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Comparison between land suitability and actual crop distribution in an irrigation district of the Ebro valley (Spain)

J. A. Martínez-Casasnovas[1]*, A. Klaasse[2], J. Nogués[3] and M. C. Ramos[1]

[1] *Departamento de Medio Ambiente y Ciencias del Suelo. Universidad de Lleida. Av. Rovira Roure 191. 25198 Lleida. Spain.*
[2] *WaterWatch. Generaal Foulkesweg 28A. 6703 BS Wageningen. The Netherlands.*
[3] *Departamento de Agricultura. Gobierno de Aragón. Ps María Agustín 36. 50004 Zaragoza. Spain.*

Abstract

The present research aims to obtain a better insight into the agreement between land evaluation results and actual crop spatial distribution by comparing biophysical land suitability with different crop frequency parameters and with crop rotations derived from multi-year crop maps. The research was carried out in the Flumen district (33,000 ha), which is located in the Ebro Valley (northeast Spain). Land evaluation was based on a 1:100,000 soil survey according to the FAO framework for the main crops in the study area (alfalfa, winter cereals, maize, rice and sunflower). Three crop frequency maps and a crop rotation map, derived from a time-series of Landsat TM and ETM+ images of the period 1993-2000 were used for comparison with land suitability maps. The relationships between the two types of variables were analyzed by means of statistical tests (Pearson chi-square (χ^2), Cramer´s V, Gamma and Somers´ D). The results show the existence of a significant (P=0.001) relationship between crops' location and land suitability, except for opportunist crops as sunflower, which is very much influenced by subsidies in the study period. The alfalfa-based rotations show the highest distribution percentages (52%) on the land most suitable for agriculture in the area. The present multitemporal analysis approach offers a more realistic insight than the comparison between a land evaluation map and static year crop map in assessing the degree of agreement of land evaluation recommendations with crops actually cultivated by farmers.

Additional key words: biophysical land suitability, crop rotation, land evaluation.

Resumen

Comparación entre la aptitud de las tierras y distribución real de los cultivos en un distrito de riego del valle del Ebro (España)

El objetivo de la presente investigación fue analizar la correspondencia entre los resultados de una evaluación de tierras con la distribución real de los cultivos. Para ello la aptitud biofísica de las tierras se comparó con diferentes tipologías de frecuencia de ocurrencia de los cultivos y rotaciones derivadas de mapas de cultivos multitemporales. La investigación fue llevada a cabo en el distrito de riego de Flumen (33.000 ha), localizado en el valle del Ebro (NE España). La evaluación de tierras se basó en una cartografía de suelos 1:100.000, según el esquema FAO, para los principales cultivos presentes en el área de estudio (alfalfa, cereales de invierno, maíz, arroz y girasol). Se utilizaron tres mapas de frecuencia de cultivos y un mapa de rotaciones, derivado de una serie temporal de imágenes Landsat TM y ETM+ del periodo 1993-2000, y se compararon con los mapas de aptitud de tierras para los diferentes cultivos. Se analizó estadísticamente (Pearson χ^2, Cramer V, Gamma y Somers D) la relación entre los dos tipos de variables. Los resultados muestran la existencia de una relación significativa (P=0,001) entre la localización de los cultivos y la idoneidad de las tierras, excepto de cultivos oportunistas como el girasol, muy influenciado por las subvenciones en el periodo estudiado. Las rotaciones basadas en la alfalfa muestran los mayores porcentajes (52%) de ocupación en las tierras más aptas para la agricultura en el área de estudio. El presente enfoque multitemporal de análisis de la información ofrece una visión más real que la comparación entre un mapa de evaluación de tierras y un mapa de cultivos de una fecha determinada, cuando se valora el grado de acuerdo entre las recomendaciones sobre la aptitud de las tierras y los cultivos realmente cultivados por los agricultores.

Palabras clave adicionales: aptitud biofísica de las tierras, evaluación de tierras, rotación de cultivos.

* Corresponding author: j.martinez@macs.udl.es
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Abbreviations used: CAP (common agricultural policy), EC (European Community), EU (evaluation unit), FAO (Food and Agriculture Organization), GIS (geographical information system), IPP (index of productive potential), LEU (land evaluation unit), NS (not significant), NVE (numerical value of evaluation), RSME (root square mean error).

Introduction

Existing land use systems and cropping patterns are the result of past and present decisions by farmers, which are usually well adapted to the potential and constraints of their land (Cools *et al.*, 2003). However, although it is widely accepted that farmers are the best experts at understanding local environments, their decisions are strongly influenced by a range of factors such as market demands, prices or subsidies in addition to the biophysical suitability of the land for specific uses (Veldkamp *et al.*, 2001; Bontkes and Keulen, 2003; Ambrosio Flores *et al.*, 2008). This means that land uses are often not in agreement with land suitability (fitness of a given type of land for a specified kind of crop or land use; FAO, 1976).

To try to redirect land uses in accordance with biophysical land suitability, resource professionals, scientists and land use planners have widely applied the principles of land evaluation. The main schema followed is the Framework for Land Evaluation (FAO, 1976), in which land evaluation is considered as a key tool for land use planning. There are many examples in the literature showing the use of this framework for land use planning to increase crop diversification and yield potential (Hennebert *et al.*, 1996; Boje *et al.*, 1998; Messing and Fagerstrom, 2001), and to ensure that lands are used according to their potential capacity to satisfy human needs in the present and future (Kilic *et al.*, 2005). However, it is often also used to achieve a more sustainable and environment-friendly agriculture through the identification of areas sensitive to land degradation, where land resource conservation programmes can be proposed (Igwe, 1999; d'Angelo *et al.*, 2000), or to refocus the application of agricultural policies (Nogués *et al.*, 2000). Other approaches (Ambrosio Flores *et al.*, 2008) make use of spatial models of the dynamics of agricultural uses to generate impact maps of policies on land use. Those, together with environmental indicators, allow the assessment of environmental impacts of agricultural policies and could help to the promotion of policies in more precise ways.

In spite of those research efforts, the degree of agreement between land evaluation results and actual spatial distribution of land uses and crops is usually unknown. In some cases land evaluation results are compared with the present crops planted by farmers (Hennebert *et al.*, 1996; d'Angelo *et al.*, 2000; Chen *et al.*, 2003), in order to measure the accuracy of the evaluation proposal. However, in most cases the results are limited to the recommendation of different crops or land uses according to the land qualities of a region (Boje *et al.*, 1998; Igwe, 1999; Martínez-Casasnovas *et al.*, 2000; Dogliotti *et al.*, 2004; Igue *et al.*, 2004; Kilic *et al.*, 2005), without any re-evaluation of the results.

Although the assessment of land evaluation results, especially in the medium or long term, should produce a better understanding of farmers´ decision-making in land use planning, it is not a common practice among evaluators. It would be particularly interesting in the case of land evaluation for land resource conservation or at refocusing the application of agricultural policies. The latest is mostly the case of agriculture in regions of Europe, where it is strongly dependent on the subsidies of the Common Agricultural Policy (CAP), and farmers are often more governed by subsidies and prices than by land capabilities (Ambrosio Flores *et al.*, 2008). In this respect, several cases have been documented, such as the sunflower and flax after the reform of the CAP in 1992 to promote industrial crops as an alternative to cereals even on unsuitable land (Herrero and Casterad, 1999; Winter, 2000; Martínez-Casasnovas *et al.*, 2005; San José Alonso *et al.*, 2005), or the more recent policy for vineyard restructuring and conversion (Cots-Folch *et al.*, 2006).

In this context, the present research aims to obtain a better insight into farmers´ choice of crops by analyzing whether crops are in agreement with biophysical land suitability. In contrast with previous research on land evaluation, which assesses results with present crops (a static land use map of a given year), the proposed approach considers the assessment by comparing land evaluation results with crop frequency and crop rotation maps in an agricultural region of interest. Differently from other approaches (e.g. Ambrosio Flores *et al.*, 2008), this research does not make use of spatial models to predict land uses on the basis of farmer's behaviour indicators (e.g. policies on land use, prices and/or environmental indicators, among others). The research is based on previous work which evaluated land for planning aimed at refocusing the application of agricultural policies (Nogués *et al.*, 2000), and maps of crop occurrence, frequency and crop rotations from time-series analysis of remote sensing data (Martínez-Casasnovas *et al.*, 2005). In the present paper the aim was to determine the degree of agreement between land evaluation results and actual crop spatial distribution.

Material and methods

Study area

The research was carried out in the Flumen district (33,000 ha), which is located in the Ebro Valley, northeast Spain (Figure 1). The climate is semi-arid, with a mean annual temperature of 14.5ºC, a mean annual precipitation of 423 mm and a mean annual evapotranspiration (ETo) of 1142 mm (Nogués *et al.*, 2000). The main geological materials are Miocene lutites and sandstones, often saline. Coarse deposits (gravel) are found on top of isolated platforms and on the river terraces. Most of the area has been irrigated since the construction of reservoirs in the pre-Pyrénées mountains about 60 years ago. The typical electrical conductivity of the irrigation water is 0.4 dS m^{-1}, indicating very low amount of salts in the water. However, due to the combination of parent materials (lutite alternating with sandstone), the relief and the evaporative deficit, soils in some areas are salt-affected (Herrero and Aragüés, 1988; Herrero and Pérez-Coveta, 2005).

The main crops are alfalfa (*Medicago sativa* L.), cereals [barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.)], maize (*Zea mays* L.), rice (*Oryza sativa* L.) and sunflower (*Helianthus annus* L.). Rice is usually associated with saline-sodic soils (Herrero and Snyder, 1997), although in some years, when the price of rice rises, the crop is extended to less saline soils. Other minority crops (about <10% surface) are flax (*Linum usitatissimum* L.), forage, vetch (*Vicia sativa* L.), almonds (*Prunus amygdalus* Batsch) and olives (*Olea europea* L.). The district also includes some small non-irrigated land as well as about 3,300 ha that have been irrigated for more than six centuries by taking water from the abutting rivers using small diversion dams (Nogués and Herrero, 2003). The main irrigation method is flooding, although some fields are watered by sprinklers.

Figure 1. Location of the study area.

Land evaluation

Land in the study area was evaluated according to the FAO (1976) framework for the above mentioned leading crops in the study area, which are also the most suitable for the region under the present climatic, technical and economic conditions (Nogués *et al.*, 2000). The evaluation was based on a 1:100,000 soil survey whose map units are associations[1] and consociations[2] of soils (Soil Survey Division Staff, 1993) named as phases of the subgroups established according to the keys to soil taxonomy (Soil Survey Staff, 1999). From these map units, land evaluation units (LEU) composed of evaluation units (EU) corresponding to all subgroup phases that are the dominant soils within the associations and consociations were characterized. For the evaluation process, nineteen land qualities were selected from a longer list proposed in FAO (1976) because they were judged relevant to the Flumen district on the basis of previous works in the study area (Herrero and Aragüés, 1988; Herrero and Snyder, 1997; Herrero and Casterad, 1999; Nogués *et al.*, 2000): suitability of the irrigation water delivery system, chemical fertility, ease of crop establishment, flood risk, growth period, hailstorms and winds, location, mechanization potential, oxygen availability, pests and diseases, pre- and post-harvest management,

[1] Complexes and associations of soils consist of two or more dissimilar components occurring in a regularly repeating pattern. Only the following arbitrary rule related to mapping scale determines whether the name complex or association should be used. The major components of a complex cannot be mapped separately at a scale of about 1:24,000. The major components of an association can be separated at a scale of about 1:24,000.

[2] Consociations: The soil map unit is dominated by a single soil taxon (or miscellaneous area) and similar soils. As a rule, at least one-half of the pedons in each delineation of a soil consociation are of the same soil components that provide the name for the map unit.

rooting depth, salinity, sodicity, salinization/sodication risk, soil suitability for trafficability and ploughing, solar radiation, temperature regime and water availability. Numerical values of evaluation (NVEs) were assigned to all combinations of LEUs and the above mentioned crops (Table 1). An index of productive potential (IPP) was computed as the average of the NVE ranges. The IPP quantifies the potential of each LEU in a scenario determined by the most widespread crops at present (Nogués *et al.*, 2000).

Using the IDRISI 32R2 GIS software (Clark Labs), the NVEs from Table 1 were combined with the LEU map, resulting in seven maps: five maps describing the crop-specific NVE for each of the five crop classes, one map describing the average NVE obtained considering all crops, and one map describing the average NVE obtained considering all crops except rice. The NVEs were converted into four land suitability categories: not suitable, marginally suitable, suitable, and very suitable. Some categories were merged to avoid empty categories (Table 2). More general categories can be derived from those land suitability classes (suitable or not suitable) according to the following criteria: $0 \leq NVE \leq 49$, not suitable; $50 \leq NVE \leq 100$, suitable.

Crop frequency and crop rotation maps

The occurrence, frequency and typical location of crops (crop frequency parameters) in 25 m resolution grid cells and the crop rotation in those spatial units were mapped using a time-series of Landsat TM and ETM+ images of the years 1993, 1994, 1996, 1997, 1998, 1999 and 2000. For each year, a land use map was produced by supervised classification of spring and summer scenes (2 or 3 scenes per year) in order to characterize the different crops and land uses. The dates of the images were: 1993 (06/03 and 12/07), 1994 (28/05 and 29/06), 1995 (15/04, 18/06 and 20/07), 1997 (02/04, 07/07 and 24/08), 1998 (07/05, 10/07 and 11/08), 1999 (23/03, 29/07 and 14/08), 2000 (17/03, 21/06 and 08/08). The images cover the stage of crops in spring and summer. Those periods are important to characterize crops such as winter cereals and alfalfa+forage (present in spring scenes), maize, sunflo-

Table 1. Index of productive potential (IPP) assigned to the land evaluation units (LEU) and numerical value of evaluation (NVE) for the combination of each LEU with main crops present in the Flumen district

LEUs	NVEs of each considered crop					IPP[a]	
	Cereals	Rice	Sunflower	Maize	Alfalfa	(1)	(2)
C.1: Soils of the Flumen and Alcanadre river terraces on fine detrital sediments. Association of Typic Xerofluvents and Typic Xerorthent	75	50	75	75	75	70.8	75.0
C.2: Soils of the Flumen terrace on fine detrital sediments. Association of Typic Xerofluvents and slightly saline Typic Xerorthents	75	75	75	62	62	70.8	69.8
A.2.1: Soils of the irrigated residual platforms with coarse detrital sediments. Consociation of Calcixerollic Xerochrepts with inclusions of Petrocalcic Xerochrepts, Xeric Haplocalcids, and Xeric Petrocalcids	75	25	75	75	75	66.7	75.0
A.1.1: Soils of the irrigated structural platforms of sandstone and lutite. Association of Typic Xerorthents and Xeric Torriorthents, with inclusions of Lithic Torriorthents	75	25	37	37	75	54.2	59.8
B.1: Soils of the glacis slopes on fine detrital sediments. Association of Typic Xerofluvents and slightly saline Typic Xerorthents, with inclusions of Typic Natrixeralfs and Fluventic Xerochrepts	50	62	50	44	50	51.0	48.8
B.2.1: Soils of the other irrigated slopes on fine detrital sediments. Association of moderately saline Typic Xerofluvent, and slightly saline Typic Xerorthent, with inclusions of Typic Natrixeralfs; Calcixerollic Xerochrepts and slightly saline Xeric Torriorthents	56	69	37	37	37	49.0	44.6
D.1: Soils of the irrigated bottoms on fine detrital sediments. Association of strongly saline, sodic Typic Xerofluvents; strongly saline, sodic Oxyaquic Xerofluvents and strongly saline, sodic Typic Xerorthents; with inclusions of strongly saline, sodic Typic Natrixeralfs; slightly saline, sodic Xeric Torriorthents and moderately saline, sodic Aquic Xerochrepts	50	81	31	25	44	46.9	40.0
C.4: Soils of the Flumen terrace. Moderately saline, sodic Typic Xerofluvents	50	75	25	25	25	41.7	35.0
C.3: Soils of the Flumen terrace on fine detrital sediments. Strongly saline, sodic Xeric Torriorthents	37.5	25	25	25	25	29.2	30.0
A.2.2: Soils of the nonirrigated residual platforms with coarse detrital sediments. Consociation of Calcixerollic Xerochrepts with inclusions of Petrocalcic Xerochrepts, Xeric Haplocalcids, Xeric Petrocalcids, and Calcic Haploxeralfs	37.5	0	50	0	0	20.8	25.0
A.1.2: Same that A.1.1, but nonirrigated	37.5	0	37	0	0	18.7	22.4

[a] (1): IPP obtained considering all crops; (2): IPP obtained considering all crops except rice. Source: Nogués *et al.* (2000) (slightly modified)

Table 2. Conversion of numerical evaluation values (NVEs) to specific land suitability categories

Land suitability class	NVE	Description
Crop-specific	0 - 49	(N) Not suitable / (S3) marginally suitable
	50 - 74	(S2) Suitable
	75 - 100	(S1) Very suitable
Average, obtained by considering all crops	0 - 24	(N) Not suitable
	25 - 49	(S3) Marginally suitable
	50 - 100	(S2) Suitable/ (S3) very suitable
Average, obtained by excluding rice	0 - 24	(N) Not suitable
	25 - 49	(S3) Marginally suitable
	50 - 74	(S2) Suitable
	75 - 100	(S1) Very suitable

wer (only present in summer scenes) and rice, which is best characterized in late spring scenes (flooded fields). The images were processed and classified at the Centre for Research and Agro-Food Technology (Aragón Government, Spain). For that, ground training data were surveyed each year by a systematic random sampling with three replicates in blocks of 5 x 5 km (Herrero and Casterad, 1999). Forty four sampling units ('segments') of 500 x 500 m were used, resulting in a 3.4% sampling of the 33,000 ha studied. The ground survey was conducted in two steps. Winter crops, permanent crops, and fields ploughed for rice were inventoried at the end of spring. The summer inventory was carried out for summer crops (sunflower and maize), for detection of changes in permanent crops, and for confirmation of the existence of rice fields. Aerial photographs aided the identification and location of segments on 1:5,000 maps. Radiometric correction of the atmospheric effects, using the minimum histogram values, and geometric correction of the images based on ground control points and nearest neighbor resampling were performed before supervised classification. The root square mean error (RSME) of the geometric corrections was always less than 1 pixel, varying between 14.5 and 20 m (0.48–0.67 pixels). Supervised classifications were applied by taking training areas from the field inventory and using a maximum likelihood classifier (Lillesand and Kiefer, 1994). Among the parallelepiped and minimum distance classifiers, the maximum likelihood classifier was the one that achieved the best results.

The resulting land use maps, that are used as input material in the present research, have the following classes: alfalfa (mainly fields of alfalfa and some fields of other forage species), cereals (barley and wheat), maize, rice and sunflower (Barbosa *et al.*, 1996; Herrero and Casterad, 1999), uncultivated land (fallow and other uncultivated enclaves), pines and other classes (pixels that were not classified in any other of the established classes because of their low probability of belonging to any of them). Water and urban areas are digitized from existing maps and superposed on the final land use maps. The classification accuracy of the seven land use maps (pixels correctly classified in relation to total pixels of the images) range from 72 to 80% (average 76.2±2.5%). Those accuracies are the best achieved having into account the characteristics of the study area, with abundance of small fields (< 2 ha). Rice, winter cereals, uncultivated land, alfalfa+forage and maize are the classes with the most satisfactory results (Barbosa *et al.*, 1996). Rice is the class with the highest classification accuracy (73.3% and 96.4% producer's and user's accuracy respectively). Winter cereals present producer's and user's accuracy of 70.7% and 84.5% respectively, being alfalfa+forage and maize between 52.9% and 70.8%. Sunflower present lower values (47.5% and 31.3% respectively). The maps were in raster format, with a spatial resolution of 25 m.

From the resulting land use maps, crop occurrence, frequency and typical crop location maps were derived by means of GIS raster analysis. Table 3 provides an overview of the description of the maps and class values that were considered in the present study: a) crop frequency map indicates the number of years that a given crop is present in each grid cell of the map, b) crop occurrence map shows the occurrence or non-occurrence of a given crop in each grid cell along the analyzed time-series; and c) typical crop location map shows either if a given crop is present in a grid cell in more than 50% of the analyzed years (typical location), or in less that 50% of the analyzed years (fluctuate location) or is not present at all. In the present case study, a grid cell is a typical location of a crop if the crop is present in at least 4 years out of 7. Once obtained, those maps were compared with the land evaluation map in order to establish the relationships between planted crops and land suitability.

In addition, a crop rotation map was obtained according to the method proposed by Martínez-Casasnovas *et al.* (2005). This method looks for the spatial and temporal relationships between the main crops present in the study area, in their typical locations (25 m resolution grid cells in the present case study) and the alternate crops that have been in those locations in other years of the analyzed time-series. This mapping process resulted

Table 3. Description of the different crop frequency maps considered in the present research for comparison with land suitability categories

Map class or grid cell value	Crop frequency	Crop ocurrence	Typical crop location
0	Crop X not present in the grid cell		Crop X not present in the grid cell
1	Crop X present 1 year	No occurrence of crop X in the grid cell (freq. = 0)	Fluctuation area: crop X is present in the grid cell 1-3 years out of 7
2	Crop X present 2 years	Occurrence of crop X in the grid cell (freq. > 0)	Typical location: Crop X is present in the grid cell ≥4 years out of 7
≥3	Crop X present ≥ 3 years		

Description: Crop frequency map indicates the number of years that a given crop is present in each grid cell of the map. Crop occurrence map shows the occurrence or non-occurrence of a given crop in each grid cell along the analyzed time-series. Typical crop location map shows either if a given crop is present in a grid cell in more than 50% of the analyzed years (typical location), or in less that 50% of the analyzed years (fluctuate location) or is not present at all. In the present case study, a grid cell is a typical location of a crop if this is present in at least 4 years out of 7.

in a crop rotation map with 22 categories (Table 4), of which categories 17 (water) and 18 (villages) were excluded from further analysis. The details of the process are explained in Martínez-Casasnovas *et al.* (2005). If we consider an average global accuracy of 76.2% in each of the seven crop maps used along the study period, the global accuracy of the resulting crop rotation map is 15%. This poor performance is influenced by the small fields present in the study area and the different phenology of summer crops (mainly sunflower) at the moment of the acquisition of the satellite images.

Analysis of the relationship between land suitability and crop distribution (crop frequency and crop rotation maps)

The relationships between land suitability and crop occurrence, frequency and typical crop location, and between land suitability and crop rotations were analyzed by means of cross-tabulations and GIS overlaying. The resulting contingence tables contain the frequency of occurrence of particular combinations of the analyzed variables and can be used to determine whether there is any association (in terms of statistical dependence) between them. In the present research, suitability (crop-specific, average for all crops, and average for all crops except rice) was considered as the depen-

Table 4. Description of the classes of the crop rotation map

Map class	Crop rotation
0	No rotation class
R1	Alfalfa - fallow
R2	Alfalfa - cereal
R3	Rice - fallow
R4	Fallow - cereal
R5	Alfalfa - maize
R6	Fallow - other classes
R7	Rice - fallow - other classes
R8	Alfalfa - fallow - other classes
R9	Fallow - cereal - other classes
R10	Alfalfa - fallow - cereal
R11	Alfalfa - cereal - maize
R12	Alfalfa - fallow - cereal - other classes
R13	Alfalfa - cereal - sunflower - maize
R14	Uncultivated
R15	Conifers
R16	No main crop (variety of crops)
R17	Water
R18	Villages
R19	Alfalfa - rice - fallow - cereal - sunflower - maize
R20	Alfalfa - rice - fallow - cereal – sunflower - other classes
R21	Rice - fallow - cereal - sunflower - maize - other classes
R22	Alfalfa - rice - fallow - cereal - sunflower - maize - other classes

dent variable, being measured on an ordinal scale. Crop occurrence and frequency (according to the description given in Table 3) and crop rotations were considered as independent variables, being measured in nominal scales.

Since the dependent variable is ordinal, non-parametric statistical tests were applied to determine the association between the variables. The applied test was the Pearson chi-square (χ^2) test (Clark and Hosking, 1986) to determine the significance of the relationship. The research objectives were to determine the association between the suitability of a specific location (grid cell) with either the occurrence of a crop in that location, the typical crop in that location, the frequency of a crop in that location or the crop rotation in that location. The hypothesis of statistical independence is rejected when the χ^2-test exceeds or equals the critical value at α level of significance for certain degrees of freedom. A chi-square probability ≤ 0.05 was used as a criterion for rejecting the null hypothesis.

Other measures to determine the strength and the direction of the association were applied. One of the tests used in the present research was Cramer´s V (Ott *et al.*, 1983), which is useful for comparing multiple χ^2-test statistics across contingency tables of varying sizes. It is interpreted as a measure of the relative strength of an association between two variables. It is also considered as the best choice for nominal by ordinal tables. In practice, Cramer's V of 0.10 provides a good minimum threshold for suggesting that there is a substantive relationship between two variables. Over 0.30 the association is considered as strong.

For ordinal data ordinal measures are preferred because they also indicate direction, lying between –1 (perfect negative relationship) and 1 (perfect positive relationship), with 0 indicating no relationship. Examples of ordinal measures are Gamma and Somers´ D (Norusis, 2005). These measures were considered in the present research to analyze the strength and relationships between the crops and land suitability classes.

In addition to nominal and ordinal measures of association, and in the case of crop rotation analysis, percentage distribution was also analyzed to determine patterns in association. Percentage distribution tables were created by calculating each cell as a percentage of the column total.

Results and discussion

Relationships between land suitability and crop frequency maps

Table 5 shows the results of the analysis of significance between the different types of land suitability and

Table 5. Analysis of significance between land suitability and crop frequency maps in the Flumen district

Crop and crop frequency map considered in the analysis[a]		Crop-specific suitability for the crop			Average suitability by considering all crops			Average suitability by considering all crops except rice		
		Chi-square test		Cramer's V[c]	Chi-square test		Cramer's V[c]	Chi-square test		Cramer's V[c]
		χ^2	***P*** [b]		χ^2	***P*** [b]		χ^2	***P*** [b]	
Cereals	(1)	87	0.000 *	0.015	2611	0.000 *	0.080	1278	0.000 *	0.056
	(2)	3357	0.000 *	0.064	5811	0.000 *	0.084	5931	0.000 *	0.085
	(3)	4839	0.000 *	0.077	7221	0.000 *	0.093	6975	0.000 *	0.075
Rice	(1)	20154	0.000 *	0.221 *	7514	0.000 *	0.135 *	20116	0.000 *	0.221 *
	(2)	37540	0.000 *	0.213 *	10550	0.000 *	0.113 *	22946	0.000 *	0.167 *
	(3)	39857	0.000 *	0.220 *	11403	0.000 *	0.117 *	24600	0.000 *	0.141 *
Sunflower	(1)	551	0.000 *	0.037	436	0.000 *	0.033	0	0.623	NS [d]
	(2)	816	0.000 *	0.031	861	0.000 *	0.032	198	0.000 *	0.015
	(3)	1014	0.000 *	0.035	978	0.000 *	0.034	396	0.000 *	0.018
Maize	(1)	9915	0.000 *	0.155 *	8970	0.000 *	0.147 *	4658	0.000 *	0.106 *
	(2)	11066	0.000 *	0.116 *	11201	0.000 *	0.116 *	12734	0.000 *	0.124 *
	(3)	12295	0.000 *	0.122 *	11934	0.000 *	0.120 *	13965	0.000 *	0.106 *
Alfalfa	(1)	12032	0.000 *	0.171 *	12032	0.000 *	0.171 *	7853	0.000 *	0.138 *
	(2)	12601	0.000 *	0.124 *	14076	0.000 *	0.131 *	13003	0.000 *	0.125 *
	(3)	13594	0.000 *	0.128 *	15155	0.000 *	0.135 *	13957	0.000 *	0.106 *

[a](1) Crop occurrence, (2) Typical crop location, (3) Crop frequency. [b*] P<0.001. [c*] Cramer´s V > 0.1 (minimum threshold for suggesting that there is a substantive relationship between the two variables). [d*] NS: not significant according to the chi-square test

crop maps (see description of maps and map classes in Table 3). Except for the relationship between the occurrence of sunflower and the average land suitability (all crops except rice), the Pearson χ^2-test is significant at the 0.001 level, indicating a relationship between crop distribution and land suitability.

The analysis for determining the strength of the association, by Cramer's V test, shows that sunflower distribution is not related either to the specific suitability for this crop or to the average suitability for all crops (Table 5). Cereals, although related to land suitability, show a weak association, with Cramer's V values less than 0.100. This indicates that sunflower and cereals seem to be sown in any place, regardless of the suitability. Among the rest of the crops, maize and alfalfa show a moderate association with land suitability classes, whereas rice is most strongly associated with LEUs that are more suitable for rice (Cramer's V values of 0.141–0.221).

Several could be the reasons for the weakness of the associations of crops with land suitability. One is related to the process through which farmers decide to sow one crop or another in a specific location. This is a complex process that is not only governed by the factors determining the biophysical land suitability, but it could depend on multiple drivers that should be considered under a spatial multi-scale analysis approach (Veldkamp *et al.*, 2001; Verdoodt and van Ranst, 2006). In addition to biophysical constrains (soil salinity and sodicity, limitations of irrigation water in some years or rotational requirements in particular), farmers' decisions in the study area are influenced by CAP subsidies. A clear example is the sunflower, which is an irregular crop. During the 1990s it was greatly influenced by subsidies, and the area cultivated ranged from 354 to 3698 ha in the study period. The second figure was attained in 1993 when the European Community (EC) decided to reduce cereal excess and to subsidize industrial crops such as sunflower (Martínez-Casasnovas *et al.*, 2005). However, it decreased sharply in 1994 due to EC restrictions obliged farmers not only to sow the fields but also to harvest the crop in order to receive the subsidies. As alfalfa, maize and rice are highly sensitive to fluctuations in water availability, they have a moderate association with the crop-specific or average suitable areas (Feijóo *et al.*, 2000; Nogués and Herrero, 2003). This means that in years in which water shortages are expected, because of dry winters and low water storage in dams, those crops are not sown in lands that are suitable for them, thus reducing the degree of association between crops and land suitability. In those cases, less water-demanding crops, such as cereals (spring-sown) or short-season sunflower, are the alternative to maize or rice in particular (since they are annual crops) and less to alfalfa (multi-year crop), which is usually sown in the most suitable lands. Rice shows a high degree of association with crop-specific land suitability because of the presence of saline-sodic soils among the LEUs. No other crops except rice are suitable for this type of soil (Herrero and Aragüés, 1988; Herrero and Snyder, 1997). This makes rice one of the typical crops in the pattern: the area cultivated with rice ranged from 3,000 to 4,500 ha in the study period (in typical years without major irrigation water constraints) (Martínez-Casasnovas *et al.*, 2005).

Regarding the analysis of the ordinal measures of association (gamma and Somers' D tests), Table 6 shows the results of the cross-tabulations of suitability classes with crop occurrence, typical crop location and crop frequency. Gamma and Somers' D values above 0.3 are considered to indicate a moderate positive association while those above 0.6 indicate a strong positive association (Norusis, 2005).

Except for cereals and sunflower, the rest of the crops show a positive association with their crop-specific suitability areas. The results for cereals and sunflower are in accordance with the interpretation given above: sunflower is an opportunity crop and cereals are spread out over the irrigation district because of rotational requirements and water shortages in some years. In addition, these crops are also typically located in lands with lower suitability for agriculture.

In the case of rice, the association between the occurrence of the crop and its crop-specific suitable areas (with saline-sodic soils) is strong and positive, with gamma values of 0.636. However, it is strongly negatively associated with the land suitable for all crops (on average) and with the land suitable for all crops except rice, with gamma values of -0.319 and -0.595, respectively. This indicates that rice is not typically located in other land units out of its suitable areas. Nevertheless, according to observations of Martínez-Casasnovas and Martín-Montero (2004), there are rice fluctuation areas (low-frequency occurrence) outside its suitable areas. This occurs after campaigns with higher prices. Then, if water shortages are not expected, the crop is extended to less saline soils than those in which is usually sown. This is a frequent practice in the study area, in which rice is an alternative to high-income crops. The association between the most frequent location of rice, or the

Table 6. Analysis of association between land suitability and crop frequency maps in the Flumen district

Crop and crop frequency map considered in the analysis [a]		Crop-specific suitability for the crop		Average suitability by considering all crops		Average suitability by considering all crops except rice	
		Gamma[b]	Somers´ D	Gamma	Somers´ D	Gamma	Somers´ D
Cereals	(1)	-0.107	-0.053	0.161	0.081	0.122	0.061
	(2)	0.092	0.051	0.117	0.065	0.090	0.050
	(3)	0.094	0.094	0.111	0.111	0.078	0.078
Rice	(1)	0.636 *	0.219	-0.319 *	-0.119	-0.595 *	-0.211
	(2)	0.540 *	0.227	-0.276	-0.109	-0.554 *	-0.197
	(3)	0.528 *	0.528 *	-0.272	-0.272	-0.551 *	-0.551 *
Sunflower	(1)	0.084	0.033	0.074	0.029	NS [c]	NS [c]
	(2)	0.063	0.025	0.082	0.032	0.010	0.004
	(3)	0.056	0.056	0.075	0.075	-0.002	-0.002
Maize	(1)	0.344 *	0.176	0.296	0.147	0.230	0.114
	(2)	0.336 *	0.179	0.303 *	0.155	0.257	0.132
	(3)	0.305 *	0.305 *	0.276	0.276	0.236	0.236
Alfalfa	(1)	0.339 *	0.173	0.339 *	0.173	0.300 *	0.151
	(2)	0.251	0.158	0.301 *	0.188	0.269	0.170
	(3)	0.230	0.230	0.278	0.278	0.242	0.242

[a] (1) Crop occurrence, (2) Typical crop location, (3) Crop frequency. [b] * Gamma > 0.3 (significant); [c] NS not significant according to the chi-square test

frequency of occurrence, and the different land suitability types shows the same tendency as the crop-specific evaluation, although with slightly lower values for gamma and Somers' D tests.

Alfalfa and maize show similar distribution characteristics, with moderate positive association with their crop-specific suitable areas (gamma values of 0.305–0.344). The association between the occurrence of these crops and the land suitable for all considered crops (on average) and with the land suitable for all crops except rice is in this case positive (gamma values of 0.236–0.303), being weaker for maize than for alfalfa. Gamma and Somers' D values are always lower for the relationship with land suitability for all crops (as average), since the consideration of the numerical evaluation values for rice reduces the average suitability of the rest of the crops. These results indicate that these crops are usually located on the most suitable land for agriculture. However, frequent irrigation water shortages, due to limitations of either the reservoir's capacity or the delivery network during the peak season (Nogués and Herrero, 2003), explain the lack of a stronger association either with their crop suitable areas or the average suitable areas for the considered crops, since other crops (e.g. cereals and sunflower) are in fact sown in these areas. Since alfalfa is a multi-year crop, it shows a stronger association than maize, for which the decision to sow has to be taken yearly. This is because the decision to sow alfalfa has to be taken having into account that in some of the following four or five years that the crop is at the field water shortages may happen. Then, alfalfa tends to be sown in the most suitable land for the crop instead to occupy soils with lower water retention capacity.

Analysis of the relationships between land suitability and crop rotations

The rotations identified from the multitemporal analysis of remote sensing images (Table 4) were compared with the land suitability classes for each of the considered crops plus the average suitability for all crops and the average suitability for all crops except rice. Table 7 shows the chi-square test results of the relationship between rotation type and suitability. They are all significant, indicating the existence of an association between land suitability and crop rotation. This association is moderate with all the considered land suitability types.

Further details of this association are shown in Table 8, which presents the distribution of the frequency percentages between crop rotations and suitability classes for all considered crops. Crop rotation categories R14 to R18 (Table 4) were not considered because they do not include any of the evaluated crops. The results indicate that, in general, all crop rotations identified from the 7-year crop maps are located on land with low or moderate suitability for the considered crops' requirements. This can be observed in the row corresponding to average crops (Table 8) by adding suitability classes S2 and S3, which account for more than 92% of the grid cells of each crop rotation distribution in the study area. This fact is in agreement with the findings of Nogués *et al.* (2000), who estimated that 59% of the Flumen district presents productive potential index under 50% mainly because of the abundance of salt-affected soils.

All crop rotations also show moderate or high suitability (S1+S2 classes) for the requirements of cereals. This is because cereals were assigned higher NVEs for all the LEUs than other crops (Nogués *et al.*, 2000) and most of the rotations incorporate cereals as an alternative crop, due to the marginal to moderate suitability of the area for high-income crops because of salinity-sodicity problems and/or irrigation water shortages.

Rotations R11 (alfalfa - cereals - maize) and R13 (alfalfa - cereals - sunflower - maize), together with rotations R5 (alfalfa – maize), R22 (alfalfa – rice – fallow – cereals – sunflower – maize – other classes) and R2 (alfalfa – cereals) show the highest distribution percentages in the S2 average crops class, with more than 52% of these crop rotation locations lying in this suitability class. They also occur very often in areas with a high average suitability for all crops except rice (39 to 43% of the grid cells lying in S1+S2 land suitability classes). All of them are alfalfa-based rotations, which indicate that this crop is used as the main crop on most suitable land for agriculture in the Flumen district, giving the alternate crops the advantage of nitrogen fixation.

Crop rotation categories having rice as a main crop or second crop, except rotation R19 (alfalfa – rice – fallow - cereals – sunflower - maize), show an association with land suitable for rice. Specifically, rotations R3 (rice - fallow) and R7 (rice – fallow - other classes) in particular, and also rotation R6 (fallow - other classes), are clearly associated with areas with moderate to high suitability for rice, 80 to 94% of their grid cells being included in these classes of suitability (S1+S2). Rotation categories R3 and R7 also appear with low frequencies in areas highly suitable for cereals, sunflower, maize and alfalfa, and in areas where the average suita-

Table 7. Summary of the analysis of the relationship between crop rotations and land suitability

Crop rotation	Suitability categories: Chi-square test χ^2	Suitability categories: Chi-square test P [a]	Suitability categories: Cramer's V [b]
Specific suitability for cereals	19922	0.000 *	0.157 *
Specific suitability for rice	19760	0.000 *	0.157 *
Specific suitability for sunflower	20183	0.000 *	0.158 *
Specific suitability for maize	18084	0.000 *	0.150 *
Specific suitability for alfalfa	21127	0.000 *	0.162 *
Average suitability obtained by considering all crops	**	**	**
Average suitability obtained excluding rice	17613	0.000 *	0.148 *

[a] *P<0.001; [b] *Cramer´s V > 0.1 (minimum threshold for suggesting that there is a substantive relationship between the two variables); ** zero values for the very suitable class (S1), calculation not permitted

Table 8. Percentages of each rotation class over the four suitability categories: not suitable (N: 0-24), marginally suitability (S3: 25-49), moderately suitable (S2: 50-74) and highly suitable (S1: 75-100) for each considered crop

	Suitability class	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**	**R19**	**R20**	**R21**	**R22**
Cereals	N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	S3	1	0	0	8	0	3	1	2	6	2	0	3	0	1	2	1	0
	S2	60	61	94	61	61	76	92	66	68	57	57	64	59	69	76	75	62
	S1	39	39	6	31	39	22	7	32	25	41	43	33	41	30	23	24	38
Rice	N	1	0	0	8	0	2	0	1	6	2	0	3	0	1	1	0	0
	S3	34	27	6	29	32	19	7	25	21	36	37	26	34	24	18	17	29
	S2	53	55	52	56	56	62	51	58	61	51	51	56	53	55	55	63	55
	S1	13	18	42	7	12	18	42	16	12	11	12	16	12	20	26	19	16
Sunflower	N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	S3	59	52	85	71	49	79	83	64	72	58	44	58	48	60	65	62	49
	S2	6	13	11	8	15	6	12	9	11	8	14	14	14	14	16	18	15
	S1	35	35	4	21	36	15	5	28	17	34	42	28	38	26	19	21	36
Maize	N	1	0	0	8	0	2	0	1	6	2	0	3	0	1	1	0	0
	S3	64	65	96	72	64	83	95	71	77	64	58	69	62	73	81	79	64
	S2	1	11	0	1	3	1	0	2	3	2	1	4	3	2	4	2	2
	S1	34	24	4	20	33	14	4	26	14	32	40	24	35	24	15	19	33
Alfalfa	N	1	0	0	8	0	2	0	1	6	2	0	3	0	1	1	0	0
	S3	54	48	83	58	46	72	81	59	62	50	43	53	45	56	61	58	47
	S2	7	23	11	4	18	7	12	10	9	9	15	16	17	16	19	19	18
	S1	38	29	6	30	36	20	6	30	23	39	42	29	37	27	19	22	35
Average crops	N	1	0	0	8	0	2	0	1	6	2	0	3	0	1	1	0	0
	S3	54	48	83	58	46	72	81	59	62	50	43	53	45	56	61	58	47
	S2	45	52	17	34	54	27	18	40	32	48	57	44	55	43	38	41	53
	S1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average crops except rice	N	0	0	0	3	0	1	0	0	2	1	0	0	0	0	0	0	0
	S3	61	61	94	66	61	77	93	68	73	58	57	67	59	70	77	76	62
	S2	5	15	2	11	6	8	2	6	11	10	3	9	6	6	8	5	4
	S1	34	24	4	20	33	14	4	26	14	32	40	24	35	24	15	19	33

bility excluding rice is high. Other rotations of six crops in which rice is present (rotations R20 and R21, Table 4) also have a preferential location in moderate to high suitable areas for rice. These are usually lands with low to moderate saline-sodic content where other crops are seeded after salts are leached by the water floods required by rice. Then, after a few years of cultivation with other crops, the salt content rises to the top soil horizons and rice again becomes the most suitable and necessary crop to leach the salts.

Limitations of the research

In addition to the above mentioned reasons for weak associations between land suitability categories and crop frequency and crop rotations, other factors related to the methodology to determine the spatial information used in the research and the working scale could be influencing the results. As stated in section "Land evaluation" (M&M), land was evaluated on the basis of LEUs derived from a 1:100,000 soil survey (Nogués *et al.*, 2000). The requirements for the leading crops in the area were compared with nineteen land qualities and were rated, according to a survey of farmers and local agricultural experts, for the productive potential of each crop in the different LEUs. In contrast to other methodologies (e.g. Ambrosio Flores *et al.*, 2008), land suitability was not based on agrometeorological and/or crop development models, in addition to soil information. This could have given more possibilities to quantify the effect of different variables influencing the spatial location of crops in different years and to enable the generation of impact maps of policies on land use and contribute to the promotion of agricultural policy in a more precise way.

On the other hand, and with respect the crop maps derived from remote sensing analysis, the relative low global classification accuracy of the crop frequency maps was 76.2% as average in each year. Those accuracies, however, were the best achieved having into account the characteristics of the study area, with abundance of small fields (< 2 ha) (Barbosa *et al.*, 1996). Higher resolution images could have produced better classification results to produce the crop maps. However, this was not possible since the only available images for the analysed period were the 30 m resolution Landsat images.

Conclusions

In front of land evaluation assessments in which results are compared with the present land uses or crops, this research addresses the analysis of the degree of accordance between the biophysical land suitability land results with different crop frequency parameters (occurrence, frequency and typical crop location) and with crop rotations derived from multi-year crop maps by means of remote sensing techniques. This offers a wider and dynamic perspective, giving more information than a static year crop map in assessing the degree of agreement of land evaluation with the crops actually cultivated. In addition, this method has the advantage that overcomes possible masking problems in land evaluation assessments due to opportunist crops in regions where agriculture is highly influenced by subsidies, and political decisions can lead to rapid changes in the crop pattern. However, poor global image classification accuracies can influence the strength of the association between crop frequency and/or crop rotation maps with land suitability maps, particularly in areas with small agricultural fields.

The multitemporal land evaluation assessment of the Flumen district (Ebro valley, Spain), as a case study, has revealed that there are opportunists crops, such as sunflower, whose distribution is not related either to the specific suitability for this crop or to the average suitability for other crops cultivated in the area. Cereals, although related to their crop-specific suitability, are spread out over the region because of crop rotation requirements and irrigation water shortages. Rice is another important crop in the area, being associated with saline-sodic soils. Although it shows a high degree of association with LEUs with those soil characteristics, the analysis has confirmed previous research that identified rice as an alternative crop in land units with lower salinity-sodicity problems in years of no irrigation water shortage and good market conditions. Alfalfa and maize, on the other hand, are usually located on the most suitable land for agriculture, because of their higher demanding soil and water requirements and the higher return of those lands in relation to the inputs. However, problems related to frequent irrigation water shortages explain the lack of a stronger association with the land suitability. Regarding crop rotations, the alfalfa-based rotations are the ones showing the highest distribution percentages on the land most suitable for the average of the main crops cultivated in the area, which indicates that this crop is used as the main crop on the most suitable land for agriculture in the study area.

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References

AMBROSIO FLORES L., IGLESIAS MARTÍNEZ L., MARÍN FERRER C., PASCUAL GALLEGO V., SERRANO BERMEJO A., 2008. A spatial high-resolution model of the dynamics of agricultural land use. Agr Econ 38, 233-245. doi:10.1111/j.1574-0862.2007.00296.x.

BARBOSA P.M., CASTERAD M.A., HERRERO J., 1996. Performance of several Landsat 5 Thematic Mapper TM image classification methods for crop extent estimates in an irrigation district. Int J Remote Sens 17, 3665-3674. doi:10.1080/01431169608949176.

BOJE G., RUCKER G., SENZIGE S., SKOWRONEK A., 1998. Land suitability for crop diversification and yield potential of a drained swamp area in NW-Tanzania. Tropenlandwirt 99, 65-75.

BONTKES T.S., VAN KEULEN H., 2003. Modelling the dynamics of agricultural development at farm and regional level. Agr Syst 76, 379–396. doi:10.1016/S0308-521X(02)00128-2.

CHEN L., MESSING I., ZHANG S., FU B., LEDIN S., 2003. Land use evaluation and scenario analysis towards sustainable planning on the Loess Plateau in China – case study in a small catchment. Catena 54, 303-316. doi:10.1016/S0341-8162(03)00071-7.

CLARK W.A., HOSKING P.L., 1986. Statistical methods for geographers. John Wiley & Sons, New York.

COOLS N., DE PAUW E., DECKERS J., 2003. Towards an integration of conventional land evaluation methods and farmers' soil suitability assessment: a case study in northwestern Syria. Agr Ecosyst Environ 95, 327–342. doi:10.1016/S0167-8809(02)00045-2.

COTS-FOLCH R., MARTÍNEZ-CASASNOVAS J.A., RAMOS M.C., 2006. Land terracing for new vineyard plantations in the north-eastern Spain Mediterranean region: Landscape effects of the EU Council Regulation policy for vineyards. Agr Ecosyst Environ 115, 88-96. doi:10.1016/j.agee.2005.11.030.

D'ANGELO M., ENNE G., MADRAU S., PERCICH L., PREVITALI F., PULINA G., ZUCCA C., 2000. Mitigating land degradation in Mediterranean agro-silvo-pastoral systems: a GIS-based approach. Catena 40, 37-49. doi:10.1016/S0341-8162(99)00063-6.

DOGLIOTTI S., ROSSING W.A.H., VAN ITTERSUM M.K., 2004. Systematic design and evaluation of crop rotations enhancing soil conservation, soil fertility and farm income: a case study for vegetable farms in South Uruguay. Agr Syst 80, 277-302. doi:10.1016/j.agsy.2003.08.001.

FAO, 1976. A framework for land evaluation. FAO Soils Bulletin No. 32. Rome.

FEIJOÓ M.L., CALVO E., ALBIAC J., 2000. Economic and environmental policy analysis of the Flumen-Monegros irrigation system in Huesca, Spain. Geographical Analysis 32, 187-204.

HENNEBERT P.A., TESSENS E., TOURENNE D., DELVAUX B., 1996. Validation of a FAO land evaluation method by comparison of observed and predicted yields of five food crops in Burundi. Soil Use Manage 12, 134-142. doi:10.1111/j.1475-2743.1996.tb00534.x.

HERRERO J., ARAGÜÉS R., 1988. Suelos afectados por salinidad en Aragón. Surcos de Aragón 9, 5-8. [In Spanish].

HERRERO J., SNYDER R.L., 1997. Aridity and irrigation in Aragón, Spain. J Arid Environ 35, 535-547. doi:10.1006/jare.1996.0222.

HERRERO J., CASTERAD M.A., 1999. Using satellite and other data to estimate the annual water demand of an irrigation district. Environ Monit Assess 55, 305-317.

HERRERO J., PÉREZ-COVETA O., 2005. Soil salinity changes over 24 years in a Mediterranean irrigated district. Geoderma 125, 287-308. doi:10.1016/j.geoderma.2004.09.004.

IGUE A.M., GAISER T., STAHR K., 2004. A soil and terrain digital database (SOTER) for improved land use planning in Central Benin. Eur J Agron 21, 41-52. doi:10.1016/S1161-0301(03)00062-5.

IGWE C.A., 1999. Land use and soil conservation strategies for potentially highly erodible soils of central-eastern Nigeria. Land Degrad Dev 10, 425-434. doi:10.1002/(SICI)1099-145X(199909/10)10:5<425::AID-LDR338>3.3.CO;2-X.

KILIC S., EVRENDILEK F., SENOL S., CELIK I., 2005. Developing a suitability index for land uses and agricultural land covers: a case study in Turkey. Environ Monit Assess 102, 323-335. doi:10.1007/s10661-005-6030-6.

LILLESAND T.M., KIEFER R.W., 1994. Remote sensing and image interpretation. John Wiley & Sons, New York, USA.

MARTÍNEZ-CASASNOVAS J.A., BLANCO O., BOIXADERA J., 2000. Avaluació del territori de l'àrea de Lleida per a usos agrícoles. Perspectives Territorials 9, Departament de Política Territorial i Obres Públiques de la Generalitat de Catalunya, Barcelona. [In Catalan].

MARTÍNEZ-CASASNOVAS J.A., MARTÍN-MONTERO A., 2004. Variabilidad espacial del arroz como cultivo indicador de salinidad en regadíos del valle del Ebro a partir de series temporales de imágenes Landsat TM. Revista de Teledetección 21, 11-14. [In Spanish].

MARTÍNEZ-CASASNOVAS J.A., MARTÍN-MONTERO A., CASTERAD M.A., 2005. Mapping multi-year cropping patterns in small irrigation districts from time-series analysis of Landsat TM images. Eur J Agron 23, 159-169. doi:10.1016/j.eja.2004.11.004.

MESSING I., FAGERSTROM M.H.H., 2001. Using farmers' knowledge for defining criteria for land qualities in biophysical land evaluation. Land Degrad Dev 12, 541-553. doi:10.1002/ldr.470.

NOGUÉS J., HERRERO J., 2003. The impact of transition from flood to sprinkler irrigation on water district consumption. J Hydrol 276, 37-52. doi:10.1016/S0022-1694(03)00022-2.

NOGUÉS J., HERRERO J., RODRÍGUEZ-OCHOA R., BOIXADERA J., 2000. Land evaluation in a SALT-affected irrigated district using an index of productive potential. Environ Manage 25, 143-152. doi:10.1007/s002679910011.

NORUSIS M.J., 2005. SPPS 14.0 Statistical procedures companion. Prentice-Hall, Upper Saddle River, NJ.

OTT L., LARSON R.F., MENDENHALL W., 1983. Statistics: a tool for the social sciences. Duxbury Press, Boston, MS.

SAN JOSÉ ALONSO J.F., LÓPEZ SASTRE J.A., ROMERO-ÁVILA C., LÓPEZ ROMERO-ÁVILA E., IZQUIERDO IGLESIAS C., 2005. Using mixtures of diesel and sunflower oil as fuel for heating purposes in Castilla y León. Energy 30, 573–582. doi:10.1016/j.energy.2004.05.021.

SOIL SURVEY DIVISION STAFF, 1993. Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18, Washington, D.C.

SOIL SURVEY STAFF, 1999. Soil taxonomy. 2nd ed., Agriculture Handbook no. 436, USDA Natural Resources Conservation Service, Washington DC.

VELDKAMP A., KOK K., DE KONING G.H.J., SCHOORL J.M., SONNEVELD M.P.W., VERBURG P.H., 2001. Multi-scale system approaches in agronomic research at the landscape level. Soil Till Res 58, 129-140. doi:10.1016/S0167-1987(00)00163-X.

VERDOODT A., VAN RANST E., 2006. Environmental assessment tools for multi-scale land resources information systems - A case study of Rwanda. Agr Ecosyst Environ 114, 170-184. doi:10.1016/j.agee.2005.10.006.

WINTER M., 2000. Strong policy or weak policy? The environmental impact of the 1992 reforms to the CAP arable regime in Great Britain. J Rural Stud 16, 47-59. doi:10.1016/S0743-0167(99)00018-2.