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Changes in landscape fire-hazard during the second half of the 20th century: Agriculture abandonment and the changing role of driving factors

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ABSTRACT

Past the middle of the 20th century, forest fires started to increase markedly in the Mediterranean countries of southern Europe. Hazardous land-use and land-cover (LULC) changes are considered major drivers of increased fire-hazard and fire risk. However, the contribution of various LULC changes to increased fire-hazard, as well as the role of environmental or socioeconomic factors in driving them, including its changing role over time, are poorly known. Understanding how changes in socio-economics in interaction with other factors modify landscape fire-hazard and risk is a major priority in fire-prone areas. Here we determined changes in fire-hazard through time, focusing on the contribution of agriculture abandonment to it, and on the changing role of its driving factors, in a large (56,000 km^2) rural area in West-Central Spain. The study period covers from 1950s to 2000. LULC maps at different time steps (1950s, 1978, 1986 and 2000) were available, as well as environmental and socioeconomic information at various scales. We analyzed trends in LULC change, focusing on those altering fire-hazard, and used general linear models (GLM) with generalized linear mixed models (GLMM) to account for the effects of variables at different spatial scales in determining changes leading to shifts in fire-hazard. We found that the proportion of hazardous LULC types increased twofold (26–42%) from 1950s to 2000. Until 1986, agriculture abandonment was the dominant LULC change leading to increased fire-hazard. Post-1986, LULC changes were mainly driven by deforestation due to fires and densification caused by natural vegetation dynamics. Models showed that the first abandoned lands were driven by local environmental and socioeconomic constraints (small farms, in distant locations, in municipalities with low population), whereas later abandonments were driven by non-local ones (large farms, in more productive soils, closer to towns, populations with high unemployment, and higher employment in the services sector). Throughout the entire period, high proportion of wildland vegetation, low mechanization level, and large number of land-holders older than 55 years favored abandonment. This implies that as the population ages, larger, more accessible and productive areas are abandoned, fire-hazard will increase closer to human settlements, increasing the wild-land urban interface and fire risk.

1. Introduction

Fire activity has increased markedly during the second half of the last century in many parts of the world (FAO 2001; Bowman et al., 2009). Fires are mainly driven by climate, fuels, availability of ignitions and, in some countries, firefighting capacity. While changes in climate (Westerling et al., 2006; Koutsias et al., 2012) and urban encroachment (Syphard et al., 2007, 2012; Lampin-Maillet et al., 2011) have been proposed as major drivers of change in fire regime in some areas, changes in fuels and landscape-level fire-hazard might have also played a dominant role (Fernandez-Ales et al., 1992; Lepart and Debussche, 1992; Moreira et al., 2001; Kalabokidis et al., 2007; Carmel et al., 2009). In the case of Mediterranean countries of southern Europe, fires started to increase during the early 1970's, but not so much in Northern Africa, indicating that socioeconomic factors were a major driver of change. More so, trends in fire activity in various countries was decoupled from changes in climate (San-Miguel-Ayanz et al., 2012), which further supports that socioeconomic changes, including changes in fuels and landscapes

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(Moreno et al., 1998; Rego, 1992), and also firefighting capacity in recent times (Brotons et al., 2013), were behind it, although additional effects of changes in climate cannot be excluded (Koutsias et al., 2013; Bedia et al., 2014). Recent studies indicate that trends in fire activity in some of the southern European countries have discontinuities that suggest a role for various factors, including land-use and land-cover (LULC) changes (Moreno et al., 2014).

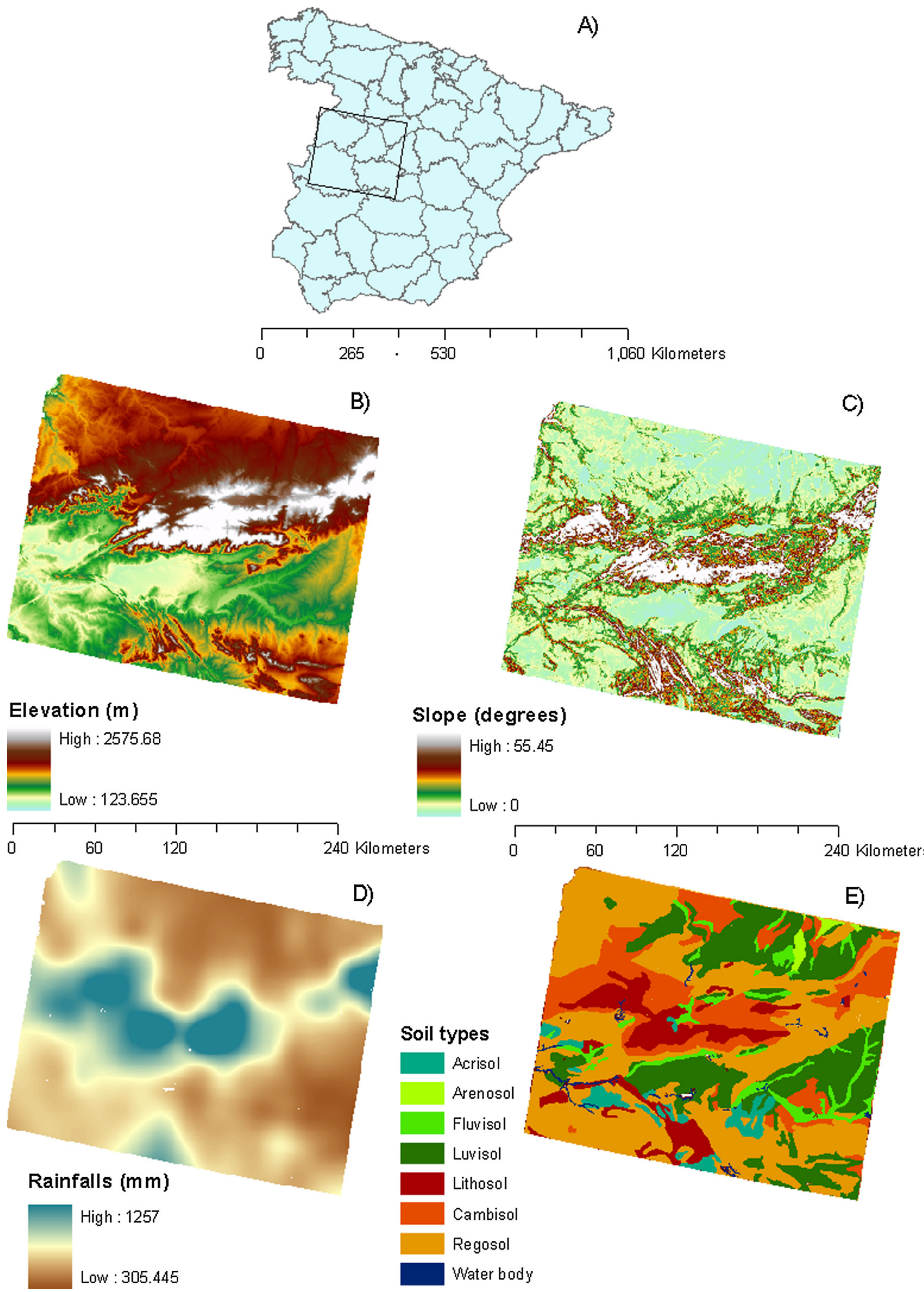

Fig. 1. Location of the study area in West-Central Spain (A). Map of elevation in meters (B), map of slopes in degrees (C), map of mean annual rainfalls in mm (D) and map of soil types (E).

In spite of LULC changes being widely recognized as driving factors of changes in fire, a quantification of this process, including the factors driving them, is yet poorly known. Moreover, considering the ever dynamic nature of the factors affecting fires, an assessment of the variable role that the different factors play through time in affecting landscape fire-hazard is lacking. Nowadays, the validity of the stationary role of environmental and socioeconomic factors in explaining LULC changes, mainly agriculture abandonment, has been questioned (Hatna and Bakker, 2011; Bakker and Veldkamp, 2012); suggesting that relationships between croplands and environmental conditions (Bakker and Veldkamp, 2012) as well as the role of socio-economic factors (Kuemmerle et al., 2008; Müller and Munroe, 2008; Baumann et al., 2011) have changed during last decades. This is important because socioeconomics and their effects on the landscape continue changing. Anticipating how these factors vary through time to affect landscape level fire-hazard is important to project future changes in fire regime, notably in a context of changing climate, land-use patterns and life styles.

Moreover, establishing cause–effect relationships between explanatory factors and LULC changes have also proven difficult (Irwin and Geoghegan, 2001; Nelson, 2001) mainly due to: (i) the patterns of LULC changes are spatially heterogeneous and location specific (vary spatially from one region to another, being anisotropic), (ii) LULC changes have a clear hierarchical spatial structure being scale-sensitive (i.e., the probability of LULC change depends on factors operating at different scales), and (iii) the role of driving factors are spatially heterogeneous (Koutsias et al., 2010) and temporally non-stationary (Bakker and Veldkamp, 2012). In spite of these limitations, the most common statistical approach for explaining LULC changes has been based on general linear model (GLM), such as logistic or multinomial regression, which assume independence of observations and relate LULC changes with explanatory factors acting at different scales obscuring patterns and processes across scales (e.g., Serneels and Lambin, 2001; Bakker et al., 2005; Améztegui et al., 2010). Multilevel modeling or general linear mixed models (GLMM) can include explicitly spatial structures as municipalities or other spatial divisions, thus allowing studying the effects of different spatial scales on a particular response variable, while providing a robust estimation of error (Snijders and Bosker, 1999; Diez-Roux, 2000). Apart from providing better statistical inference by modeling excess heterogeneity present in the data, GLMM address spatially misaligned explanatory variables and spatial structure in the ecological pattern. Recently, several works have used GLMMs to develop explanatory models on land-use patterns and changes around the world (Pan et al., 2004; Overmans and Velburg, 2006; Neumann et al., 2011; López-Carr et al., 2012). In the case of models of agriculture abandonment in Mediterranean rural areas the standard GLMs (logistic and/or multinomial) have been used (Van Doorn and Bakker, 2007; Millington et al., 2008); or only descriptive analyses about the relationship between agricultural abandonment and driving factors have been carried out (Moreira et al., 2001; Romero-Calcerrada and Perry, 2004). No study has approached agriculture abandonment in this region of the world based on robust approaches such as GLMMs. This is important for understanding causal factors in the modification of a landscape highly reactive to fire.

Here we studied that the main LULC changes occurred from 1950s to 2000 by three distinctive periods (1950s–1978; 1978–1986 and 1986–2000), in a large rural area in Central-Western Spain, focusing on changes leading to shifts in fire-hazard. For this purpose, we focused on the contribution of agriculture abandonment to such changes. Furthermore, we modeled agriculture abandonment using GLMMs based on environmental and socio-economic factors at each time-step to detect possible changes in drivers through time. Finally, we developed spatially-explicit maps of agriculture abandonment from GLMMs and tested their predictive capacity. The hypotheses to be tested were: (a) early abandonments were driven by local constraints due to low economic development, but late abandonments would be driven by non-local factors due to the effects of globalization process; consequently, (b) drivers of land abandonment leading to change in fire-hazard were not constant over time, varying in their relative role with time.

2. Methods

2.1. Study area

The study area is in Central-Western Spain; UTM coordinates 4369–4551 and 201–394 in the zone 30 North, covering 56,000–km^2 (Fig. 1A). The area is characterized by the mountainous landscapes of Sierra de Gredos, running across the northern half of the area, flanked by relatively flat areas towards the North and South (Fig. 1B–C). The climate is mild and relatively wet in the flat areas and cold and very wet in upper mountains (Fig. 1D). Soils in the mountain areas are shallow, with high stoniness and coarse texture (Cambisol, Regosol and Lithosol), whereas, in the flat areas, they are deep and fine textured (Luvisol and Fluvisol) (Fig. 1E) (see on-line material Table 1 for further details).

2.2. LULC changes

Maps of changes in LULC types were produced for the periods 1950s–1978, 1978–1986 and 1986–2000, using all available information sources. The first period (1950s–1978) covered the change from traditional agriculture to first mechanization and technological change. The second period (1978–1986) was characterized by the continuity of the mechanization process and subsequent socio-economic changes caused by the economic oil crisis and emigration from agricultural areas. Finally, the third period (1986–2000), covered the effects of changes due to the incorporation of Spain to the European Economic Community (EEC) (1986) and of land reforms derived from European Community Common Agrarian Policy (CAP). Fires in the region and in the rest of Spain started to be important in the early 1970’s, peaking by the mid 1980’s (Moreno et al., 1998).

The LULC maps before 2000 were developed by the National Geographic Institute of Spain (IGN). For the first date (1950s), several tiles were available from various years (from 1939 to early 1960s; dominating tiles from 1950s). The various dates produced nearly identical maps, which allowed the merging of tiles into one single map. These old maps were geo-referenced and digitized using ArcGIS 9.3.1 software (www.esri.com). The LULC map from 2000 was available from the CORINE land cover project (http://www.eea.europa.eu/). To allow comparison across dates, spatial and thematic features were homogenized, minimizing possible positional errors and eliminating sliver polygons (<5 ha) from crossed LULC maps (Petit and Lambin, 2002). A common LULC legend based on CORINE land cover project was applied to all maps (Bossard et al., 2000): croplands (herbaceous and woody crops), agroforestry areas (open oak woodlands with pastures called “*dehesas*”), pastures (natural and artificial herbaceous vegetation), shrublands (evergreen sclerophyllous bush and scrub), open forests (bushy or herbaceous vegetation with scattered trees [<30% tree cover]), dense forests (separating deciduous, conifer and mixed forests with >30% tree cover), artificial uses (urban, industrial, and so on) and water bodies.

To assess changes in fire-hazard in the landscape, the hazardousness of the different LULC types was determined based on a qualitative assessment (Viedma et al., 2009; Moreno et al., 2011). Based on previous works, the most hazardous LULC types were pine woodlands, shrublands and, to a lesser extent, pastures. On the contrary, the less hazardous LULC types were: deciduous forests, croplands and agroforestry areas. Accordingly, a broad reclassification of the main LULC types was carried out as follow: "non-hazardous" LULC types (croplands, agroforestry areas, deciduous forests, artificial uses and water bodies) and "hazardous" LULC types (pastures, shrublands, open forests, conifer and mixed forests). Based on this, the percentage of occupation of each category was calculated at each time step. Moreover, LULC changes between consecutive dates were classified into the following classes: agriculture conversion, agriculture abandonment, deforestation, densification and afforestation (Table 1). These two latter changes leading to conifer and mixed forests were categorized as hazardous LULC changes; by the contrary, changes leading to deciduous forests were considered as "non-hazardous". Moreover, when LULC remained stable between consecutive dates, such "stability" was classified as "hazardous" when stable LULC types were pastures, shrublands, open forests, conifer and mixed forests, and "non-hazardous" when stable LULC types were croplands, deciduous forests, open spaces, artificial uses and water bodies. Once LULC changes were completed, binary maps (0, 1) for agriculture abandonment (i.e., changes from croplands to pastures and shrublands; from pastures to shrublands and, from agroforestry to open forests) were produced and later used for modeling (Table 2).

2.3. Environmental and socio-economic variables

Following standard terminology on multilevel models or GLMMs (Diez-Roux, 2002), we defined *individual level variables* as the covariates or explanatory variables that characterize individuals (i.e., sampling points), and *group level variables* as the variables that characterize groups (in our case, municipalities and soil polygons). Individual variables, measured at grid cell (100 m) (level 1), were topography, climate and distance measures (see later); group variables measured at soil polygons level (level 2), were soil derived variables; and those at municipalities level (level 3) were socio-economic factors and percentage occupation of LULC types. To facilitate modeling on a pixel-by-pixel basis, all variables were rasterized to a common resolution of 100 m and equally referenced (ETRS89 LAEA: Lambert azimuthal equal area).

2.3.1. Variables at grid-cell (level 1)

A digital elevation model (DEM) with a spatial resolution of 5 m (Table 2) was used to derive, using ArcGIS 9.3.1. (www.esri.com), the following variables: elevation (m), slope (°), topographic wetness index (TWI), mean annual solar radiation (direct (kW m^{-2}) and duration (h)), curvature (negative value indicates that the surface is convex; a positive value indicates that the surface is concave, and a value of zero indicates that the surface is flat), and landforms (based on the topographic position index (TPI) (Jenness, 2006)) (Table 2). The 10 original slope position classes were reclassified following a rank of topographic constraints into: (i) canyons-ridges (class 1), mid-up-slope and hills (class 2), and valleys-plains (class 3) (see on-line material Table 1 for further details). A map of distance to the main roads was also created to quantify the distance from each pixel to the nearest road pixel. In addition, a map of cost distances (impedances by slope) to the main villages was calculated using ArcGIS 9.3.1. (Table 2). Maps of mean annual precipitation (mm) and mean maximum and minimum annual temperature (°C) were derived by interpolating multiple grids of points at 20 km of distance (Spain02 database) for the period from 1950 to 2008 (Herrera et al., 2012) using the package *akima* in R software (R Core Team, 2013).

2.3.2. Variables at soil level (level 2)

The soil variables used were: soil type (FAO, 1988), parent material, soil depth (i.e., obstacles to roots), erosion and stoniness (Table 2).

2.3.3. Variables at municipality level (level 3)

We used number of inhabitants, employment rate by economic sector, instruction level and unemployment rate, density of farms (no. km^{-2} based on municipality area), proportion of farms by size classes, proportion of farms by land tenure, density of agriculture machines, proportion of full-time farmers, proportion of land-holders older than 55 years and livestock (caprine, ovine and bovine) density (Table 2) (see on-line material Table 1 for further details). Finally, the proportion of different LULC types at

Table 1
Main land-use land-cover (LULC) changes that increase and/or decrease landscape fire-hazard.

LULC change	From	To
Agriculture conversion	All LULC types	Croplands (labor and woody crops)
		Agroforestry areas
		Pastures
Agriculture abandonment	Croplands (labor and woody crops)	Pastures/shrublands
	Agroforestry areas	Open forests
	Pastures	Shrublands
Deforestation	Agroforestry	Shrublands/pastures/burnt areas/artificial uses
	Open forests	Shrublands/pastures/burnt areas/artificial uses
	Forests (conifer, mixed and deciduous)	Open forests/shrublands/pastures/burnt areas/artificial uses
	Shrublands	Pastures/burnt areas/artificial uses
Densification	Open forests	Forests (conifer, mixed, deciduous)
	Shrublands	Open forest
Afforestation	Croplands (labor and woody crops)	Forests (conifer, mixed, deciduous)
	Agroforestry areas	Forests (conifer, mixed, deciduous)
	Pastures	Forests (conifer, mixed, deciduous)
	Shrublands	Forests (conifer, mixed, deciduous)

Table 2
Variables used for explaining agriculture abandonment in West-Central Spain from 1950s to 2000 by pair of dates (1950s–1978, 1978–1986 and 1986–2000) measured at three levels [grid cell (level 1), soil polygons (levels 2) and municipalities (level 3)].

Explantory variables	Source	Spatial resolution	Dates
Level 1 (grid cell)			
Elevation (m)	Digital elevation model (IGN)	5 m	
Slope angle (°)			
Topographic wetness index			
Solar radiation (kW m^{-2})			
Curvature			
Landforms			
Mean annual precipitation (mm)	Spain02 dataset[a]	20 × 20 km	1950–2008 (monthly)
Average minimum annual temperature (°C)			
Average maximum annual temperature (°C)			
Distance to roads (km)	Roads map (IGN)	100 m	
Cost distance to villages	Villages map (IGN)		
Level 2 (soil polygons)			
Soil types	European soil database (ESDB)	1 × 1 km	
Parent material			
Soil depth			
Erosion			
Stoniness			
Level 3 (municipality)			
Population density (inhabitants/km^2)	Spanish population register (INE)		From 1900 (yearly)
Unemployed people (%)	Unemployment statistics (SEPE)		From 1983 (yearly)
Employees in economic sectors	Spanish population census (INE)		From 1981 (at each 10 years)
Farms density (n°/km^2)	Spanish agrarian census (INE)		From 1962 (at each 10 years)
Farms by land tenure (%)			
Farms by size (%)			
Full-time farmers (%)			
Agrarian holders older than 55 years (%)			
Machine density (n°/km^2)			
Livestock density (n°/km^2)			
Land use-Land cover percentage	IGN, CORINE land cover (EEA)	100 m	1950s, 1978, 1986 and 2000

IGN, National Geographic Institute; INE, Spanish National Statistics Institute; SEPE, Public Service of State Employment; ESDB, European Soil Database (http://eusoils.jrc.ec.europa.eu); EEA, European Environmental Agency.
[a] Herrera et al., 2012.

municipality level was computed at the beginning of each period (i.e., 1950s, 1978 and 1986).

2.4. Socio-economic changes

Changes in the main socio-economic variables occurred between consecutive dates of the various periods were statistically characterized by changes in the cumulative distribution function (CDF), using the package *reldist* in R program (R Core Team, 2013; Handcock and Morris, 1998). The variables used were population density, number of employees in the primary sector, farm density, percentage of large farms (>50 ha), proportion of land-holders older than 55 years, and livestock density.

2.5. The modeling approach

We modeled agriculture abandonment based on binary maps between the various periods using sets of variables at different scales and 3 level random intercept models (3L-RIMs), a specific type of generalized linear mixed model (GLMM) in which only the intercept is allowed to vary randomly across groups (i.e., municipalities and soil levels) (Snijders and Bosker, 1999; Overmars and Verburg, 2006). In RIMs we distinguish between the *fixed part* (i.e., regression coefficients or covariate effects that are not allowed to vary randomly across groups and that can be measured at different levels) and the *random part* (i.e., the group dependent deviation of the intercept or macro-errors) (Diez-Roux, 2002) (Fig. 2). Macro errors are assumed to be independent across groups or levels and independent of the individual-level errors. The individual error is fixed in logistic RIMs (Snijders and Bosker, 1999) (i.e., the residual variance of level 1 (individuals) (σ^2) is fixed being $\sigma^2 = \pi^2/3 = 3.29$). Interpretation of the fixed part in RIMs is like in conventional logistic regression models whereas the interpretation of the random part is based on the intraclass correlation (ICC) that can be interpreted as both the residual variance that is attributable to differences between units within any level of interest or "between-subject variance", and the degree of resemblance between lower level units (individuals) belonging to the same higher level unit or "within cluster correlation". The ICC was calculated by dividing the residual variance of any level of interest by itself, and the variance of other levels. An ICC of 5% is substantive evidence of a clustering effect (Glaser and Hastings, 2011).

Sampling followed a hierarchical systematic stratified random method called Generalized Random-Tesselation Stratified design (GRTS) (Stevens and Olsen, 2004) using the package *spsurvey* (Kincaid and Olsen, 2012) in R program (R Core Team, 2013). Firstly, we sampled 1000 points (50% for abandonment [1 in the binary map] and 50% for no abandonment [0 in the maps]) weighted by area of the polygon where the sample point was located. From 1000 sampling points, 75% of them were selected for training and 25% for validating the models. For robust calculations, GLMMs need enough groups in each level and enough individuals within them. In our case, the number of municipalities ranged from 19 to 31 for each period; and the number of soil polygons, from 9 to 15. In all groups, the number of individuals was >5 cases.

Laplacian algorithm and the Bayesian approaches were both used in RIM's calculations. The first approach allowed estimating conventional accuracy measures (AIC, pseudo R^2, AUC-ROC, kappa index and Moran's test), while the second one provided reliable parameters estimates (β coefficients for the variables in the fixed part, variances associated to random factors and residuals)

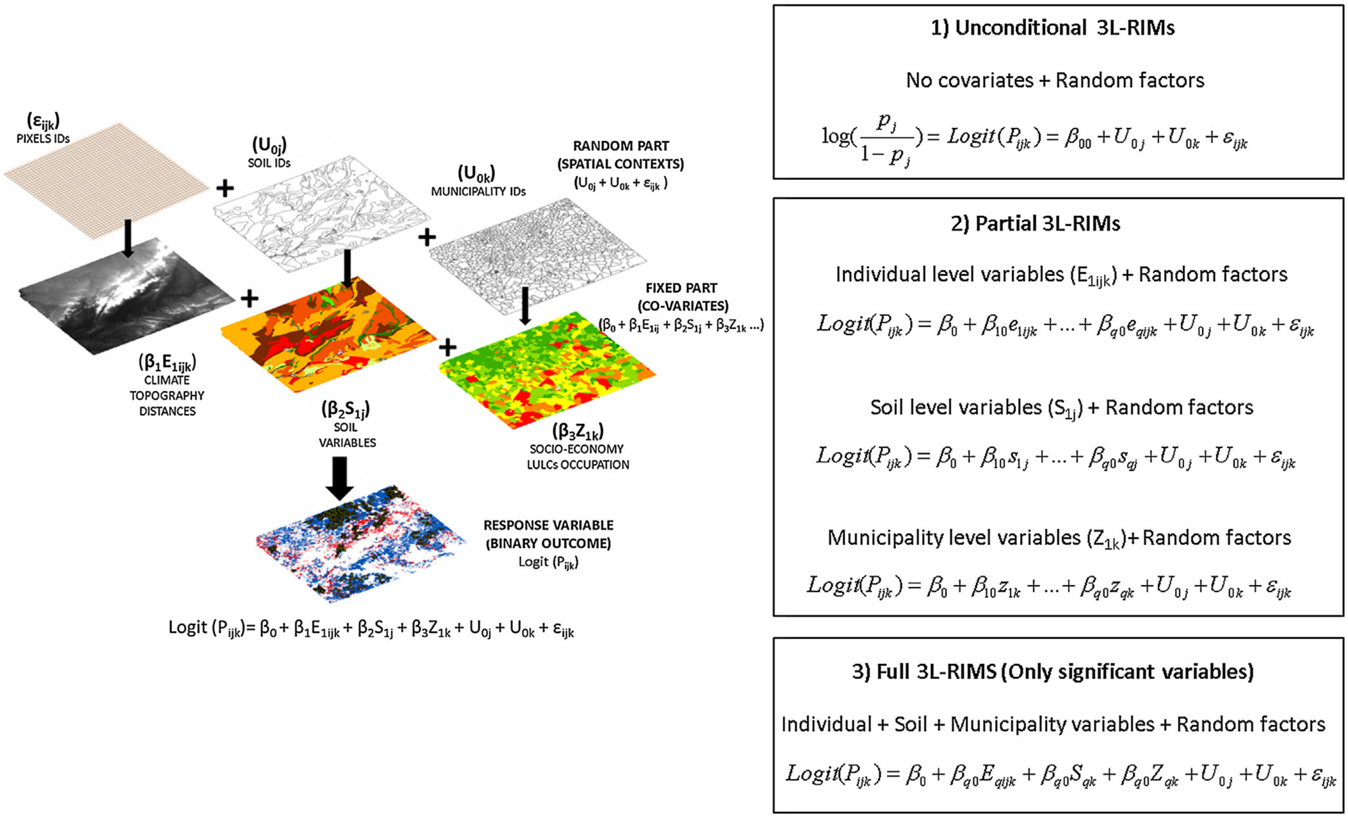

Fig. 2. In the left panel, flow-diagram of the structure of a 3 level random-intercept model (3L-RIM) (i.e., random and fixed parts at the levels at which fixed variables were measured, and the dependent variable); and in the right panel, flow of the strategy to model agriculture abandonment by using 3L-RIMs: (1) the "Unconditional or Empty 3L-RIM's" with no covariates in the fixed part and only random factors; (2) "Partial 3L-RIM's" with covariates in the fixed part and random factors, and calculated for each set of covariates measured at each level (i.e., grid-cells, soils and municipalities); and (3) the "Full 3L-RIM's" with all the significant covariates obtained from previous Partial 3L-RIM's.

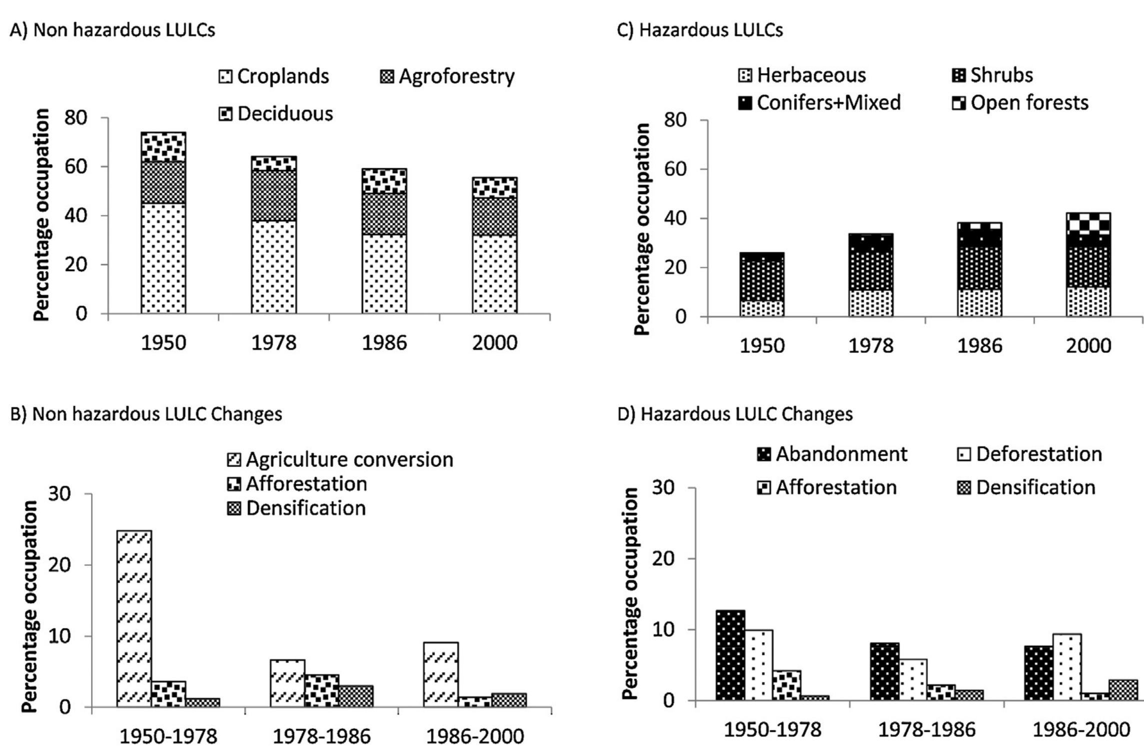

Fig. 3. Percentage occupation of non-hazardous land-use land-cover (LULC) types (A), non-hazardous LULC changes (B), hazardous LULC types (C), and hazardous LULC changes (D) respect to the entire study area and during the study periods (1950s–1978, 1978–1986 and 1986–2000).

(Hadfield, 2010). Laplacian random-intercept models were calculated using the package *lme 4.0* (Bates et al., 2014) in R program (R Core Team, 2013), and Bayesian random-intercept models were estimated using the package *MCMCglmm* (Hadfield, 2010).

To determine the most significant predictive factors and more parsimonious models we followed a common strategy (Snijders and Bosker, 1999) (Fig. 2): (i) the "Unconditional or Empty 3L-RIM's": no covariates in the fixed part and random factors (i.e., soils and municipalities) in the random part in order to assess the portion of variance accounted only by the random factors. (ii) "Partial 3L-RIM's": covariates were included in the fixed part and random factors in the random part. These Partial 3L-RIMs were calculated separately for each set of covariates measured at each level (i.e., grid-cells, soils and municipalities) to see the influence of these fixed sets of variables on the variance accounted by the random factors. (iii) The "Full 3L-RIM's": all the significant covariates obtained from previous Partial 3L-RIM's were included in the fixed part and random factors in the random part. The Unconditional 3L-RIMs provided the base for subsequent extending models to identify which fixed variables at different levels might explain some part of the variance accounted by random factors (Hox, 1994). Accordingly, the proportional decrease

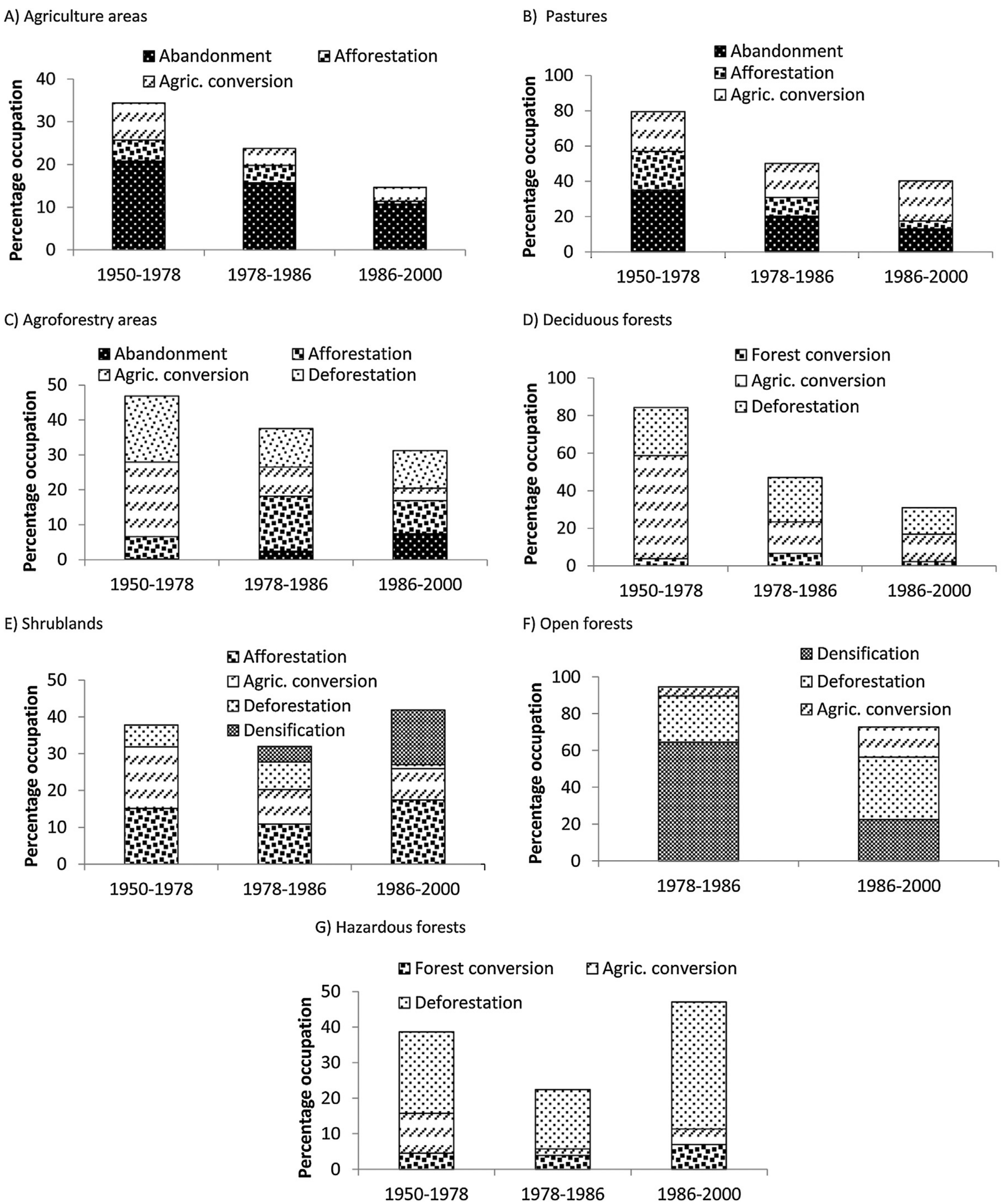

Fig. 4. Percentage occupation of main land-use land-cover (LULC) changes respect to the area occupied by each LULC type for: agriculture (labor and croplands) (A), pastures (B), agroforestry areas (C), non-hazardous forests (deciduous) (D), shrublands (E), open forests (F) and hazardous forests (mixed and conifers) (G) for the study periods: 1950s–1978, 1978–1986 and 1986–2000 (in shrublands, deforestation means the change from shrublands to pastures).

of the random variance in Partial and Full 3L-RIMs respect to the Unconditional ones will be interpreted as explained variance by the fixed effects (Hox, 1994).

For comparative purposes, fixed logistic regression models or general linear models (GLM) were calculated separately for each set of covariates measured at each level for each period ("Partial GLMs"); as well as "Full GLMs" using the significant covariates obtained from previous Partial GLMs.

Finally, spatially explicit predicted maps were elaborated using the fixed-effects (regression coefficients) derived from the Full 3RIMs calculated by the Bayesian approach, for each period using the package *raster* in R program (Hijmans and van Etten, 2013). The accuracy of the spatially explicit predicted maps was evaluated by two measures of agreement between categorical maps: the producer's and user's agreement; and by two measures of disagreement: quantity and allocation. The producer's accuracy refers to the classification accuracy of true land-cover class in the predicted map, while the user's accuracy refers to the classification accuracy of the predicted land-cover class in the true or ground based map. On the other hand, the quantity disagreement refers to the amount of difference between the reference map and a comparison map in the proportions of the categories; whereas the allocation disagreement refers to the amount of difference between both maps in the spatial allocation of the categories (Pontius and Millones, 2011).

Before modeling, a cutoff level of collinearity at $R^2 \geq 0.70$ was established. At the same time, continuous variables were mean-centered, to render the regression coefficients more interpretable (Glaser and Hastings, 2011). Moreover, to avoid problems of reversed causality between explanatory factors and the outcome, all socio-economic factors were included in the models at the state before or during the initial year of the period, as much as possible (Hatna and Bakker, 2011).

3. Results

3.1. General LULC trends

From 1950s to 2000 there was a continuous decrease of the non-hazardous LULC types (Fig. 3A). Croplands were the ones that lost a larger extension (−13%), followed, at a distance, by deciduous forests (−4%) and agroforestry areas (c.a. −2%) (Fig. 3A). In relation to non-hazardous LULC changes, agriculture conversion was maximum during the first period and decreased sharply in the latter period; afforestation with non-hazardous species and densification to deciduous forests was reduced (<5%) and did not show any clear trend (Fig. 3B). In contrast, the extension of hazardous LULC types continuously increased (from +26% to +42%) during the studied period (Fig. 3C). In absolute values, open forests and pastures were the hazardous LULCs that gained greater extension (+9% and c.a. +6%, respectively), whereas shrublands were almost stable (in extension but not in location) as well as conifer-mixed forests that had a net loss of c.a. −2% of their initial occupation at the ending date (Fig. 3C). By extension, the most important hazardous LULC changes during the entire period were agriculture abandonment and deforestation (Fig. 3D). Agriculture abandonment was high until 1986, but this pattern changed from that date dominating deforestation over abandonment (Fig. 3D). Following them, afforestation with conifer species showed a progressive decrease through time; whereas densification of open forests to conifer forests followed the inverse trend (Fig. 3D). In spite of these LULC changes, the most outstanding feature was the increased occupation of stable hazardous LULC types (from c.a. 10% (1950s–1978) to 22% (1986–2000)) that contributed to increase the landscape fire-hazard over time.

A deeper analysis of hazardous LULC changes within each LULC type showed that croplands and pastures increased their

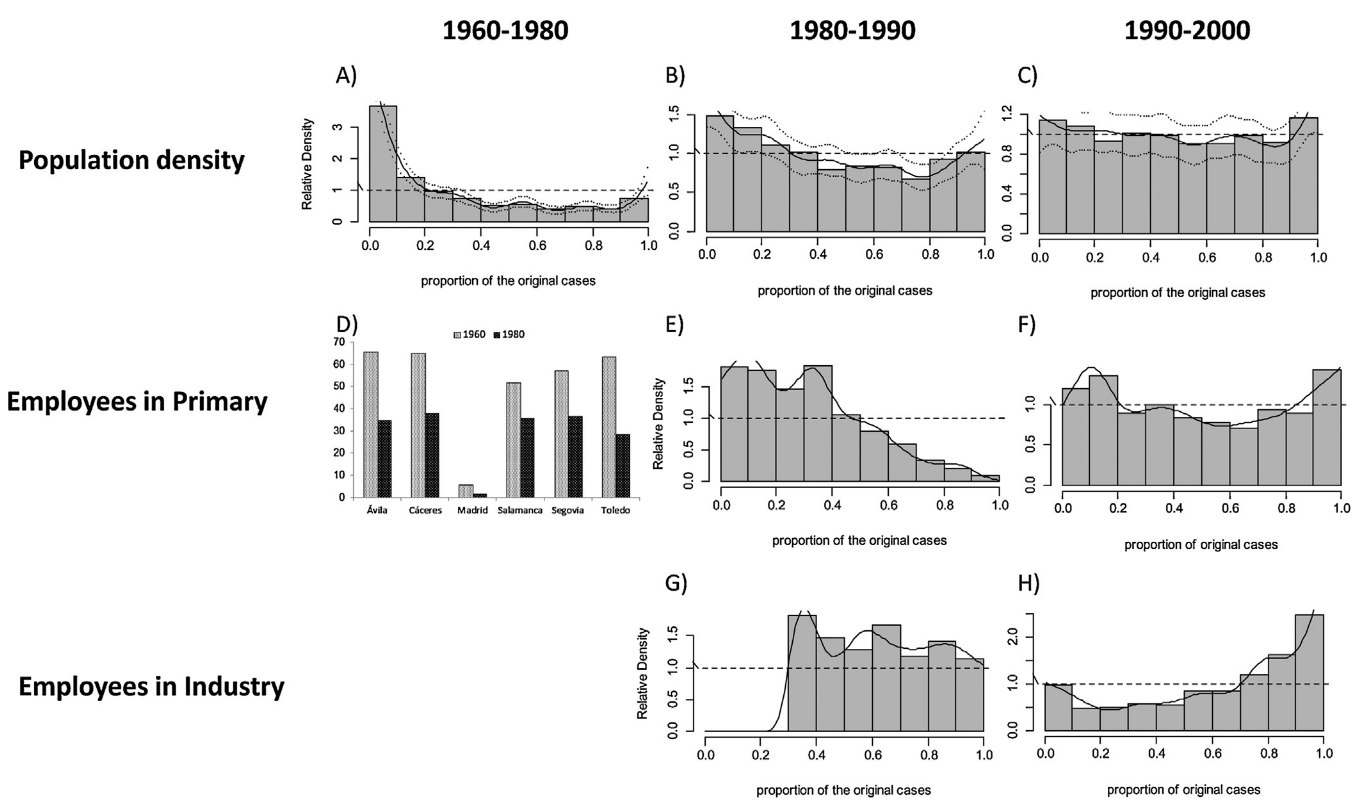

Fig. 5. Comparisons by pair of dates (1960–1980, 1980–1990 and 1990–2000) of the cumulative distribution functions (CDF) of the following socio-economic variables: population density (A–C); employees in agriculture (D–F) and employees in industry (G–H). Values above 1 (in the *Y* axis) represent more density in the recent distribution (of the latest year in each pair of dates), while values below 1 represent less.

hazardousness mainly due to abandonment and afforestation; although part of the pastures were intensively used for crops during the last periods (Fig. 4A–B). On the contrary, agroforestry areas were converted into intensive croplands or deforested, as occurred with deciduous forests, mainly during the first period; whereas hazardous afforestation, abandonment and deforestation contributed to increase its hazardousness during the last periods (Fig. 4C–D). Shrublands showed the same trend of increasing hazardousness by afforestation with conifer species and densification of clearings (Fig. 4E). Open forests experienced a high densification process from 1978 that was replaced by its deforestation by wildfires from 1986 onwards (Fig. 4F). Finally, conifer and mixed forests areas showed a pronounced increase in hazard after 1986 due to deforestation and subsequent encroachment by shrublands (Fig. 4G).

3.2. General trends in socio-economic changes

The study area suffered important socio-economic changes from 1950s to 2000. Population density decreased almost by half from 1960 to 1980 (see on-line material Table 1 for further details). In 1980, the proportion of municipalities with low population density (located in the first quartile of 1960 ($<$16.2 inhab. km^{-2})) increased three times relative to 1960 (Fig. 5A). From 1980 to 2000, population density was rather stable, although population concentration in some villages (increased proportion of municipalities in the upper quartiles) and depopulation in others (increased proportion of municipalities in lower quartiles) was observed (Fig. 5B–C). Population dedicated to agrarian activities decreased significantly from 1960 to 1980 in all provinces, being the average change of agrarian population around −50% (±15) (Fig. 5D). From 1980 to 1990 the agrarian people continued its reducing trend, and from 1990 to 2000 certain polarization became evident (increased number of municipalities with low and high proportion of agrarian people) (Fig. 5E–F, on-line material Table 1). Moreover, a significant shift from agriculture to other economic sectors, mainly industry, was observed from 1980 to 2000 (Fig. 5G–H, on-line material Table 1).

Similarly, farm density was reduced significantly from 1960 onwards (on-line material Table 1). In 1980, the proportion of municipalities in the first quartile of 1960 increased three times (Fig. 6A). From 1980 to 1990 there was certain stability, although the trend to reducing farm density turned more pronounced from 1990 to 2000 (Fig. 6B–C, on-line material Table 1). Farm density decreased due to the significant increase of large farms (>50 ha) and the loss of very small farms (<5 ha) during the entire studied period (Fig. 6D–F, on-line material Table 1). Moreover, significant changes were observed in relation to farmer's age. Until 1990, there was a continuous increase of the proportion of land-holders older than 55 years, but from 1990 the trend was inverted (Fig. 6G–I, on-line material Table 1). For livestock density, from 1960 to 1980 half of the provinces included in the study area reduced their livestock density, whereas the other half increased it (Fig. 6J). From 1980 to 1990 there was stability, and from 1990 the polarization process became acute (Fig. 6K–L, on-line material Table 1).

3.3. Models for agriculture abandonment from 1950s to 2000

To avoid duplicities in models explanations, only the results derived from the Unconditional and the Full 3 level

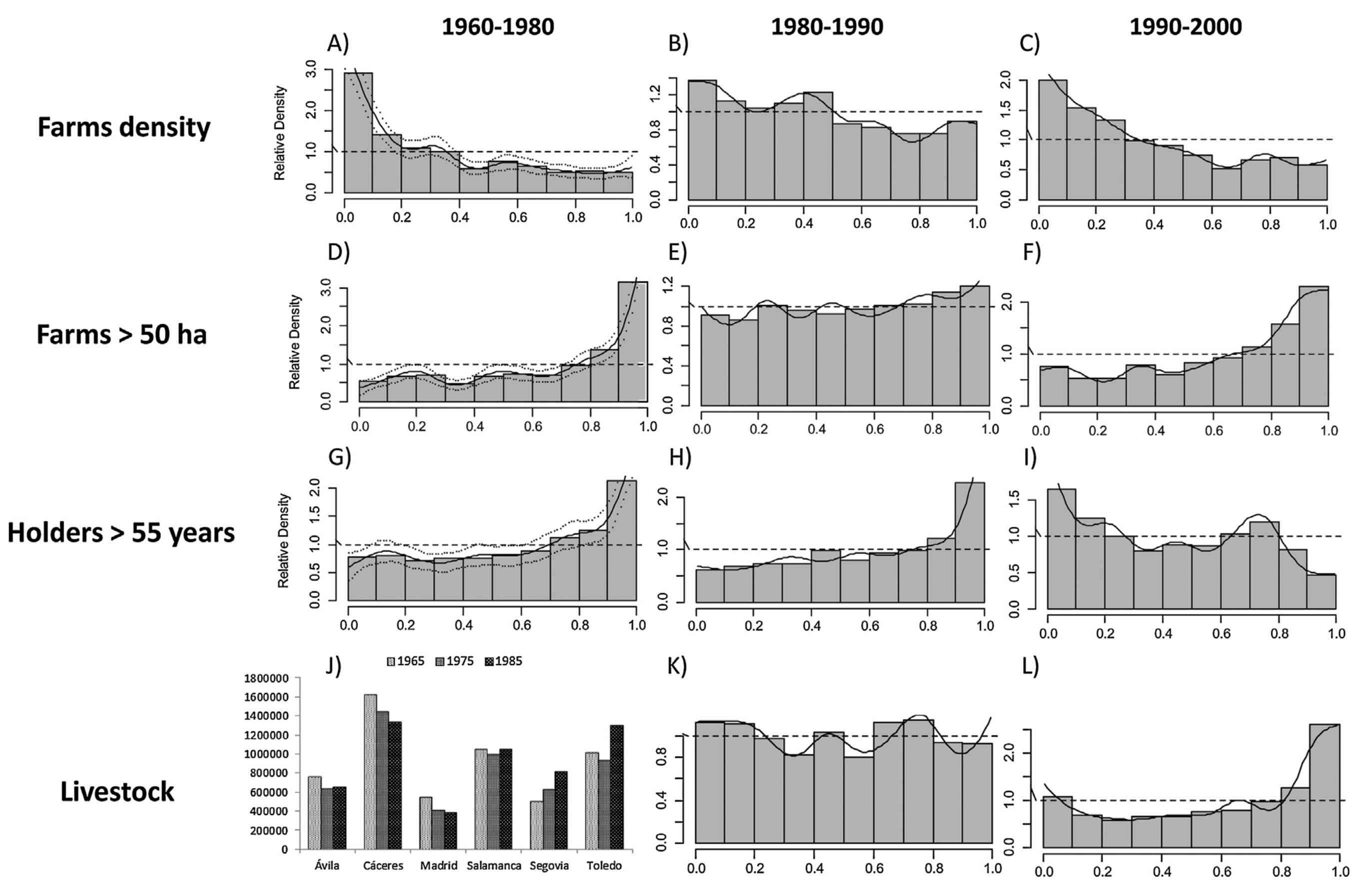

Fig. 6. Comparisons by pair of dates (1960–1980, 1980–1990 and 1990–2000) of the cumulative distribution functions (CDF) of the following socio-economic variables: farms density (A–C); farms >50 ha (D–F); agrarian holders older than 55 years (G–I), and livestock density (J–L). Values above 1 (in the *Y* axis) represent more density in the recent distribution (of the latest year in each pair of dates), while values below 1 represent less.

Table 3
Unconditional or Empty 3 Level Random-Intercept Models (3L-RIMs) for explaining agriculture abandonment in West-Central Spain from 1950s to 2000 by pair of dates (1950s–1978, 1978–1986 and 1986–2000), using soil polygons (level 2) and municipalities (level 3) as random factors. Logit coefficients B estimated using the Bayesian approach, their confidence Intervals (CI) at 95%, their transformation in probabilities ([exp(logit)/1+exp(logit)], and the Intraclass correlation (ICC), are given.

Unconditional models	1950s–1978	CI 95%	PROB	1978–1986	CI 95%	PROB	1986–2000	CI 95%	PROB
Intercept	−1.64	(−1.9,0.3)	0.19	−0.45	(−1.1,0.3)	0.64	−0.96	(−1.7,−0.2)	0.38
Variance components									
Municipality	1.69	(0.7,1.5)		3.86	(2.1,5.5)		3.32	(1.8,5.2)	
Soil	9.69	(4.8,15.0)		2.46	(2.5,1.3)		1.5	(0.7,2.3)	
Intraclass correlation (ICC)									
Municipality	0.12			0.4			0.41		
Soil	0.66			0.26			0.19		

random-intercept models (3L-RIMs) for each period are shown herein (see on-line material Tables 2–4 for Partial 3L-RIMs).

3.3.1. Unconditional 3 level random-intercept models (Unconditional 3L-RIMs)

According to the models with no covariates and only random terms, the average probability of agriculture abandonment was low (negative logit coefficients); although it increased through time (Table 3). The main cause of this increase was related to a more dispersed spatial pattern of abandonment from 1978 onwards (Fig. 7A–C). The variance associated to random terms was relatively high, and varied with time (Table 3). The variance accounted by municipality level increased, whereas that associated to soils decreased (Table 3).

3.3.2. Full 3 level random-intercept models (Full 3L-RIMs)

During the pre-1990 period (until 1986, in our case) the rate of agriculture abandonment was high in colder and remote, steep

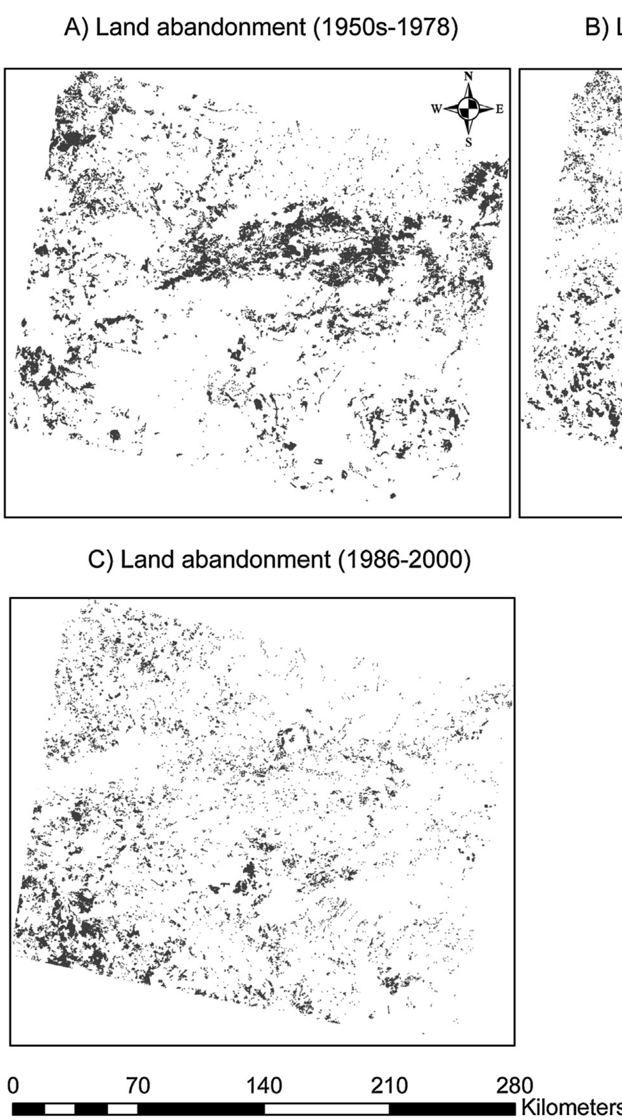

Fig. 7. Binary maps of the spatial patterns of agriculture abandonment during the study periods: 1950s–1978 (A), 1978–1986 (B) and 1986–2000 (C).

Table 4
Full 3 Level Random-Intercept Models (3L-RIMs) using only the significant fixed explanatory variables derived from Partial 3L-RIMs for explaining agriculture abandonment in West-Central Spain by pair of dates (1950s–1978, 1978–1986 and 1986–2000). Soil polygons (level 2) and municipalities (level 3) were considered random factors. Logit coefficients B estimated using the Bayesian approach, their confidence Intervals (CI) at 95%, their transformation in probabilities ([exp(logit)/1+exp(logit)], as well as the residual variance difference respect to the Unconditional 3L-RIMs and the Intraclass correlation (ICC), are given. Explanatory variables which were significant in their respective Partial 3L-RIMs but were not included in the Full 3L-RIMs are highlighted in grey.

Full model (all levels)	1950s–1978	CI 95%	PROB	1978–1986	CI 95%	PROB	1986–2000	CI 95%	PROB
(Intercept)	−3.77	(−5.4,−2.2)	0.02	−3.04	(−4.1,−2.0)	0.05	0.71	(−0.5,1.8)	0.67
Slope	+			1.04	(0.4,1.6)	0.74			
Solar duration				−0.56	(−1.1,-0.0)	0.36			
Min. temperature	–						0.71	(−0.2,1.5)	0.67
Cost distance to villages	4.06	(1.8,6.3)	0.98	+					
Igneous rocks	5.55	(3.1,8.4)	1						
Metamorphic rocks							+		
Soil depth				4.47	(3.1,5.7)	0.99	1.5	(−3.1,0.1)	0.82
Cambisol–Litosol–Regosol	4.41	(2.4,6.6)	0.99						
Agroforestry (1950s)	−1.8	(−2.7,−0.9)	0.14	−1.54	(−2.0,-1.1)	0.18	−1.41	(−2.1,-0.7)	0.2
Artificial (1978)				−0.62	(−1.0,-0.2)	0.35			
Deciduous (1950s)	1.2	(0.6,1.8)	0.77						
Mixed forests (1978)				1.28	(0.3,2.3)	0.78			
Open forests (1986)							0.69	(0.1,1.3)	0.67
Population density (1960)	−0.95	(−1.7,−0.1)	0.28						
Employees in primary (1981)	−1.8	(−2.8,−0.7)	0.14						
Unemployment (1983)				0.85	(0.3,1.3)	0.7			
Employees in services (1991)							1.11	(0.3,1.9)	0.75
Farms > 50 ha (1962, 1989)	−1.35	(−2.3,−0.4)	0.21				1.11	(0.4,1.9)	0.75
Holders > 55 years (1982, 1989)	1.13	(0.2,1.9)	0.76				0.64	(0.0,1.3)	0.65
Full-time farmers (1982)				−0.45	(−0.9,−0.0)	0.39			
Machinery (1982, 1989)	−1.40	(−2.2,−0.6)	0.20	−1.82	(−2.6,−1.0)	0.14	−1.84	(−3.5,−0.1)	0.14
Livestock (1989)				+			0.80	(0.0,1.6)	0.69
Variance components									
Municipality	1.09	(0.7,1.8)	(−35.4%)	1.68	(1.0,2.24)	(−54.4%)	1.68	(1.0,2.5)	(−49.3%)
Soil	1.92	(1.0,3.1)	(−80.2%)	1.52	(0.9,2.2)	(−38.2%)	1.17	(0.7,1.7)	(−22.1%)
Intraclass correlation (ICC)									
Municipality	0.17			0.26			0.27		
Soil	0.30			0.23			0.19		

areas, with shallow soils of low productivity, in municipalities with high occupation of wildland vegetation and low occupation of agriculture, and in municipalities with low population density, low proportion of agrarian population, and high proportion of land-holders older than 55 years, managing small farms with low mechanization level (Table 4). During the post-1990 period (from 1986 to 2000), the rate of agriculture abandonment was high in warmer areas, with shallow soils, low occupation of agriculture land-uses and high proportion of open forests, in municipalities with high number of employees in the services sector, high proportion of land-holders older than 55 years, and abundant large farms with low mechanization level (Table 4). Fixed factors at the three levels partially reduced the unconditional variance accounted for by municipality and soils contexts (Table 4). However, some variance linked to random effects remained after accounting for fixed factors (ICC around 45%) (Table 4).

3.4. Models accuracy

The Effron's pseudo-R^2 for Unconditional 3L-RIMs ranged from 0.96 to 0.72 and 0.76 for the three periods, indicating that soil and municipality contexts are of utmost importance to explain agriculture abandonment (on-line material Table 5). ROC and Kappa values were very high (greater than 97% and 0.84, respectively). Autocorrelation in residuals was low, and non-significant, in almost all models (on-line material Table 5). Partial and Full 3L-RIMs reached nearly the same explained variance than Unconditional 3L-RIMs, but with the inclusion of fixed explanatory factors, the AIC values and the portion of variance related to random factors was significantly reduced (on-line material Table 5). Using validation sampling data (25%), Full 3L-RIMs run rather well, with Effron's pseudo-R^2 values ranging from 0.90 to 0.57 and 0.60, respectively (on-line material Table 5). Comparatively, all 3L-RIMs (Partial and Full) performed better than fixed logistic models (GLMs) (on-line material Table 5). Overall, GLMs based on fixed municipality variables (level 3) explained more variance than those based on fixed soil or individual variables (levels 1 and 2) whose performance was lower as time went on (on-line material Table 5).

The producer's accuracy indicated that true stable (no change) agriculture lands were slightly best predicted (70–77%) than true abandoned lands (48–71%) due to the large overestimation of predicted abandonment (Fig. 8A). Similarly, the user's accuracy indicated that predicted stable agriculture lands matched rather well (89–92%) with real data than the predicted pixels of abandoned lands (22–49%); and these latter reduced their accuracy with time (Fig. 8B). The overall disagreement was around 25–31%, being the first period the best predicted (Fig. 8C). Quantity disagreement was around 11–21% (Fig. 8C), whereas allocation disagreement was relatively low during the entire studied period (10–14%) (Fig. 8C). Overall disagreement was directly related to the overestimation of abandoned lands by our models (Fig. 9A–C).

4. Discussion

4.1. LULC and socio-economic changes from 1950s to 2000: implications for fire-hazard

We have shown that landscape fire-hazard continuously increased from 1950s to 2000 due to hazardous LULC changes and stability of hazardous LULCs, both of which tended to occupy greater extension over time. The most important hazardous LULC changes during the entire period were agriculture abandonment and deforestation, the former being dominant until

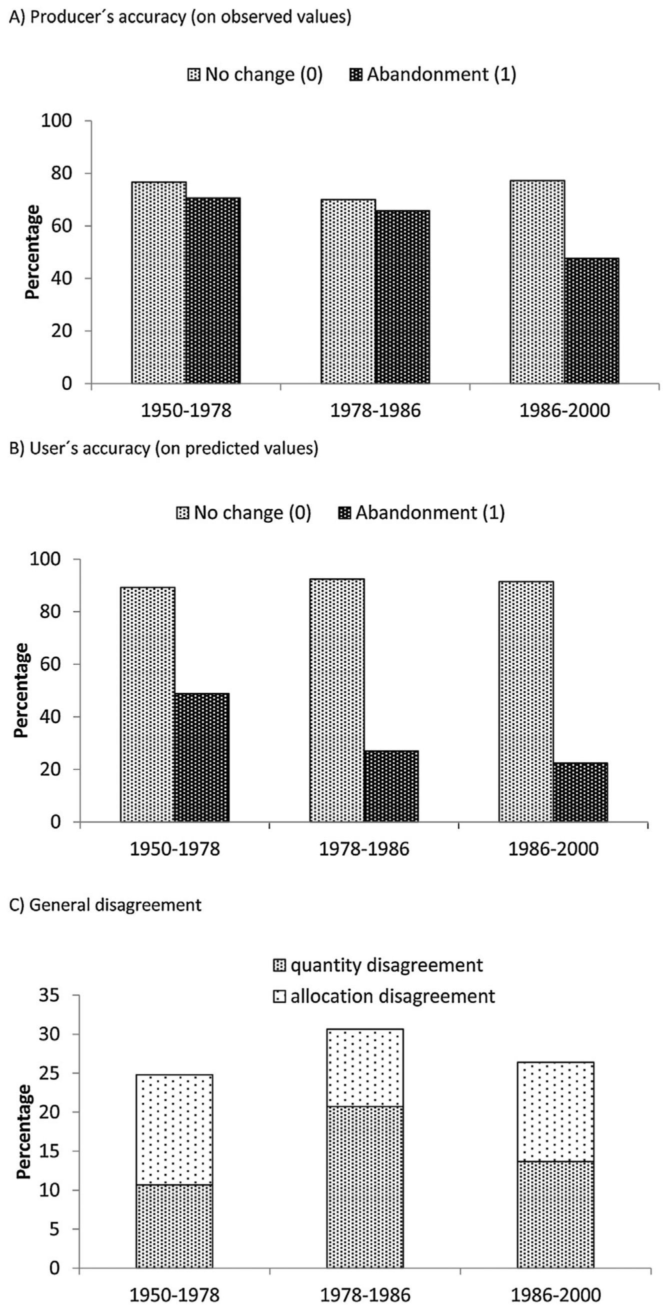

Fig. 8. Main accuracy measures of prediction maps derived from spatially explicit extrapolation of Full 3 levels random-intercept models (3L-RIMs) for each study period (1950s–1978, 1978–1986 and 1986–2000). (A) The producer's accuracy (spatial matching of observed values on predicted ones); (B) user's accuracy (spatial matching of predicted values on observed ones); and (C) general disagreement: allocation and quantity.

1986 (pre-1990 period) and the latter thereafter. The intense agriculture abandonment of marginal areas and the concentration of agriculture in the most fertile ones after the 1950s can be explained by the agriculture reforms derived from the Liberation and Stabilization Plan of 1959, and the socio-economic recovery of Central Europe after the IIWW, which encouraged emigration from rural areas (Casares, 2000). The 1982 agrarian census recorded the disappearance of about half million small farms between 1962 and 1982, whereas the large ones (>50 ha) increased (Goñi and Ayuda, 2006). Moreover, the number of farm tractors expanded more than tenfold between 1960 and 1982 (Corbelle-Rico et al., 2012); and the energy uses of wood suffered a considerable decline due to the incorporation of new sources of energy (butane gas) for domestic uses from middle 60s (Goñi and Ayuda, 2006). During the pre-1990 period, the most critical situation was that agriculture abandonment occurred very close to areas occupied by high flammable vegetation which suffered other hazardous LULC changes, like afforestation with conifer species and densification (Ceballos, 1966; Maestre and Cortina, 2004) increasing sharply landscape fire-hazard due to spatial continuity of high flammable vegetation over large extensions (García-Vega and Chuvieco, 2006; see Moreira et al., 2011 for a deep review). After such changes, wildfires started to grow (Moreno et al., 1998) and, deforestation and densification processes turned into more significant LULC changes, favoring also fire-hazard. Some studies applying fire resistance rules to LULC types at the scale of fire events (Viedma et al., 2009) or at both stand and landscape scales (González et al., 2005) showed that landscape resistance to fire was negatively influenced by the spatial contiguity of high-flammable LULCs, and positively influenced by the diversity resulting from fuel contrast at fire edges.

During the post-1990 period (from 1986, in our case), agriculture abandonment decreased, although continued being significant. In 1986 Spain entered in the European Economic Community (EEC), and the subsequent Community Agrarian Policy (CAP) reforms were carried out. These land reforms further continued the process of agricultural abandonment, due to the globalization process and parcel consolidation, although new abandoned lands did not resemble the initial ones (MacDonald et al., 2000; Busch, 2006). In the post-1990 period, the abandoned lands were mainly located in warm and dry areas close to settlements (Bakker and Veldkamp, 2012) with significant proportion of wildland vegetation (mainly open forests) increasing the wildland–urban interfaces, and consequently, the fire risk (Martinez et al., 2009).

4.2. The role of environmental and socio-economic factors on agriculture abandonment

Several theoretical models have been used to explain agriculture location and abandonment according to environmental factors and accessibility. For example, the Ricardian model which assert that environmental variables such as climate, topography and soil quality determine crop yields and consequently, its maintenance (Serneels and Lambin, 2001); and the von Thünen model which asserts that distance to markets diminishes land rents of fields located in remote areas favoring abandonment (Verburg and Overmans, 2009). Our main results indicated that during the pre-1990 period, the first abandoned lands were located in remote, cold steep areas, with important soil limitations according to the Ricardian and the von Thünen models, whereas the recent ones were in warm, less environmental constrained and accessible areas responding to socio-economic and political factors driving at other scales, that can amplify or attenuate the local driving forces of land-use change (Lambin et al., 2001; Barbier et al., 2010; Müller and Munroe, 2008; Baumann et al., 2011).

Although physical attributes of landscape and climate play a major role in determining the LULC patterns and changes, exogenous socio-economic forces can modify these relationships (Barbier et al., 2010). Following the Chayanovian model or consumer–labor ratio, socio-economic factors can serve as a proxy for the pressure on the land (e.g., population density) (Serneels and Lambin, 2001; Verburg and Overmars, 2009) and proxies of the potential opportunity costs of agricultural labor (Strijker, 2005; Gellrich et al., 2007). Equally, farm structure (i.e., farm size,land tenure, mechanization, aging of farmers and dedication, among others) have had marked effects on abandonment rates (MacDonald et al., 2000). Our results show that local

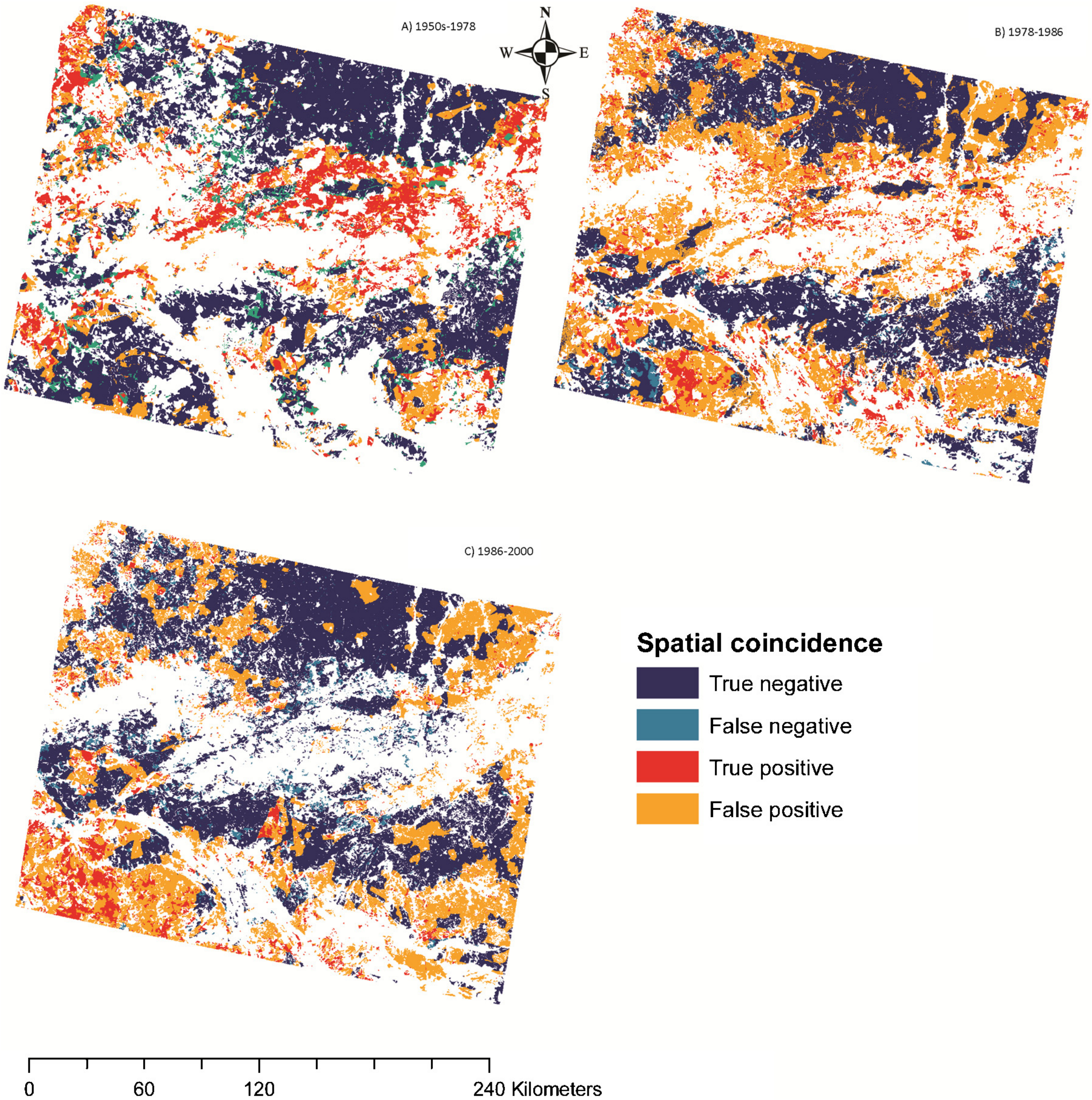

Fig. 9. Maps of predicted agriculture abandonment derived from the extrapolation of the Full 3 Levels Random-Intercept Models (3L-RIMs) for the three time steps studied: A) 1950s–1978, B) 1978–1986 and C) 1986–2000. The true negatives (0 in ground and 0 in predicted maps) are drawn in dark blue; false negatives (1 in ground and 0 in predicted maps) are in light blue; true positives (1 in ground and 1 in predicted maps) are in red; and false positives (0 in ground and 1 in predicted maps) are in orange. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

socio-economic factors at municipality level responded as expected according to the theoretical framework; although their role also changed through time. From 1950s to 1978, the first abandoned agriculture areas were those located in municipalities with low population density and low percentage of employees in the primary sector according to hypothesis of opportunity costs of land (i.e. the value of the alternative use) in the Chayanovian model (Geoghegan et al., 2001). In contrast, after 1978, municipalities with high unemployment rates and employees in services suffered higher rates of agriculture abandonment according to the hypothesis of opportunity costs of agricultural labor forces (Schmitz et al., 2003; Strijker, 2005; Gellrich et al., 2007). In contrast, the probability of abandonment was high for all periods in municipalities with low mechanization level and high proportion of land-holders older than 55 years. These results are in accordance with several studies in which adaptive capacity like technological and financial ability as well as individual farmers' welfare (i.e., farmers' age and health) have great influence on the probability of agriculture maintenance (MacDonald et al., 2000; Metzger and Rounsevell, 2006; Gellrich et al., 2007). Finally, other explaining socio-economic factors changed their role over time or were not significant. For example, livestock density was only significant after 1978, increasing the probability of agriculture abandonment; small farms showed high probability of abandonment until 1978, whereas large farms were the most abandoned in the last period (post-1990); or land tenure variables which were not significant during the entire period; as was expected according to other studies (Serneels and Lambin, 2001; Holland et al., 2014).

4.3. Models accuracy

3 Level random-intercept modeling (3L-RIMs) or GLMMs showed better performance than conventional fixed logistic models or GLMs for all set of variables and during all periods. The variance accounted by the random effects was very high and changed over time, indicating the importance of taking into

account the dynamic nature of spatial contexts on explaining agriculture abandonment. Fixed explanatory factors included in the Full 3L-RIMs were not able to eliminate all the variance linked to random effects (around 45% remained after accounting for fixed factors). Hence, the random-effects remaining represented the unmeasured variation across municipalities due to exogenous and random shocks (such as climate, policy and economic cycle fluctuations, etc.) (Munroe et al., 2002). The portion of variance accounted by soils context declined over time reducing the ICC or autocorrelation within soils units; whereas the portion of variance accounted by municipalities increased as well as the autocorrelation within municipality units. These results reflected that during the pre-1990 period, environmental factors were the most important drivers of abandonment; whereas in the post-1990 period, socio-economic factors turned more significant; although operating at other scales beyond the local ones.

Moreover, models of agriculture abandonment were better explained during the first period than subsequently. The lower explanatory power of models in the second period (1978–1986) could be related to different processes. On the one hand, part of abandoned lands was the result of the inherently dynamics of previous abandoned lands, without being subjected to any extrinsic driving forces. This is what Bürgi et al. (2004) termed as the "inherently dynamic landscape". The most obvious example of inherent dynamics is the natural succession on abandoned fields from pastures to shrublands. On the other hand, during that period started the disconnection of environmental and local socio-economic conditions from land-decisions by farmers, mainly due to the greater role of international land policies and global markets. In the case of the last period, the second process was clearly applicable.

Our spatially-explicit maps of agriculture abandonment indicated that stable (no change) agriculture lands were highly predicted and better than the abandoned ones, and that the accuracy of such predicted maps decreased over time. The overall disagreement was around 25–31%. In general, quantity disagreement was higher than allocation disagreement mainly due to the clear overestimation of abandoned lands by the Full 3L-RIMs.

5. Conclusions

We have shown that the main LULC changes occurred from 1950s to 2000 globally increased fire-hazard in the study area. During the pre-1990 period, agriculture abandonment occurred in mosaic mountain rural areas, with high proportion of wildland vegetation, that were also affected by other hazardous changes (deforestation, afforestation and densification), increasing sharply the landscape fire-hazard. During the post-1990 period, deforestation by forest fires dominated over agriculture abandonment, which occurred in warmer and more accessible areas near to settlements and with extensive open forests, increasing the wildland–urban interface and, consequently, the fire risk. Hence, from a management perspective, landscape fire-hazard can be reduced by managing successional processes after abandonment and introducing spatial discontinuities on high fire-prone LULC types to avoid the loss of landscape assets. Moreover, we have shown that the role of environmental constraints and several socio-economic variables on agriculture abandonment changed over time. During the pre-1990 period, local environmental constraints had stronger effects on abandoned lands, whereas during the post-1990 period, socio-economic factors driven at local and global scales turned more important. Due to the non-stationary and spatially heterogeneous nature of the driving forces of agriculture abandonment, hierarchical or multilevel models using long-time series should be applied in LULC models. On the other hand, models that allocate future LULC changes based on time-constant relationships between land use and environment or socio-economy should be re-evaluated, due to limitations in their ability for wide ranging extrapolations.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2015.04.011.

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