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Thomas Houet, Laurence Hubert-Moy

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MODELING AND PROJECTING LAND-USE AND LAND-COVER CHANGES WITH A CELLULAR AUTOMATON IN CONSIDERING LANDSCAPE TRAJECTORIES: AN IMPROVEMENT FOR SIMULATION OF PLAUSIBLE FUTURE STATES.

Thomas HOUET, Laurence HUBERT-MOY

Université de Rennes 2, Place du recteur Henri Le Moal, 35043 Rennes (France), COSTEL, UMR CNRS LETG 6554 / IFR 90 CAREN ; Thomas.Houet@uhb.fr

ABSTRACT:

The modeling and projecting of land use change is essential to the assessment of consequent environmental impacts. In agricultural landscapes, land use patterns nearly always exhibit spatial autocorrelation, that is due in large part, to the clustered distribution of landscape features as hedgerows and wetlands, and also to the spatial interactions between land uses types itself. The importance of such structural spatial dependencies has to be taken into account when conducting land use projections, more especially as landscape features influence the precision of land use and land cover classifications of remote sensing imagery. The objective of this work is to improve land-use projections in considering landscape features in the modeling process.

Cellular automata (CA), that provide a powerful tool for the dynamic modeling of land use changes, are a common method to take spatial interactions into account. They have been implemented in land use models that are able to simulate multiple land use types. This research adopts the spatial evolution concept embedded in CA and applies it to land-use and land-cover change study in one watershed inserted in an intensive agricultural area in Central Brittany, where water quality problems are often prevalent. A time-series of multi-scale and multi-temporal (including historical) satellite imagery and aerial photographs were used to determine both landscape features and the spatial characteristics and the temporal dynamics of land-use and land-cover over the period 1950 to 2003. Socio-economic and biophysical driving forces of observed changes have been established through a network of collaborating partners and agencies willing to share resources and eager to utilize developed techniques and model results. All these input data were compiled, analysed and assessed in using spatial statistical techniques to quantify spatial dependencies. Cellular automaton modeling procedures were then applied to develop a spatially -explicit model- based simulations of future land use and cover change in considering that the evolving landscape frame slows down or accelerates changes according to the cases. Summary of neighbourhood conditions of each target cell reveals the dynamic processes of land use change constrained with the landscape frame and thus enhance our understanding on transition rules, the heart of a CA, in different types of landscapes. Model performance was evaluated in removing landscape features and in using shorter series of past observations. The model including landscape features as hedgerows network or wetlands distribution simulated the land-cover and land use at a higher accuracy than the model excluding landscape information for the three studied watersheds. In summary, our results showed that introducing landscape features improves simulations of land-use and land-cover future states, which will contribute to build more plausible scenarios of future changes.

Key words: Land Use, Remote Sensing, Change detection, Spatial modeling, Cellular Automata (CA)

1. INTRODUCTION

Environmental impacts like water pollution have grown significantly during the last three decades in many regions, mainly due to agricultural intensification and associated farming practices, including

excessive use of nitrogen, pesticides and other soil amendments. In agricultural landscapes, management of landscape structures, such as wetlands or hedgerow systems, can contribute to the control of the non-point source pollution of surface and groundwater (i). Their evolution, e.g. removal of hedges or wetlands drainage, depends on the spatial interactions between land uses types itself (ii). Therefore, the importance of such structural spatial dependencies has to be taken into account when conducting land use projections.

The modeling and projecting of land use change is crucial to the assessment of consequent environmental impacts. Simulation of plausible human-influenced landscape changes following different scenarios may reveal strategic policies that should be modified to improve environmental issues like water quality.

Numerous methods are used to build scenarios of the future: narrative methods, models, hybrid methods using both qualitative and quantitative methods. Among models, the most often used are logistic-regression based models, multi-agents models, and cellular automaton. When they are used to simulate land-use/land-cover changes, projections are produced without taking in account the influence of landscape structure on land-use distribution (iii). The objective of this work is to improve land-use projections in considering landscape features modeling with a Markovian Cellular Automaton (M-CA) in a "current trends" scenario.

A "current trends" scenario supposes that management policies will not evolve and sudden spatial management (epiphenomenon) will not occur. Interest of such a scenario is to put on evidence the plus-value made with a contrasted scenario with which it would be compared.

Cellular Automaton (CA), that provide a powerful tool for the dynamic modeling of land use changes, are a common method to take spatial interactions into account (iv). Ulam and Von Neumann (1961) state that a CA is a cellular entity that independently varies its states based on its previous state and that of its immediate neighbors according to specific rules. It is a spaced dynamic system where the variable (ex. land cover), time and space are discrete. J. Ferber (v) considers CA as particular Multi-Agent System where agents are fixed and contiguous surface elements.

Markov chain is a convenient tool for modeling land use changes for setting "current trends" scenario, because it uses evolution from $t-1$ to t to project probabilities of land use changes for a future date $t+1$. However, a stochastic Markov model is not appropriate because it does not consider spatial knowledge distribution within each category and transition probabilities are not constant among landscape states (vi). An hybrid Markov-Cellular Automaton (M-CA) model is an interesting approach to model both spatial and temporal changes: (a) the Markov process controls temporal dynamic among the cover types through the use of transition probabilities, (b) spatial dynamics are controlled by local rules through a CA mechanism considering either neighborhood configuration and transition probabilities (vii), (c) GIS and remotely sensed data can be used to define initial conditions, to parameterize M-CA model, to calculate transition probabilities and determine the neighborhood rules (viii). They are particularly adapted when different processes interfere at different spatial and temporal scales.

They were mostly used for urban growth simulation (viii; ix; x; xi; xii) for monitoring urban sprawls and preserving natural ecosystems. They were also used as a spatial support system to assess socio-economic and environmental policies at national scale (xiii) or regional scale (xiv).

This study proposes to use this method in an agricultural context in which the temporal dimension (evolution of land-use/land-cover) is expressed by a Markovian process as a continuity of the current evolution and the spatial dimension (spatial modeling) considers the landscape structure to improve projected plausible future states in regard to the water quality.

2. METHODOLOGY

2.1. Study area

The study area is located in western part of France, in Central Brittany (Figure 1). The watershed of the Coët-Dan River, which surface area is 1200 ha, is characterized by intensive agricultural activities and thus favours an elevated prevalence of environmental exposures like an important non point source water pollution. Agriculture intensification led to important land-use changes, as well as modifications of landscape features like hedgerows removal or drainage of riparian zones.

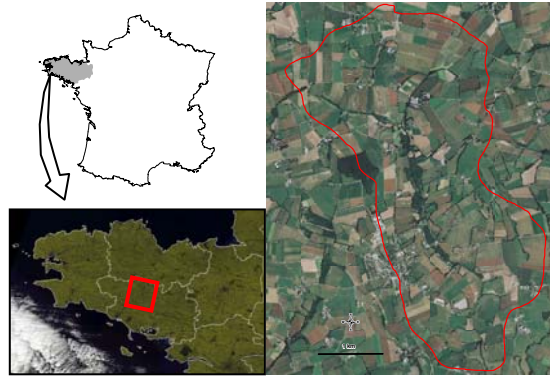


Figure 1 - Localization of the study area (The Coët-Dan watershed, Central Brittany, France)

2.2. Land use trajectories

A time-series of multi-scale and multi-temporal including historical satellite imagery and aerial photographs were used to determine both landscape features and the spatial characteristics and the temporal dynamic of land-use and land-cover over the period 1950 to 2003 (Figure 2).

Until the 60's, agriculture had many aspects of a self-sufficiency system where crops (cereals, potatoes) were the dominant products. During the 70's, the watershed of the Coët-Dan river followed changes that occurred in regional agriculture, in increasing milk production and consequently extending grassland (200 ha in 1960, 394 ha in 1972). From the end of the 70's until the beginning of the 80's, intensification of milk production explains the growth of grassland (454 ha in 1981) but a few farmers had started to change partially or entirely their production for mixed milk/pork or pork production. Then, the national restriction of milk production (1982/82) and the reform of the CAP (Common Agricultural Policy) of the EEC (European Economic Community) both cause cultures increasing to the detriment of grassland (305 ha in 1999). Therefore, since the 80's the watershed of the river Coët-Dan is still a very intensive farming area, but with a quota-limited dairy production, inserted in what is called "Le modèle agricole breton" (xv).

Synthesis of the evolution of the different land cover classes identified from remote sensing data is shown in Table 1.

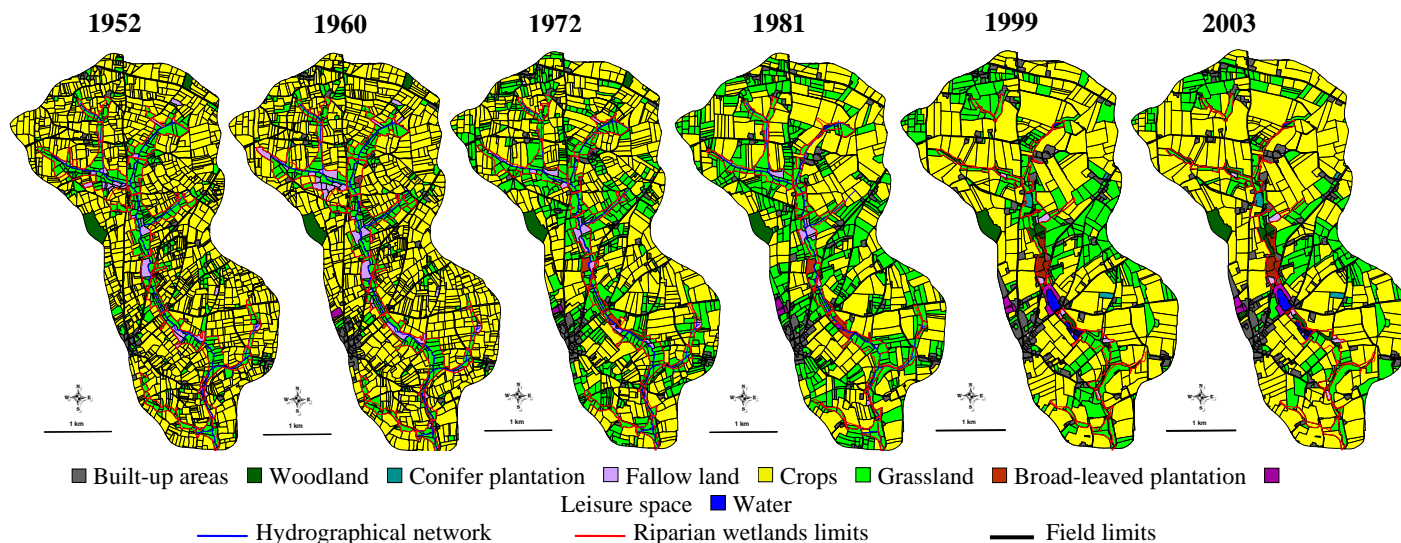


Figure 2 - Mapping long term land use trajectories (1952-2003)

Table 1 - Changes in land use and land cover classes in ha (1952-2003)

Years	Roads	Built-up areas	Woodland	Fallow-land	Crops	Grassland	Leisure space	Water
1952	40.5	26.1	14	26.6	877.6	220.4	0	0
1960	40.1	40.1	12.7	37.6	874.7	198.1	1.7	0
1972	40.5	49.2	21.8	19.9	676.4	395.6	1.3	0
1981	35.8	59.3	22	10.2	616.6	457.1	3.3	0.4
1999	35.1	76.2	36.8	7.7	730	304.8	7.8	6.2
2003	35.1	81.6	42.1	7.7	791.7	232.6	7.8	6.2

In the same time, riparian wetlands and hedgerows had regressed considerably (Table 2). Over the observational period (1952-2003), spatial dependencies between land use / land cover and landscape features have considerably evolved. In the 50's and 60's, grassland were essentially localized in riparian wetlands areas because of the hydromorphic constraints for crops production. With the modernization of agriculture through the development of milk production system, grassland located in riparian zones were less managed and exploited by farmers. This led to fallow land and woodland extension in these areas. Grassland in non-wetlands and corn extension are correlated with the size of fields: larger fields are set as the milk production system is spreading. Both local planning authorities and individual initiatives lead to the process of grouping land areas, with an important decreasing of hedgerows network, especially those located along crop fields distant from the farmstead. However, planning policies have changed in the 90's, when the effects of landscape features on water quality and erosion have been highlighted, leading to preservation and restoration program actions. Thus, spatial dependencies (spatial autocorrelations) changed with time, and landscape features influence on land use and land cover distribution is noticeable. For example, riparian zones are less extensively used by farmers and woodland has become dominant; small fields are often covered with grassland (63% of fields less than 1ha and even more when the field is surrounded by hedgerows). Most of significant changes in landscapes occurred before 1981, and only slight modifications are observed since then in the riparian wetlands, which still decrease, but more slowly.

Table 2 - Evolution of landscapes structures (riparian wetlands, hedgerows density) in 1952-1999 period

Years	Riparian wetlands area (in ha)	% of riparian wetlands / total area	Hedgerows density (in m/ha)
1952	177.2	14.8	159.3
1960	173.7	14.5	154.3
1972	137.3	11.4	122.9
1981	105.9	8.8	60.0
1999	74.8	6.2	53.7

2.3. The M-CA based model

The model used to project land use and land cover evolution from GIS/remotely sensed data introduces spatial knowledge, with respect to a transition probabilities matrix and a transition area matrix, and in considering spatial interactions explicitly through the definition of the transitions rules.

MARKOV and CA_MARKOV functions available in Idrisi Kilimanjaro software were used in this case.

2.3.1. Transition probabilities matrix / Transition area matrix

The M-CA based model is processed for two dates and produces:

A transition probabilities matrix which determines the likelihood that a cell or pixel will move from a land-use category or class to every other category from date 1 to date 2. This matrix is the result of cross tabulation of the two images adjusted by the proportional error and is translated in a set of probability images, one for each land-use class.

A transition area matrix which records the number of cells or pixels that are expected to change from each land-use class to each other land use class over the next time period. This matrix is produced by multiplication of each column in the transition probability matrix by the number of cells of corresponding land use in the later image.

This Markovian model also outputs a set of conditional probability images. Taken from the transition probability matrix, the images report the probability that each land cover type would be found at each location, in the next future phase, as a projection from the later of the two land-use/land-cover images (xvi).

Projection of land use and land cover is carried out for 2015 and 2030 in using a short time and a long time trajectory (respectively 1999-2003 and 1981-1999). Both trajectories are taken into consideration to evaluate the influence of the length of the temporal trajectory in modeling plausible land use and land cover future states. In the case of the long time trajectory, the 2015 and 2030 transition probabilities matrix are built from the land-use/land-cover images of 1981 and 1999, as far as all the period is characterized with the same farming production system, involving the spatial dependencies with the landscape features in a similar way (Tables 3 and 4); For the short trajectory, the 2015 and 2030 transition probabilities matrix are built from the land-use/land-cover images of 1999 and 2003.

Table 3 - Transition probabilities matrix used for projections of land use and land cover in 2015 for the long trajectory (1981-1999)

	Roads	Built-up area	Woodland	Fallow land	Crops	Grassland	Leisure space	Water
Roads	0.855	0.027	0.002	0.002	0.066	0.044	0.002	0.000
Built-up area	0.021	0.869	0.000	0.000	0.047	0.058	0.004	0.000
Woodland	0.008	0.016	0.721	0.004	0.046	0.092	0.058	0.057
Fallow land	0.001	0.000	0.615	0.121	0.000	0.263	0.000	0.000
Crops	0.002	0.008	0.001	0.001	0.748	0.237	0.002	0.001
Grassland	0.002	0.035	0.027	0.014	0.539	0.370	0.005	0.008
Leisure space	0.002	0.012	0.021	0.000	0.000	0.000	0.823	0.141
Water	0.000	0.013	0.258	0.036	0.129	0.346	0.015	0.203

Table 4 - Transition probabilities matrix used for projections of land use and land cover in 2030 for the long trajectory (1981-1999)

	Roads	Built-up area	Woodland	Fallow land	Crops	Grassland	Leisure space	Water
Roads	0.776	0.042	0.005	0.003	0.111	0.060	0.003	0.001
Built-up area	0.030	0.802	0.002	0.001	0.089	0.070	0.005	0.001
Woodland	0.013	0.029	0.572	0.007	0.113	0.125	0.082	0.058
Fallow land	0.006	0.015	0.565	0.021	0.149	0.185	0.027	0.030
Crops	0.003	0.020	0.007	0.004	0.691	0.268	0.004	0.003
Grassland	0.004	0.050	0.048	0.008	0.628	0.254	0.009	0.007
Leisure space	0.003	0.021	0.061	0.004	0.012	0.037	0.722	0.141
Water	0.002	0.029	0.282	0.019	0.311	0.266	0.029	0.061

2.3.2. Transition rules: the suitability maps

The transition rules result from association of socioeconomic-biophysical factors and spatial dependencies (e.g. distance of a field from the farmstead) that contribute to land use and land cover changes.

Socio-economic and biophysical driving forces have been determined through a network of collaborating partners and agencies. Then interrelations between the factors of change as well as spatial dependencies between land-use types and landscape structures have been identified and quantified.

Transitions rules are produced for each land cover class through a suitability map built from spatial dependencies and driving forces of change. Suitability maps represent the probability (range from 0 to 255) of a pixel or a cell to belong to the corresponding land-use type. Each suitability map highlights where changes are plausible for one land-use category in the future. Changes could not occur in some specific areas (e.g. urban areas can't become crops) or some land cover classes are not expected to change in a "current trends" scenario (e.g. some water areas). Thus, the set of all the suitability maps used to project and model a foresight scenario integrates transition rules and spatial knowledge.

2.3.2.1. Suitability maps without taking into account landscape features

In some cases, suitability maps correspond to boolean images where land cover types will not change (Figure 3).

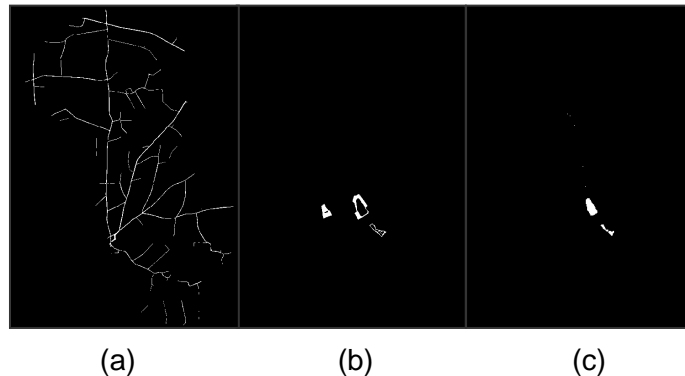


Figure 3- Suitability maps of (a) Roads, (b) Leisure space, (c) Water

Woodland, Fallow land, built-up areas, crops and grassland may evolve in the future. Their projection in the next future phase is processed in considering specific spatial rules (driven factors of changes and their respective weight) except for some areas where constraints are set.

1. The built-up area suitability map (Figure 4a) constrains future “urban” development anywhere except on actual roads, leisure space, water surfaces, woodland and within 50m from the stream. The most important factor that contributes to the “built-up” category expansion is the proximity to the village. Then, equal-weighted factors are recorded: “Proximity to main roads”, “Proximity to existing built-up areas” and “Field size”.
2. The woodland suitability map (Figure 4b) is built in considering that woodland can’t evolve towards existing roads, built-up areas, leisure space and water. Woodland will preferentially progress to the detriment of land fallow land and grassland and next to existing woodland.
3. The fallow land suitability map (Figure 4c) is processed in taking in account that they will not change to existing roads, leisure space, water surfaces and built-up areas. Factors that influence the distribution of fallow lands are the field size, the presence of grassland and fallow land, the proximity of woodland and the soil hydromorphy.
4. The crop and grassland suitability maps (Figures 4d and 4e) allows crops extension except on existing roads, leisure space, water surfaces and built-up areas. The most important factor of change is the production system type. For each production system the probability of changing from another land-use category to crops is determined (1) at the farm scale; (2) at the field scale; (3) according to the size of fields; (4) according to the distance from each field to the farmstead. Because of non-exhaustive field’s farmer affiliation, a mean value corresponding of the overall land cover class change attribute is attributed to the fields where data are missing.

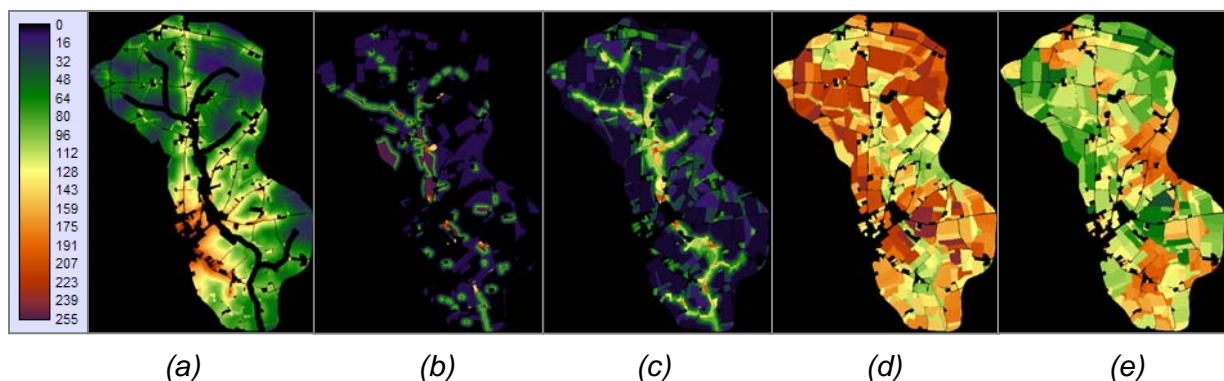


Figure 4 - Suitability maps of (a) built-up areas, (b) woodland, (c) fallow land, (d) crops and (e) grassland

They represent the probability (range from 0 to 255) of a pixel or a field to belong to the corresponding land-use/land-cover types.

2.3.2.2. Suitability maps taking into account landscape features

Landscape features as riparian wetlands influence land cover changes at local scale because spatial factors (e.g. distance) could constrain their usage (ii) which varies with the production system adopted.

Suitability maps for roads, leisure space and water surfaces do not differ from the suitability maps shown in figure 3.

The built-up area suitability map (figure 5a) takes into account riparian wetlands as non possible extension areas for built-up areas growth.

The other suitability maps (figures 5b, 5c, 5d and 5e) integrate the observed differences in land cover change inside and outside the riparian zones. For example, the woodland suitability map considers land-use change from fallow land to woodland between 1981 and 1999 occurring exclusively inside the riparian zones; the fallow land suitability map integrates also changes from grassland and cultures to fallow land inside the riparian wetlands. It also permits, when data are missing, to determine finer probability values for grassland and cultures suitability maps for fields located inside and outside the riparian zone.

Thenail C. and Baudry J. (xvii) have shown that hedgerows network (bocage) as also to be taken into account in projecting land use and land cover. Thus, a field with a “woody perimeter” (part of the perimeter occupied by a woody hedgerow) is more expected to be covered by grassland (see 2.2.).

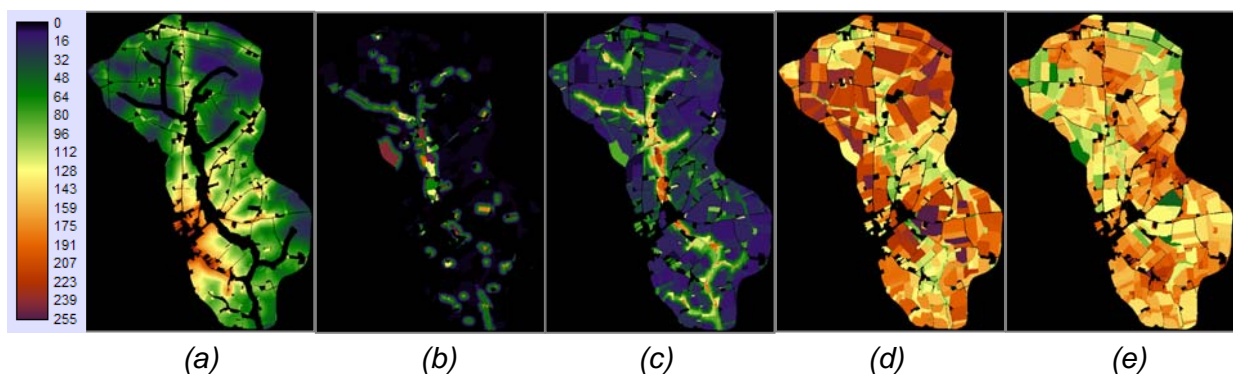


Figure 5 - Suitability maps of (a) built-up areas, (b) woodland, (c) fallow land, (d) crops and (e) grassland in considering landscape features -riparian wetlands and hedgerows network- They represent the probability (range from 0 to 255) of a pixel or a field to belong to the corresponding land-use/land-cover types.

2.3.3. The M-CA process

The M-CA method uses an iterative process of reallocating land cover until it meets the areas totals predicted by the markovian chain analysis. The predicting land-use/land-cover process specifications are:

The number of iteration (n) is determined by the projection in the future (number of years);

The model uses a contiguity filter to develop a spatially explicit contiguity-weighting factor to change the cells based on its previous state and those of its neighbors (xvi). This is a mean filter pools with a Boolean mask filter that will be then multiplied with the suitability map of the class land cover considered. By default, the filter size is a 5x5 kernel. The purpose of this filter is to down-

weight the suitabilities of pixels far from existing areas of that class, thus giving preference to contiguous suitable areas;

Within each time step, the re-weighted suitability maps are run through a multi-objective land allocation (MOLA) process to allocate $1/n$ of the total of land cover predicted to change from one land-use/land-cover change category to another. MOLA process resolves land allocation conflicts by allocating the cell to the objective for which its weighted suitability is highest, thus reducing the amount of area to be assigned to each land cover class. As a result, any particular objectives (land-use/land-cover type which compete) will lose some conflict cases and will thus need to accept cells of lower suitability weight (xvi). In the M-CA process, each land cover is considered in turn as a host category and all other land-use/land-cover classes act as claimant classes and compete with the host class for land. At the end of each iteration, a new land cover map is built with overlaying all results of MOLA operation;

The next iteration uses the new land cover map as input on which will pass the CA component to allocate another $1/n$ predicted areas totals.

3. RESULTS

Validation of the projected land use and land cover states for 2015 and 2030 is an important but difficult stage. Evaluating precisely the projected images over decades is obviously not possible. The purpose of this work is to highlight influence of landscape features in land-use/land-cover trajectories to build more plausible future states in different scenarios of evolution.

3.1. Influence of landscape features

Figure 6 shows the results of the modeling M-CA process with and without the integration of the landscape features, that is riparian wetlands and hedgerows in this case.

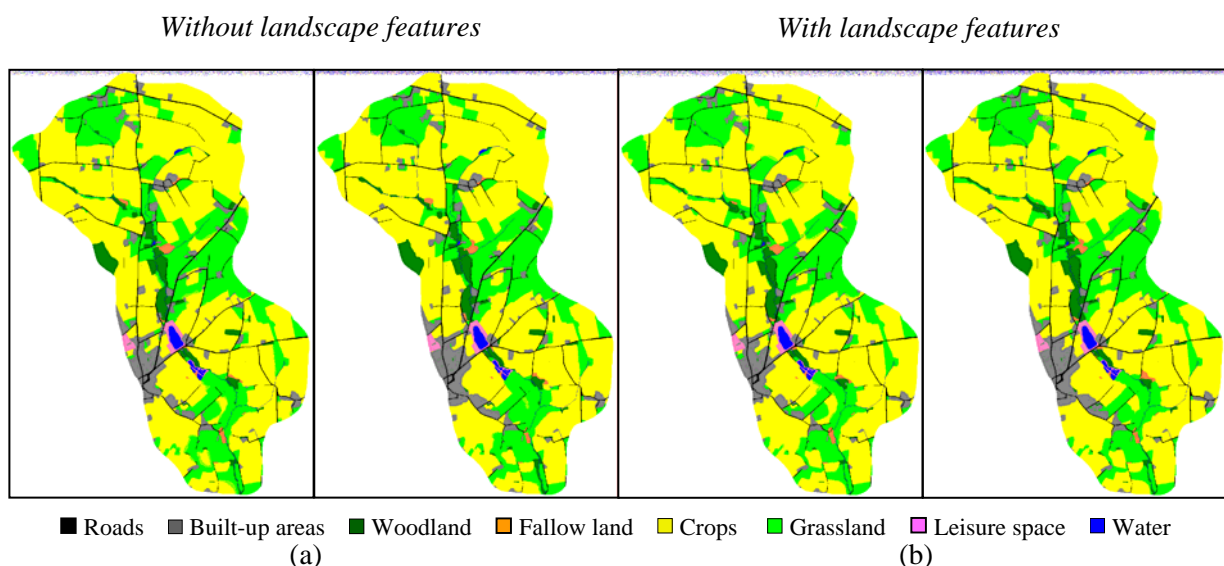


Figure 6 - The projected land use and land cover for 2015 and 2030 with a long time trajectory – 1981-1999– (a) without considering (b) or in considering the landscape features (riparian wetlands and hedgerows network)

First, results highlight the good representation of the agricultural landscape patterns, respecting the field geometry (Figure 6). Modeling the transition rules at the field scale through suitability maps which integrate both local spatial dependencies (e.g. field size) and driving factor at larger scale (e.g. farm production), appears as a necessary step to reconstitute the landscape pattern with a CA based on contiguity relations to model changes.

Secondly, the two maps of plausible future states in 2015 show very little spatial changes. Because of the M-CA process, that respects the predicted changes (see 2.3.3) the grassland and crops totalize respectively 301 ha and 721 ha for both cases “without landscape features” and “with landscape features”. Comparatively to the land-use/land-cover state in 1999 (Figure 2), these maps confirm the following trends: (1) the landscape closing up by woodland and fallow land in the riparian areas; (2) the grassland concentration around the farmsteads. In 2030, the closing up of riparian areas increases slightly. An important result concerns the land-use/land-cover modeling inside and next to the riparian zone. Without considering landscape features, the northern riparian areas are contiguous to cropland, whereas fields of grassland are surrounding them when taking landscape features in consideration in the modeling process (Figure 7). Considering riparian wetlands provides more plausible results, because of policies requiring meadows along the river network for the prevention against surface runoff and soil erosion (Figure 7).

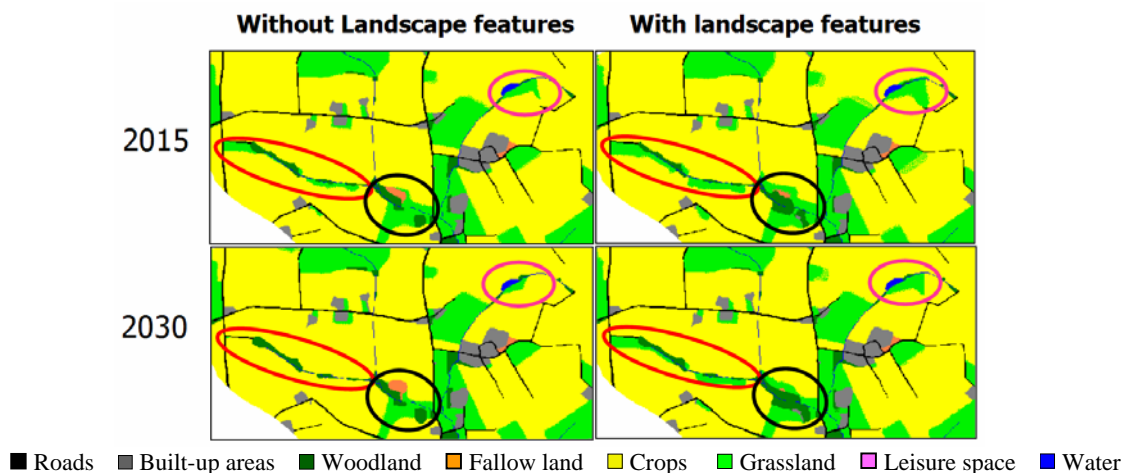


Figure 7 – Focus on the projected land use and land cover for 2015 and 2030 with a long time trajectory –1981-1999– inside and next to the riparian zone: In Red, over-estimation of crops without considering landscape features because of current policies ; in Pink, over-estimation of crops without considering landscape features because of hedgerows surrounding the field; in Black, different ways of closing-up in riparian zone.

While hedgerows network seems to have little influence on land-use/land-cover modeling, the increase of cropland concentration highlights the areas where removing hedges would accelerate soil erosion and surface runoff. Since the middle of the 70's, important hedgerows removal has been done by farmers to increase arable lands. Then, projected land-use/land-cover maps, with existing hedgerows network distribution, appear as interesting tools for water quality preservation and/or restoration.

3.2. Influence of land-use and land-cover trajectories of evolution

A comparison of the projected land-use/land-cover simulations for 2015 and 2030 with a Short Time (ST) and a Long Time (LT) trajectories considering landscapes features in the modeling process has been performed.

For both trajectories, the two major land-use/land-cover classes (crops and grassland) slow down their evolution and are almost stabilized during the last 25 years, even if the ST trajectory is higher than the LT trajectory (Figure 8a). In the same time, woodland and urban areas increase more significantly when considering the ST trajectory. Other land-use/land-cover classes do not really change.

The ST trajectory seems to be less adapted than the LT one's because it considers inter-annual changes (due to crop successions) to project land-use/land-cover in long term, whereas the LT

trajectory considers general trends of land-use/land-cover evolution, that partially smoothes changes coming from crops successions. But it shows that within a general trend of evolution, rapid inter-annual changes could occur. Therefore, land-use/land-cover changes may be easily over-estimated or under-estimated in a ST trajectory, but also a little under-estimated in a LT trajectory. For example, climate hazard as a drought may father brutal changes in cultures/grassland estimations from a year to another. It has to be taken into account in the process modeling. Figure 8b represents land-use/land-cover simulations obtained from the ST trajectory. The riparian zones are continuously covered by woodland and are under pressure of land-use and associated farming practices in upland areas. The salt and pepper effect located in the northern part of the simulations points out the inability of the M-CA model to allocate all the land-use/land-cover areas expected to change in the next years. It proves an over-estimation of crops and grassland classes by the use of a short time trajectory of evolution.

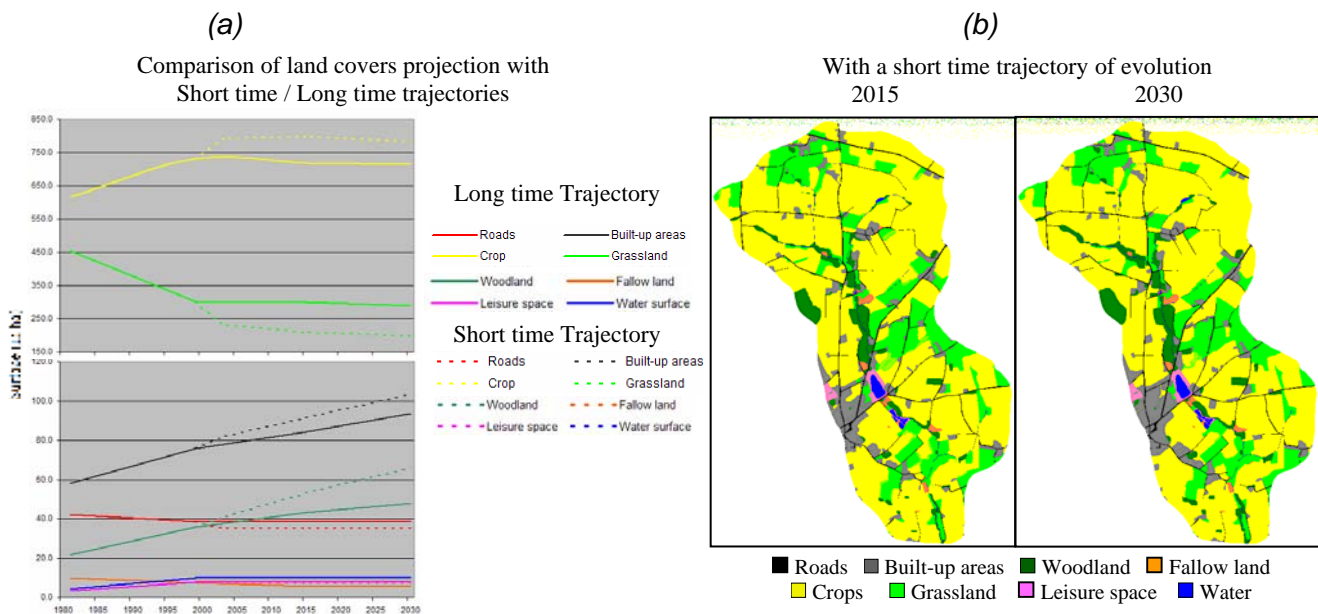


Figure 8 - Influence of land use and land cover trajectory of evolution; (a) Comparison between Short-Time (1999-2003) and Long Time (1981-1999) trajectories; (b) Projected land-use/land cover simulation for 2015 and 2030 using the Short-Time trajectory (1999-2003) and taking into account landscape features.

4. CONCLUSION

The approach described in this paper shows the influence of spatial relationships between landscape features and land-use/land-cover changes, which have to be taken into account to improve projections of plausible future states. Restoring water quality could be helped by the identification of areas potentially at risk in long term projections for soil erosion and surface run off.

A first interest in using a CA to model land-use/land-cover plausible states is the possibility of integrating multi-scaled factors of landscape evolution. The two scales used to project land-use/land-cover for 2015 and 2030 in our case are the field scale and the farm scale. An intermediate scale, the islet scale (a cluster of adjacent fields of a farm), could be integrated in the process modeling to improve the land-use/land-cover projections, as it appears that changes occur at this scale (xvii).

Limitations of the M-CA model rely in the fact that it is computationally exigent and land-use/land-cover is considered as a component of a cyclic phenomenon (crops successions) with an occurrence probability. Thus, the modeling is made considering a probability matrix of plausible future state respecting a general trend for each land-use/land-cover type. Taking into account crop successions in a new CA model -currently in development- may constitute a possible way to increase simulation accuracy in a LT trajectory of evolution, but also to discriminate different types of crops.

This model will also be able to consider future evolution not only as a “current trends” scenario, but following different strategies and policies. Though, “current trends” scenarios relatively easy to implement with a M-CA can be used as reference in comparison with contrasted scenarios.

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