parameter names become a reference when determining the index performance of limiting factor.

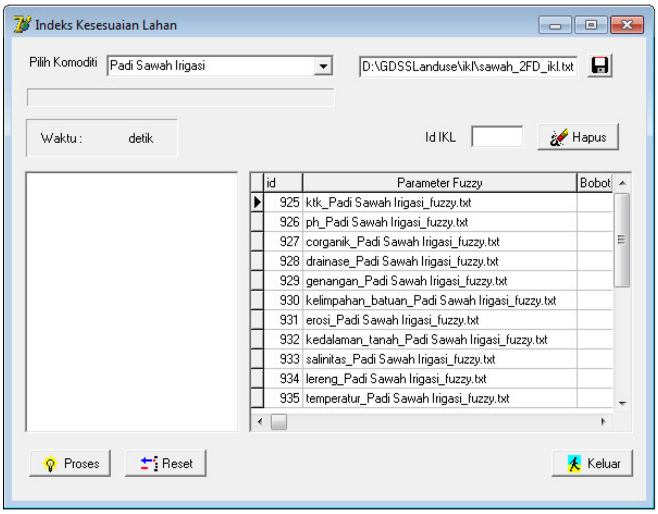


Figure 5. User interface LSI

Land suitability index (LSI) obtained from the result of SDSS calculation indicates that the main limiter in the research region is topography. From Figure 8 (a) it is seen that the green-colored area with a value near 0 (not suitable) lies in an area with high slope, this is indicated with a very low limiting factor index on the slope, namely: 0.006 (Figure 6).

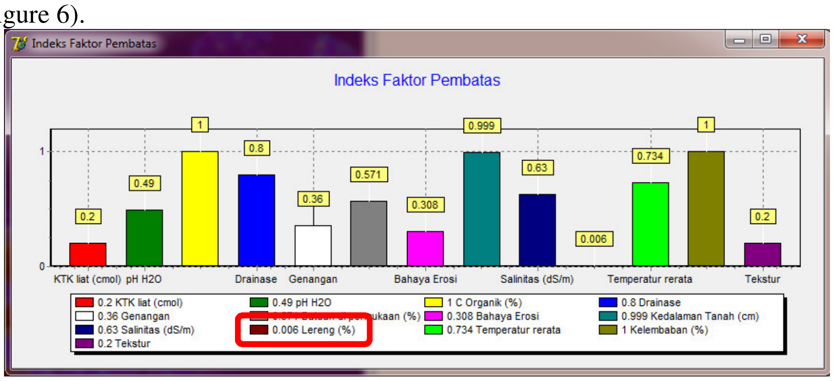


Figure 6. Performance of limiting factor index

Limiting factor index in Figure 6 is the result of SDSS calculation using fuzzy set membership function without considering the weight of each limiting factor.

3.4 Land Management Model

The land management model given as an example in this research is to see how the effect of policy (RTRW) and road accessibility is if it is involved in the best location determination process for irrigated rice-field land management. If involving nonbiophysical parameter, the next scenario is to find the value that is close to ideal value using the models of MCDM - AHP and compromise programming. The result is an optimal food-crop land management value distribution (Figure 7).

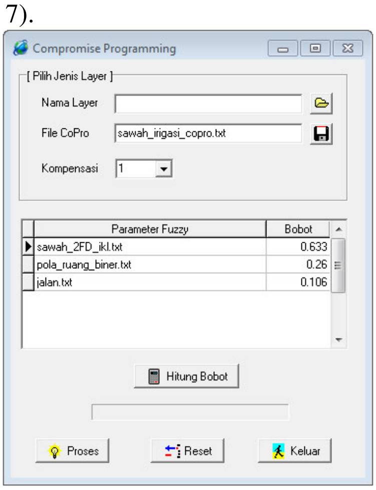
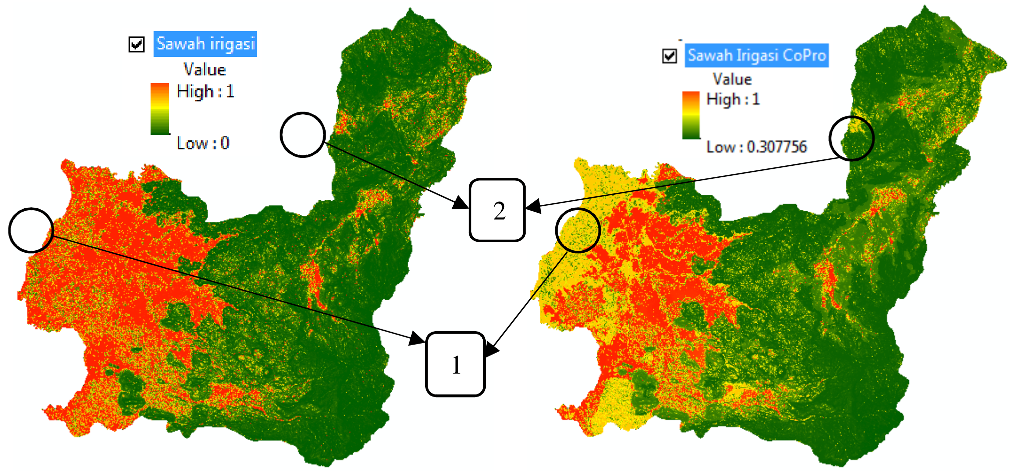


Figure 7. User Interface Compromise Programming (CoPro)



(a) (b)

Figure 8. (a) Land suitability index distribution (b) Compromise programming value distribution

Figure 8 (b) shows an optimal land distribution that is not extensive as in Figure 8 (a) but follows a wetland agricultural space use allocation pattern that has been determined by the local government (number 1). Effect of accessibility is also seen in the northern region whose color was previously red (having high value) and changed into yellow (having lower value) (number 2).

4. Conclusion

This research has produced a Spatial Decision Support System model application system of food-crop land management by integrating the modules of AHP, fuzzy set, and Compromise Programming. The system works by using spatial modeling, and is able to solve problems interactively with the support of interactive user interface. The model built can be put in a scenario to produce optimal value spatial distribution in food-crop land management. Overall, this SDSS application system of food-crop land management fulfils the characteristics of an SDSS.

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