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Application of a spatial decision support system (SDSS) to reduce soil erosion in northern Ethiopia

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Abstract

A spatial decision support system (SDSS) based on multi-criteria and multi-objective decision analysis is applied in a case study in Ethiopia to reduce soil erosion on the basis of reallocation of crops according to their capacity to protect the soil. The case study is carried out in the Adwa district. The SDSS has been implemented using the widespread GIS software IDRISI 32 (release 2) and with the direct involvement of local stakeholders in defining factors and constraints. These are based on land cover-land use, altitude, potential erosion, proximity to roads, water and the relative soil protective capacity of each crop species. A reduction of soil loss from an average of 4.5 t ha^{-1} yr^{-1} to values below the risk threshold of soil degradation (1 t ha^{-1} yr^{-1}) would be achieved through the application of the SDSS results. The biggest impediment to the reallocation exercise, however, is the shortage of cultivable land suitable for cultivation.

Keywords: Crops; Decision support system; Multi-criteria decision analysis; Reallocation; Rehabilitation; GIS

1. Introduction

Drought, unbridled population growth, declining productivity, land degradation and abject poverty contribute to the recurrent famines in many parts of tropical and subtropical countries (TSC). Survival needs supersede concerns for resource conservation and problems of biodiversity depletion and large-scale degradation of natural resources are overwhelming. Ethiopia is an emblematic example of a TSC rural country whose economy is mainly based on renewable resources (pastoralism and/or agriculture of subsistence). In most parts of Ethiopia, problems related to maintaining natural resources are critical and alternative livelihood options are limited (Egziabher, 1990). A long history of land clearance and sedentary agriculture has changed the vegetation cover in the Ethiopian highlands. Esayas (2000) has shown that a quarter of the highlands of Ethiopia are eroded. Over 4% of this area affected to a stage that it will not be economically productive in the foreseeable future. Half of the area of the highland is prone to erosion due to the expansion of cultivation to easily erodible areas. The present annual soil erosion rate in the highlands of Ethiopia can reach peaks of 300 t ha^{-1}.

Decreasing the area of rural land to reduce soil erosion may not be a viable solution under the present economic conditions, since it can result in a severe reduction of the total crop yield. It would therefore be preferable to keep the cropped area relatively constant and to reallocate crop types considering their diverse soil protection capacity along with the cropland erodibility.

This paper presents an application of a well established methodology of spatial decision support systems (SDSS) integrated in a GIS software package (IDRISI 32 for Windows, release 2 (Eastman, 2001), hereafter called IDRISI). A case study is developed in a decision frame to reduce erosion rates thus contributing to environmental rehabilitation without significantly lowering the crop yield.

The study is conducted in Adwa, which is the smallest, but the most populated district in Tigray, a Federal

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Region of Ethiopia. Adwa covers an area of 3700 km^2 (5% of Tigray total area) and the population density recorded in 1990 was 162.6 persons/km^2 compared to 42.8 in Tigray and a national average of 41.9 (source UNEP/GRID). Fig. 1 shows the location of the study area.

A European Commission funded project gave the occasion to perform a thorough environmental assessment of the area. The geology and geomorphology is described by Machado et al. (1996), a comprehensive description of the land cover-land use types is given by Egziabher et al. (1998), whereas Eweg et al. (1998) calculated the actual and potential erosion of the area by means of a modified universal soil loss equation (USLE) (Mitchell and Bubenzer, 1980; Lal, 1990). Feoli et al. (1995) provided a detailed description of the vegetation types.

2. Data and methods

The available data were stored in the raster-based GIS system implemented in IDRISI consisting of the following maps:

- Actual and potential erosion maps (Machado et al., 1996; Eweg et al., 1998)
- Land cover-land use map (Egziabher et al., 1998)
- Roads and trails map
- Rivers, streams, lakes and wetlands map.

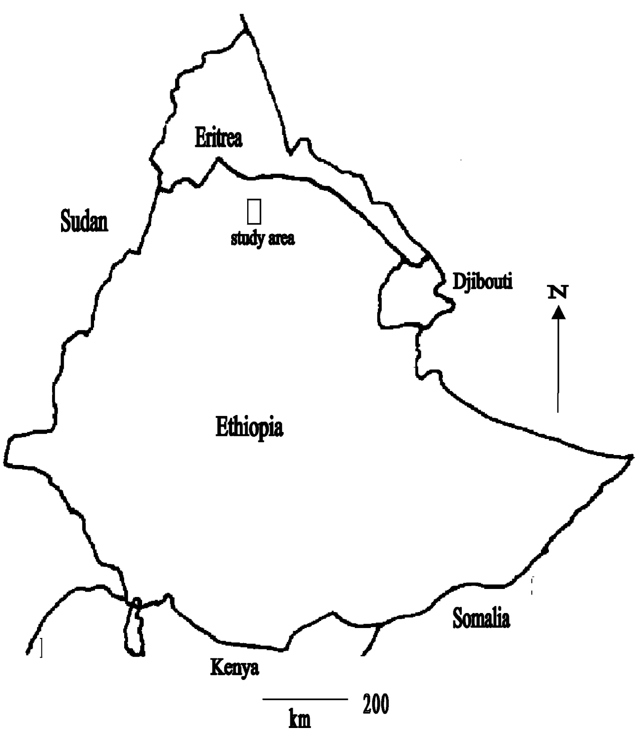

Fig. 1. Location of the study area.

The actual erosion in the study area ranges between less than 1 t ha^{-1} yr^{-1} and 80 t ha^{-1} yr^{-1} with an average value of 4.5 t ha^{-1} yr^{-1}. Only areas with actual erosion greater than 1 t ha^{-1} yr^{-1} were considered in this case study, because this value is assumed to be the risk threshold of soil degradation (Pimentel, 1993).

Four crop species in five cropping types are cultivated in the study area, namely:

1. tef (*Eragrostis tef*, L.),
2. wheat (*Triticum aestivum*, L.),
3. white and red sorghum (*Sorghum bicolor*, L. (Moench.)),
4. maize (*Zea mays*, L.) and
5. wooded cropland (woodland with tef or wheat/barley (*Hordeum vulgare*, L.)).

To achieve the goal of our study, namely reducing soil erosion without decreasing the cropland area, a multi-objective oriented SDSS (MO) based on multi-criteria decision making (MCDM) methods was selected among the available techniques of SDSS (Rosenthal, 1985; Malczewski, 1999). Spatial decision support systems (SDSS) refer to those DSS systems based on GIS technology, making use of geographic or spatial data (Densham, 1991). A multi-objective problem is encountered whenever two or more candidate sets (i.e. sets of solutions) share members. These objectives may be complementary or conflicting in nature (Carver, 1991). MCDM aims at solving problems characterized by multiple choice alternatives (multi-objective), evaluated by means of decision criteria (Jankowski et al., 2001). MCDM tools integrated with GIS have been applied in a variety of case studies in the environmental domain to address various issues such as resources management and allocation, land suitability analysis and risk assessment (Eastman et al., 1993a).

Malczewski (1999) defines SDSS as an interactive, computer-based system designed to support users in achieving effective decision making by solving semi-structured spatial problems. The case study of this paper is a typical semi-structured problem. The first step involves diverse decision groups in the subjective definition of criteria. In this phase collaboration and consensus are required to obtain effective solutions to spatial problems (Jankowski et al., 1997). In the second step, MCDM analysis routines are accessed from within the GIS software using a so-called tightly coupled approach (Jankowski, 1995).

It is common practice, in multi-criteria analysis, to distinguish criteria in two categories: factors and constraints. Factors are decision variables that enhance or detract a specific alternative from the suitability and they are weighted according to their relative importance in achieving the target objective. On the other hand, constraints represent limits to the alternatives under evaluation (Eastman, 2001). In a SDSS context, criteria are represented in separate map layers (hereafter named FACTOR and CONSTRAINT maps). The aggregation phase is eventually carried out to combine the information from the various factors and constraints. The benefit of using a GIS is that criteria can be based upon spatially related data and the GIS is a suitable computing environment to perform the MCDM analysis (Jankowski, 1995). Fig. 2 presents the logical framework of the SDSS from the problem definition to the final output map that represents the solution set of spatial decision alternatives (Ascough et al., 2002).

Within the main goal of the case study, three specific and consecutive objectives were identified:

1. Crop reallocation in croplands to reduce the soil erosion below the 1 t ha^{-1} yr^{-1} threshold of actual erosion and identification of areas not suitable for cropping when even a change of crop type does not reduce the soil erosion below the threshold.
2. Identification of non-cropped areas suitable to host the crops removed in objective 1.
3. Identification of areas of high actual erosion where the only viable protective measures could be either enclosure or terracing.

The decision support modules available in IDRISI provided the framework for the SDSS implementation. The modules MCE (multi criteria evaluation) and MOLA (multi objective land allocation) were applied to achieve the first two objectives.

MCE is a procedure that combines the selected criteria

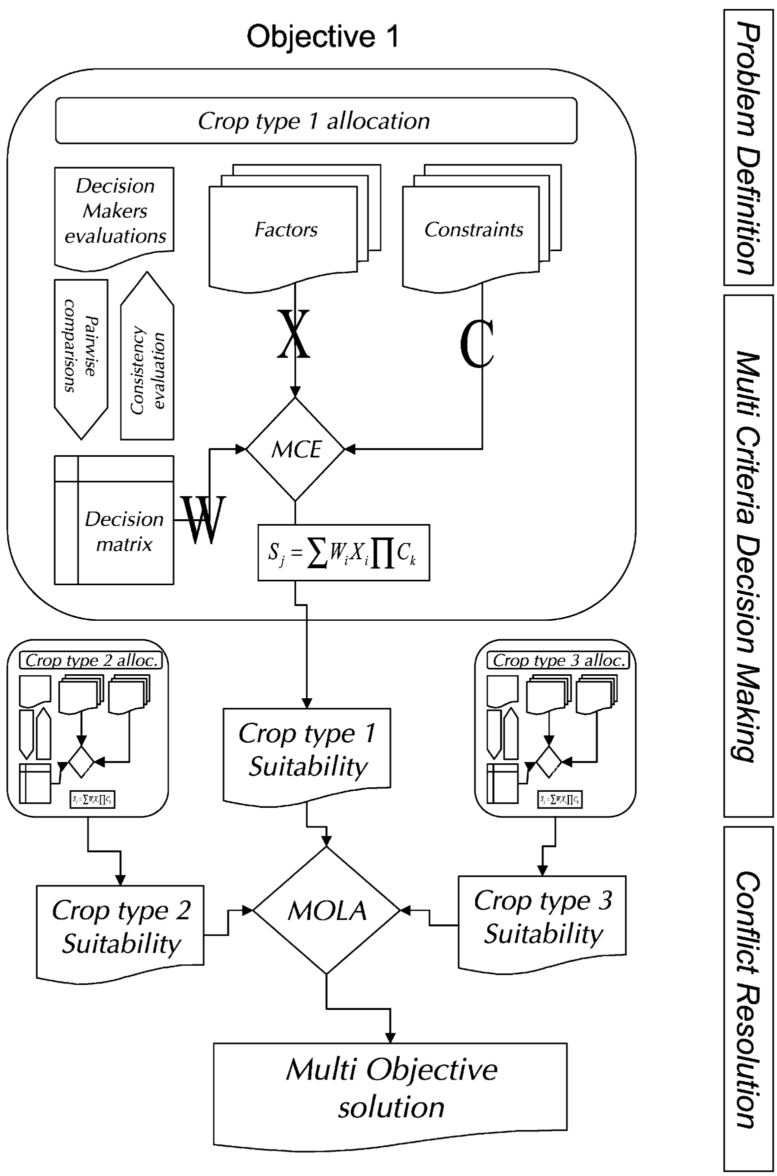

Fig. 2. Logical framework of the spatial decision support system (SDSS).

to yield a single index of evaluation, the suitability map, by means of an aggregation method (decision rule).

MOLA is a compromise solution technique developed to solve multi-objective decision problems with conflicting objectives. Multiple suitability maps are iteratively reclassified to perform a first step allocation; conflicts are addressed with successive allocations that look for a compromise solution using a minimum-distance-to-ideal-point rule (Eastman et al., 1993b).

MCE was used to produce suitability maps for each crop type based on a weighted linear combination (WLC) decision rule that combines the FACTORS and CONSTRAINTS maps according to the following formula:

$$S_j = \sum W_i X_i \Pi C_k \quad (1)$$

where S, suitability for pixel j to a crop type; Wi , weight of factor i; Xi, criterion score of factor i and C_k represents the kth constraint.

The pairwise comparison method was applied to obtain the weights of the factors, according to the analytic hierarchy process (AHP) proposed by Saaty (1977, 1999). The decision makers evaluated the relative importance of factors in determining the suitability of a pixel for a specific crop. Only two criteria are compared at a time and every possible pairing is considered. The comparisons are based on a continuous scale with values from 1/9 to 9 and the ratings are written in a square reciprocal matrix (Saaty matrix).

The matrix is submitted to the IDRISI WEIGHT module to compute the principal eigenvector, whose components are the weights of the factors. A consistency ratio (CR) is calculated to test the hypothesis that the matrix scores were randomly generated. According to Saaty (1977, 1999), matrices with CR greater than 0.10 should be re-evaluated. Several pair-wise comparison Saaty matrices were generated using the information obtained through interaction with the stakeholders (decision-makers, users and researchers). The final set of weights was derived from the matrix with the highest consistency.

MOLA is a module designed to solve multi-objective land allocation problems for cases with conflicting objectives. In our case conflict arose when a pixel had the same suitability for two or more crops. MOLA looks for a compromise solution using a set of suitability maps (computed through MCE), one for each crop, a relative weight and the amount of area to be assigned to each crop type.

MCE was applied for the first objective with the following FACTOR maps:

- Potential erosion
- Altitude
- Proximity to croplands
- Proximity to water
- Proximity to the same type of crop
- Proximity to roads.

The factor maps were standardized with the FUZZY module applying a linear function. Linearity was chosen to limit discussion with the stakeholders for selecting other membership functions.

The CONSTRAINTS (non suitable areas for the first objective) expressed in the form of Boolean maps were:

Constraint 1: pixels with actual erosion lower than 1 t ha^{-1} yr^{-1};
Constraint 2: pixels of the crop type to be reallocated;
Constraint 3: pixels of roads;
Constraint 4: pixels of rivers, streams, lakes and wetlands.

In this objective, the area cultivated with tef was not considered in the application of MCE since it is the least protective crop according to the USLE C-factor (tef, 0.25; wheat/barley, 0.15; wooded cropland, 0.1; sorghum/maize, 0.10), with higher values indicating lower protective capacity.

The pixels in each suitability map were ranked in descending order using the module RANK. The ranked maps were submitted to MOLA to perform the crop reallocation. MOLA requires relative weights for each objective that were based on the USLE C-factor proposed for Ethiopia by Hurni (1985, 1990). This means that pixels with lower potential erosion were assigned to less protective crops. The area requirement of MOLA for each crop was the number of pixels to be reallocated.

For the second objective, identification of non-cropped areas suitable to host the crops to remove, MCE and MOLA were applied with the same factor maps and weights used for objective 1, but with the following constraints:

Constraint 1: pixels of any land use type except ‘open woodland’;
Constraint 2: pixels with actual erosion higher than 1 t ha^{-1} yr^{-1};
Constraint 3: pixels of roads;
Constraint 4: pixels of rivers, streams, lakes and wetlands.

The third objective, that is identification of areas for enclosures and terracing, was achieved by considering the pixels not suitable for cropping according to objective 1 and the pixels of noncropped areas with actual erosion above the risk threshold (1 t ha^{-1} yr^{-1}).

Since enclosure (C factor, 0.05) is a less expensive protection measure it is usually preferred over terracing. A simple conditional map algebra operation was performed to identify the pixels for enclosure or terracing in order to reduce the soil erosion below the risk threshold.

Table 1
Saaty matrix used in the MCE procedure

Factor maps	Proximity to roads	Proximity to water	Altitude	Potential erosion	Proximity to croplands	Proximity to the same crop type
Proximity to roads	1.0					
Proximity to water	3.0	1.0				
Altitude	7.0	3.0	1.0			
Potential erosion	9.0	5.0	3.0	1.0		
Proximity to croplands	2.0	0.5	0.3	0.5	1.0	
Proximity to the same crop type	3.0	1.0	0.3	1	2.0	1.0

$$\text{If } AE_{enc} < 1 \text{ t ha}^{-1}\text{y}^{-1} \text{ Then ENCLOSURE Else TERRACING} \quad (2)$$

Where AE_{enc} would be the actual erosion if the current land cover type is changed to enclosure.

AE_{enc} is calculated by $PE*C_{enc}$, where PE is the pixel's potential erosion and C_{enc} is the C factor for enclosure (0.05).

3. Results

Table 1 presents the Saaty matrix. Among the many possible matrices obtained by averaging the stakeholders' scores, the one with the best consistency ratio (0.08) was chosen. The eigenvector of the Saaty matrix, i.e. the relative weights, is given in Table 2.

The results of the application of the SDSS to achieve the three specified objectives in terms of area that should undergo land use change are presented in Fig. 3. The average actual erosion value of 4.5 t ha^{-1} yr^{-1} would be reduced to values below the risk threshold of 1 t ha^{-1} yr^{-1} achieving a reduction of about nine times without diminishing the area of crops. This was judged as a very remarkable result by the local stakeholders.

The map in Fig. 4 is the final result of the MCDM analysis. This map is the decision making support tool to spatially identify new areas suitable for crop reallocation and highly erodible areas that need long term protecting measures, such as enclosure or terracing.

Table 2
Eigenvector of the matrix in Table 1

Factor	Weight
Proximity to roads	0.0375
Proximity to water	0.1079
Altitude	0.2580
Proximity to the same crop type	0.1521
Proximity to croplands	0.0855
Potential erosion	0.3590

4. Discussion

In our case, the final goal of the application of the SDSS algorithms was to obtain a map suggesting the optimal reallocation of land use types so as to reduce the soil erosion without unduly sacrificing crop yield.

The model rationale is the trade-off of cropland for natural vegetation, especially at higher altitude, which would facilitate the environmental rehabilitation and might be compensated by long-term rewards. The crop deficit resulting from the trade-off could be balanced by external sources and the conversion of the 955.6 ha of open woodland must be considered as a last resort. Moreover, the conversion of woodland to cropland must be taken with great precaution since unaccounted factors such as soil fertility, soil depth and stoniness might affect the success of this measure.

The following issues from the standpoint of local stakeholders and decision makers should also be considered.

The replacement of an existing crop field with another land use type may entail a loss or reduction of the total cropland extent or a change of crop species which may not fit the farmer's needs. It may therefore be unwise supposing that a perfect choice of land use to reduce soil erosion agrees with the choice of the farmer for a particular crop or land use. This implies that agreements should be made between farmers and decision-makers so that those who may sacrifice their advantages for the common prosperity must be compensated either by the government or by those who may benefit from the reallocation. Furthermore, since decisions are made in consultation with end-users and other stakeholders, it is an absolute necessity to foster these interactions before embarking on the task of reallocation.

Dissatisfaction of end-users and loss of confidence in decision-makers and researchers must be avoided at any cost as it will hamper further efforts to rehabilitate degraded areas and will create misinterpretation and mistrust.

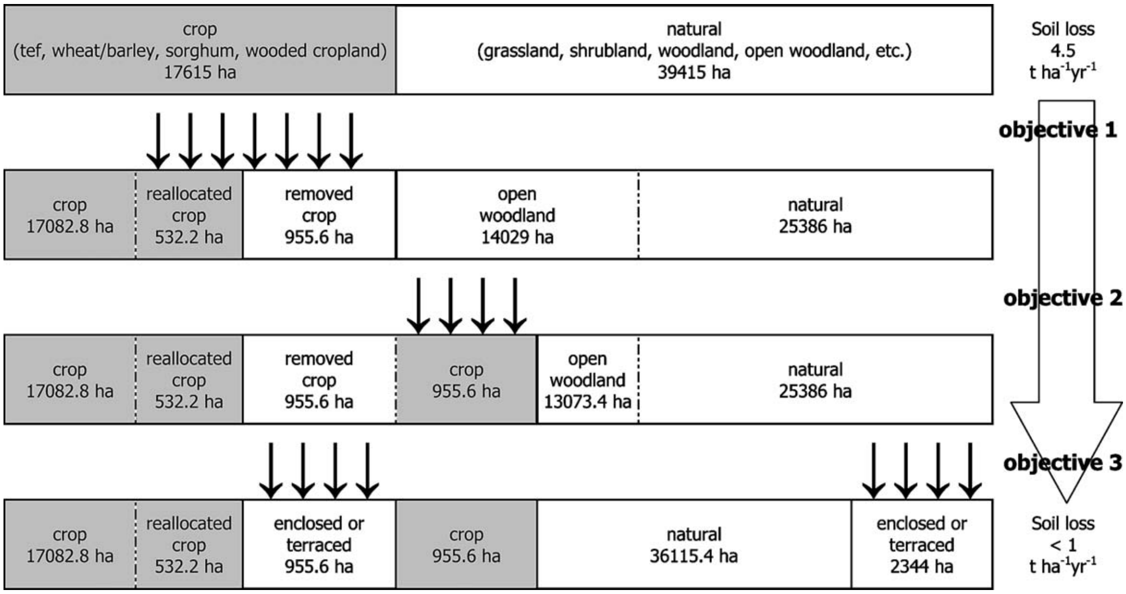

Fig. 3. Results of the application of the SDSS structured according to the objectives of the case study.

5. Conclusions

This paper presents the application of SDSS tools integrated in a GIS system to help decision makers in the development of strategies for reducing soil erosion in northern Ethiopia.

In this area, there is an urgent need to meet conservation objectives and account for the human dimension in addition to ecological considerations. The environmental degradation and the critical soil erosion rates leave no option other than finding policy tools and mechanisms for appropriate land use management, involving the stakeholders in the decision making process.

In this case study, it has been shown that the participation of local stakeholders is a critical component of the SDSS in two aspects: preparation of the decision matrix and acceptability of the results. Once the matrix is obtained, automatic procedures are applied and suitability maps are produced. Solutions are provided in the form of maps that can be easily available to stakeholders and decision-makers for evaluation and approval.

This approach is original for the geographic region and the area of application. GIS technology has been applied for the resolution of an extremely critical problem in developing countries, namely the reduction of soil erosion, using an approach which cautiously evaluates the socio-economic impact of the conventional recovery practices.

Moreover, the use of well-established models and methods allows the implementation of this prototype of SDSS to other geographic context, being aware that the necessary revisions, related to specific geographic situations, would be easily supported by the flexibility of the software tools used.

In this participatory GIS approach, broad access to information and the application of decision support tools facilitate the analysis and deliberation in a group setting (Jankowski and Nyerges, 2001). Participatory decision making also requires a thorough understanding of the underlying principles of the decision flow.

The involvement of different groups expressing different priorities and views of the problem can complicate the selection of criteria and their evaluation. Criteria evaluations are translated in sets of relative weights that allow the trade-off between factors and that might heavily influence the final outcome. A special care must be devoted to transferring a sufficient level of knowledge to the local groups involved in the process and the social aspects of this issue should be taken into consideration.

The benefit of working with the end-users has resulted in a positive sense of ownership of the results since decisions would be based on interaction and participation rather than top-down control, and this leads to introduction of novelty in management of rural areas in tropical and subtropical countries.

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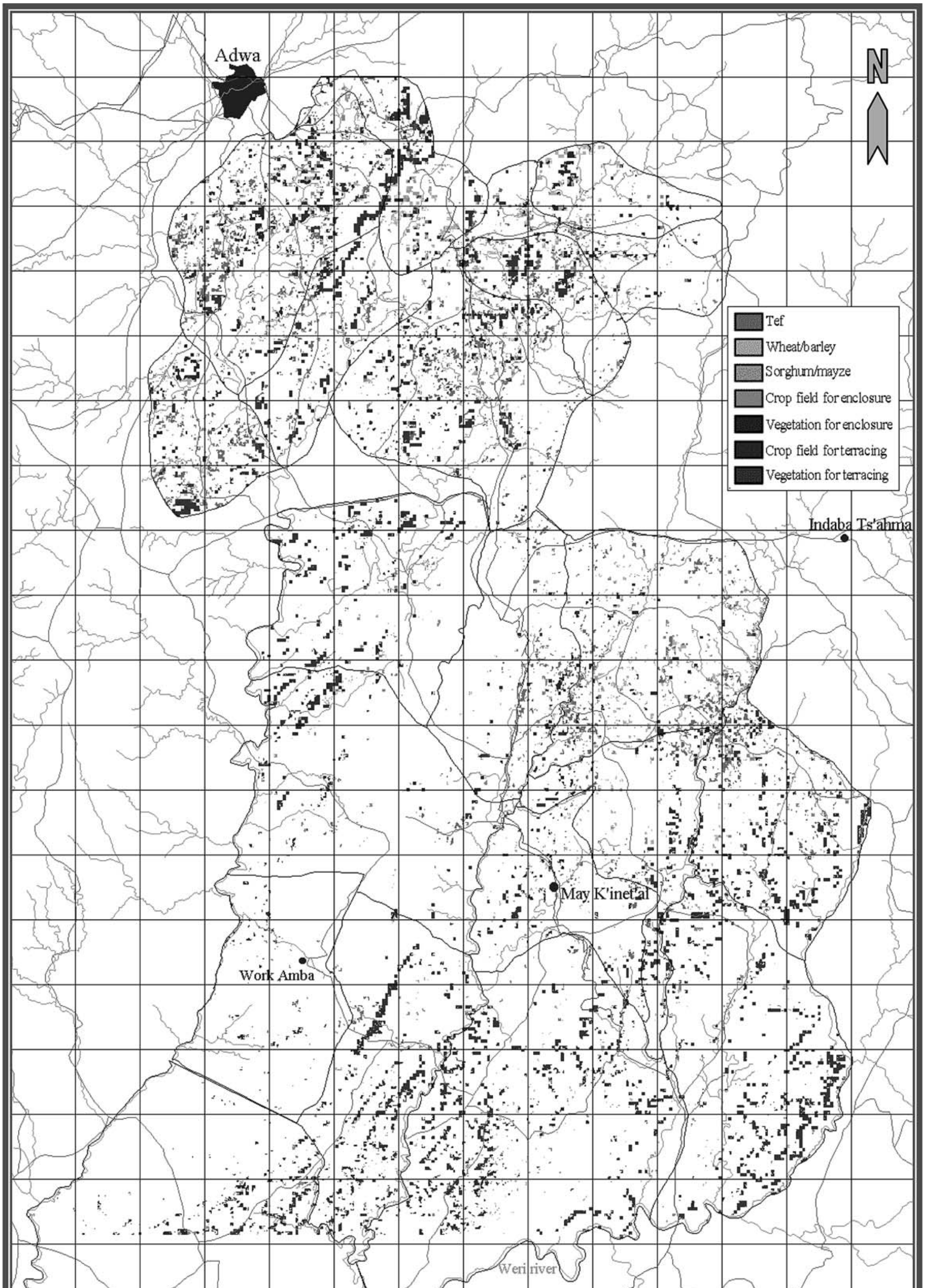

Fig. 4. Spatial distribution of the pixels subject to reallocation, enclosure or terracing according to the results obtained by SDSS application. Map scale 1:150 000.

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