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Sustainable allocation of agricultural lands and water resources using suitability analysis and mathematical multi-objective programming

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ABSTRACT

This study considers simultaneously the suitable cultivable lands and water resources to optimize the cropping pattern in the Shahrekord plain of Chaharmahal-Va-Bakhtiari province, Iran. According to a semi-detailed soil survey, 120 pedons with approximate distance of 750 m were excavated. Based on the pedons descriptions, 19 pedons were considered as representative. Soil samples were taken from different genetic horizons and their physicochemical properties were determined. Beside the soil map, the land suitability maps for wheat, alfalfa, potato and maize were also prepared. A goal programming model was developed to maximize the net return and cultivable area. Water and land availability, capital and non-negativity were considered as constraints (scenario 1). After preparing the land suitability maps, a constraint was defined. To do this, cultivable area for each crop greater than S1 (suitable class) and less than summation of S1, S1 + S2 and S2 (moderately suitable class) was determined (scenario 2). Results indicated that based on the scenario 1, the cultivable area should be allocated to potato and alfalfa. In the scenario 2 however, all the crops remain in the cropping pattern and the highest cultivable area should be allocated to potato. In the studied region, the main constraint is water shortage while the cultivable lands are surplus. It is necessary to contribute towards the efficient use of water resources to overcome the water crisis in the region. In spite of increasing the water consumption, cultivable lands increase when the suitable land and water availability are considered simultaneously. Therefore, it seems that land suitability assessment plays an important role for successful soil management.

1. Introduction

With a growing population there is a need for new agricultural patterns to meet increased food demand together with concerns for reducing environmental impact (Rotolo et al., 2015). Water crisis is a global problem, which is more severe in arid and semi-arid regions. Challenges of water and food security, climate change and population growth make it necessary to adopt any sustainable strategy. The irrigation water consumption accounts for 80% of the available water resources in the world, thus irrigation water allocation is more crucial (Ding et al., 2007) and cropping pattern plays a significant role in irrigation water use (Zeng et al., 2010).

Soil also plays a crucial role in ecosystem's functionality and mostly influenced by its use and management (Adhikari and Hartemink, 2016). Soil ecosystem services provide multiple benefits to humans but to date no consensus has been formed on a comprehensive framework for their classification and economic valuation, thus a systematic approach has not yet been developed to evaluate their importance (Jónsson and Davíðsdóttir, 2016). So a lack of suitability analysis has led to inappropriate cropping patterns leading to land degradation (FAO, 2007). There is a concern with the assessment of land performance when used for specific purposes (FAO, 1976). Land evaluation analysis is considered as an interface between land resources and land use planning and management (Davidson et al., 1994; De la Rosa et al., 2004). Land evaluation should answer to "how is the land currently managed and what will happen if present practices remain unchanged? (FAO, 1976). Therefore, proper land use planning based on the land evaluation is essential.

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Agricultural systems are complex as they depend on various interdependent aspects (environmental, economic and social) (Amini Fasakhodi et al., 2010). Since their aspects can have conflict with each other, an alternative approach is needed. Multi-criteria decision analysis (MCDA) is a popular and widely used technique to study decision problems in the face of multiple conflicting objectives function (e.g., maximizing net return versus reducing water consumption in agricultural systems) (Amini Fasakhodi et al., 2010; Jayaraman et al., 2015). Several types of MCDA approaches have been applied for cropping patterns, such as nonlinear programming model (Ghahraman and Sepaskhah, 2002), fractional programming model (Amini Fasakhodi et al., 2010) and goal programming model (GP) (Sarker and Guaddus, 2002; Xevi and Khan, 2005; Jayaraman et al., 2015). The GP model provides the ideal framework that a decision maker (DM) obtains an optimal solution for problems with multiple competing objectives function to optimize resources allocation (Jayaraman et al., 2015).

With respect to the climatic conditions of Iran, groundwater is the major source of crop irrigation (Daneshvar Kakhki et al., 2009). In recent years, drought has caused some wells, springs and qanats to be dried out in Shahrekord plain (Samadi Boroujeni, 2010). Thus, adopting a more compatible agricultural land and water management strategy is necessary to mitigate the serious problem of water scarcity in this region.

Qualitative approaches of land suitability evaluation consider information about climate, hydrology, topography, vegetation and soil properties. These approaches assume that water requirements are sufficient and optimally allocated (Sys et al., 1991, 1993; Jalalian et al., 2007; Ziadat, 2007; Safari et al., 2013; Bagherzadeh and Mansouri Daneshvar, 2014). Jalalian et al. (2007) studied the qualitative evaluation for wheat in Shahrekord plain. Results demonstrated that the study area is highly suitable for its production, as matched with the existing climatic conditions. In spite of soil importance, various mathematical programming approaches have contrarily been applied to optimize the cropping pattern without taking the soil properties and land suitability classification into account (Shangguan et al., 2002; Sarker and Guaddus, 2002; Tsakiris and Spiliotis, 2006; Sharma and Jana, 2009; Amini Fasakhodi et al., 2010). Amini Fasakhodi et al. (2010) considered the environmental, economic and social aspects of farming systems to determine an optimal cropping pattern in south Baraan (Isfahan, Iran).

A comprehensive approach is needed to simultaneously consider all the aspects of agricultural systems such as the availability of both land and water resources, economic and social. Therefore, the main objective of this study was to simultaneously consider the suitability of lands for main crops of the area as a system constraint as well as the availability of water resources to optimally determine the cropping pattern of the Shahrekord plain of Chaharmahal-Va-Bakhtiari province in central Iran using GP.

2. Materials and methods

2.1. Study area

The area under investigation has a size of approximately 10,495 ha. It is located between 32°13′ and 32°23′N and 50°47′ and 51°00′E in the Shahrekord region, Chaharmahal-Va-Bakhtiari province, Iran (Fig. 1). The mean annual precipitation and temperature in this region are 322 mm and 12.5 °C, respectively. Irrigated crops of wheat, alfalfa, potato and maize are the main land uses in this area.

2.2. Soil sampling and analyses and soil map preparation

120 pedons with approximate distance of 750 m were excavated (Soil Survey Division Staff, 1993) in different soil map units of an existing soil map (1:50,000 scale). Based on the pedon descriptions, 19 pedons were considered as representative pedons and soil samples were taken from different genetic horizons, air-dried, ground and passed through a 2 mm sieve. Percentage of coarse fragments by sieving, particle size distribution by hydrometer method (Gee and Bauder, 1986) and calcium carbonate equivalent by titration (Nelson, 1982) were determined. EC and pH were measured in 5:1 (water:soil) extract and saturated paste, respectively. A soil map (1:50,000 scale) was prepared according to the Soil Survey Manual (Soil Survey Division Staff, 1993).

2.3. Land suitability evaluation

Qualitative land suitability evaluation was performed for wheat, alfalfa, potato and maize. The average of the soil properties consisted of coarse fragment, EC, pH, $CaCO_3$ (%) and texture was determined by considering the depth-weighted coefficient up to 100 and 150 cm for annual (wheat, potato and maize) and perennial crops (alfalfa), respectively. Qualitative evaluation was determined by matching the site conditions (climate, hydrology, vegetation and soil properties) with studied crop requirement tables, presented by Sys et al. (1991, 1993). Finally, the suitability classes were defined according to the value of land index (Sys et al., 1991). In the framework suggested by Sys et al. (1991, 1993), the land suitability classification is presented in different categories: orders, classes and subclasses. The orders S and N reflect suitable and unsuitable land, respectively. The land suitability classes were indicated by an Arabic number in sequence of decreasing suitability within the S order and reflected degrees of suitability within the order as: S1 (suitable class), S2 (moderately suitable class), S3 (marginally suitable class). Then, based on the soil map, land suitability maps were prepared for different crops.

2.4. Suitable land allocation for optimization of cropping pattern

A multi-objective GP model has been developed to solve the study problem, considering two maximization objectives for the net return and total area of cultivation under two scenarios with and without considering the land suitability as a systemic constraint. To accomplish this, two lower and upper bound constraints were applied on the decision variables of the crops' area of cultivation, instead of the simple non negativity ones. The S1 class of suitability area and the summation areas of S1 (suitable), S1 + S2 and S2 (moderately suitable) classes were respectively considered as the lower and upper bounds. The rationale for applying these limitations are that the land resources are optimally allocated to crops with S1 and S2 classes and not to crops with S3 class. The framework is summarized in Fig. 2.

Detailed information about the existing pattern of cropping and technical coefficients (expenditure, yield, net return and irrigation water requirements (IWR)) for studied crops (wheat, alfalfa, potato and maize) are presented in Table 1.

2.5. The model formulation

2.5.1. Goal programming (GP) approach

Goal programming has been widely used to optimize resources allocation in the face of multiple conflicting objectives function (Jones and Tamiz, 2010). The basic components of a GP model are decision variable (a factor over which the decision maker has control), constraints and the objective function (maximizing or minimizing the goals). In order to understand a GP model, the different terms must be clear. Refer to Table 2 for definitions of the key terms.

First, the GP model was solved as a linear model for any of the objectives function (maximization of the cultivation area and net return) and for each of the objectives function a desired value was obtained. In a general form, the mathematical structure of a single objective linear program with n decision variables and m constraints can be written as (Jones and Tamiz, 2010):