Cells but not cities: building a cellular automata land use model for the Doñana natural area, SW Spain.

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Introduction:
The Doñana Natural Area (hereafter Doñana) is a series of interconnected ecosystems of outstanding importance for biodiversity at the mouth of the River Guadalquivir in the Spanish Autonomous community of Andalucía, South West Spain. A National Park since 1969 and recognized by UNESCO as a world heritage natural property since 1994, Doñana has nevertheless suffered serious degradation and loss of large areas of marshland, dune and coastal habitat since 1950, through tourism development, intensive agriculture and afforestation of fast growing non-native tree species (e.g. Eucalyptus), and corresponding contamination and over-exploitation of its aquifer. Despite a series of measures aimed a promoting sustainable development, this important natural area remains highly threatened by the modern development paradigm of growth without limits [1]. In the following communication, results are presented from the application of a Cellular Automata (CA) model, built using the Metronamica® software application, developed by the Research Institute for Knowledge Systems (RIKS), of Maastricht, Netherlands, to Doñana. The research was carried out under the remit of the DUSPANAC research project (funded by the Autonomous Body for National Parks (OAPN) on behalf of the Spanish Environment Ministry). The project is ongoing, but nevertheless, three important objectives have been already achieved: Preliminary land use change analysis [2]; Stakeholder engagement for determination of model parameters [3] and construction of a pilot model, subject of the present communication.

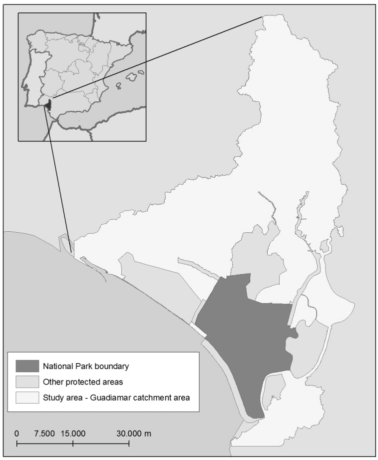
Aims of the paper:
1. to provide a brief background to the application of CA-type models to modelling of natural areas.

2. To explain the modelling procedure employed, which may serve as a prototype for future land use modelling of natural areas.

3. To review the lessons learnt from the pilot model, and the steps which will need to be taken in future to improve the model and its applicability to decision support in the Doñana natural area.

The contribution of CA to land use modeling

Most modern-day applications of CA are based on the work of von Neumann in the late 1940's, posthumously published as *The Theory of Self-Reproducing Automata* [4]. The application of CA to land use is usually attributed to the geographer Waldo Tobler, who developed the foundations for a raster-based "cellular geography" [5] . Early CA land use models were aimed principally at modeling urban growth (e.g. [6]), but the discipline has since expanded its scope to take in non-urban applications (e.g. [7]), and has increasingly moved beyond pure description and explanation of patterns of land use growth and change into, for example, policy recommendations for greener growth and sustainable development (e.g. [8]), integrated decision support and participatory approaches [9] and natural hazard assessment [10]. While CA techniques have been applied to the study of a wide range of natural and ecological phenomena [11], studies of land use change in natural areas using CA-type models are less common, principally because the pattern of cellular evolution exhibited in a typical CA land use model is particularly appropriate for modelling urban land use change. However, some notable examples do exist. White *et al* [12] constructed an integrated CA model for the Caribbean island of St Lucia, designed as a decision support tool to explore possible environmental, social, and economic consequences of hypothesized climate change. In this work (SimLucia), evolution of natural vegetation, forest and agriculture was actively modelled [12]. In a more recent study, Moreno e*t al* [13] incorporated a CA known as SpaSim to model the dynamic evolution of a forest preserve in Venezuela using land cover classes such as forest, forest plantation and agriculture. The work aimed to understand the land cover dynamics that have occurred in the reserve, simulate the effect of land use policies on the reserve, and evaluate their effect on sustainability of the forest reserve.



Map 1: Doñana study area

CA modeling and Doñana

In Doñana, the researcher is confronted with two worlds, two opposing poles, of conservation versus development. The development boom, principally based on tourism and intensive agriculture, has transformed the region over the last 60 years, from one of the most impoverished in Spain to the point where per capita income is above the national average [1]. Conversely, there has also been increasing recognition of the importance of Doñana and ever greater efforts made to protect it. Unfortunately, over the same time period, areas outside the limits of the protected space have become increasingly degraded and are clearly affecting the protected area itself (e.g. [14]. The conservation versus development model has thus entered a crisis phase. However, though it is quite easy to see what the problem might be (development that favors the regional economy in the short term but destroys an important natural area), it is not at all easy to bring about a solution. CA land use models are powerful tools for understanding this type of complexity, as they allow actor decisions to be represented as land use consequences in the territory. The CA neighborhood rules of attraction and repulsion are ideal for representing the competition and pressure for the same land use location that is so acute in, and so characteristic of, the Doñana natural area.

Methods

Drawing on historical patterns of land use change since 1990 detected by cross tabulation analysis of corine land cover maps [2], together with information gathered in participatory workshops, an initial, or 'pilot' CA model was developed. The pilot model was an essential precursor to the main modeling phase and development of future scenarios as it allowed for the testing of software, data and methodology prior to commitment of extensive resources.

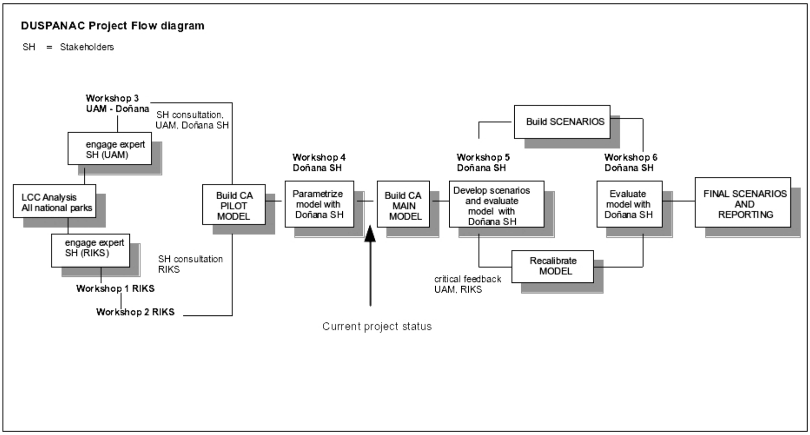


Figure 1: the Modeling chain

The modeling software that we used in this project is part of a suite of software, a tool kit called Geonamica®. Metronamica®, the land use modeling component of Geonamica®, is a *geographical* land use model (*sensu* Tobler [5]), operating in a graphical application environment for the windows platform. At the core of the model is the transition potential (TP) computation which determines the future state of the cells (change or no change). TP is calculated as a function where a set of endogenous factors interact to update the state of the cell in every time step (one year). These factors are *neighborhood rules*, which determine the relationship between different land use classes in terms of attraction and repulsion; *accessibility* to facilitate or constrain land use conversions depending on the distance from the cells to the network; *zoning*, that is, extant land planning regulations; a set of biophysical *suitability* parameters; and a *stochasticity* variable in order to avoid over-determinism in the model. This TP function determines the likelihood of each cell in the model to change from one use to another.

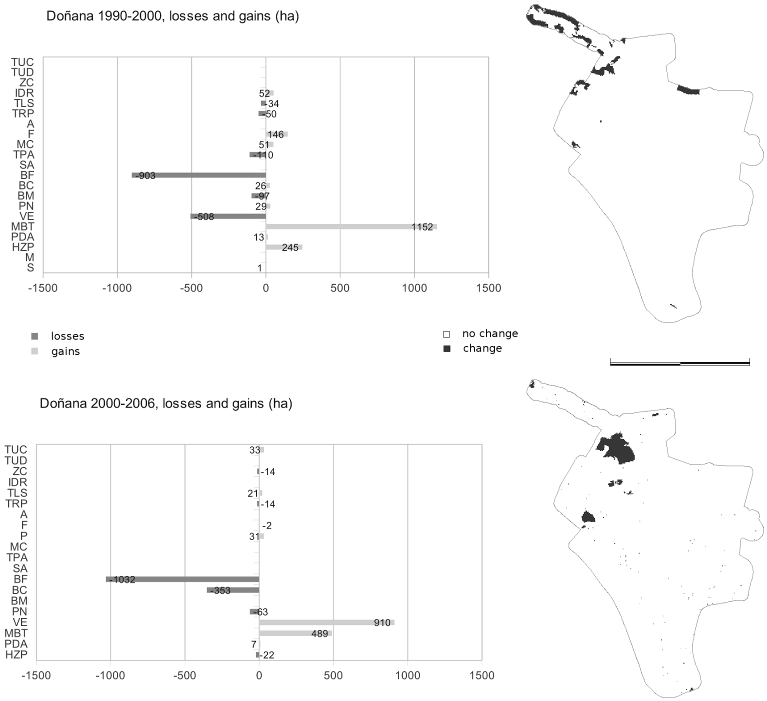
Construction of the model followed the procedure defined by RIKS [15], this can be briefly summarized as follows:

1. Analysis of dynamics of land use/cover change (LUCC) in the territory to be modeled.
2. Definition of activity types according to LUCC dynamics observed: land use classes must be divided into three groups, vacant (passive, does not grow but is occupied by other land uses - e.g. non-irrigated crops) function (active, dynamic, will grow and occupy other land uses, e.g. urban residential) and feature (static, restrictive, will not change and cannot be occupied by other land uses - e.g. water)
3. Introduction of initial land use map M1 (corine 1990), classified according to activity types.
4. Introduction of second land use map M2 (corine 2000), for model calibration.
5. Introduction of land use demand for function land use classes for calibration, taken from M2
6. Establishment of parameters (neighborhood rules, accessibility, suitability, zoning)
7. Simulated map MS2 for technical calibration
8. Other simulations, scenarios etc.

After all parameters have been set (steps 1-6), transition potential is calculated for all of the maps in the model, and then applied to M1 to produce a simulation of change over the period between M1 and M2, expressed as a new map, MS2 (step 7). In this way, the first part of the model calibration begins, which we refer to here as *technical calibration.* Once technical and empirical calibration (see final section) have been completed satisfactorily, land use simulations based on future scenarios can be developed.

Technical calibration procedure

Technical calibration of the model is defined here as the process of obtaining an acceptable degree of fit between the simulated map, MS2 and the real map, M2 of the territory at the second date (in our case, the year 2000). The degree of fit gives us a guide to the reliability (confidence level) of the model with respect to the land use change trends observed in the territory.



[Figure 2: land use changes in Doñana, 1990-2006]

Land use change dynamics and activity types:

With reference to figure 2, the principal LUCC in the territory observed from map comparison between 1990, 2000 and 2006 can be summarized as follows:

1. Significant expansion of fruit and berry plantations (F) between 1990 and 2000 (Intensive cultivation of citrus and strawberry). Principal contributing land uses (in order of greatest to least contribution) were grassland (PN) (55 ha), other irrigated crops (TRP) (44 ha), non-irrigated crops (TLS) (30 ha) and sclerophyllus vegetation (VE) (15 ha). Other irrigated crops have also increased, taking 29 hectares and 12 hectares from VE and shrubland (MBT) respectively. It is clear that these changes represent agricultural intensification; they have all occurred outside the national park, just inside the area which is also excluded from the zone of lesser protection comprising the natural park. A 50 ha area of formerly irrigated land (TRP) in 1990 had become crop mosaic (MC) by 2000. Thus, in terms of *land use dynamics* (neighborhood rules), we see that TRP, PN, TLS and MBT are likely to be sensitive to occupation by F, and that MBT and VE are sensitive to occupation by TRP. Clearly, given the location of the new

intensive cultivation, *zoning* will be very important in the model. F and TRP, and probably MC as well, need to be designated as function activity types in the model to reflect their susceptibility to increase, taking over other land use types.

2. Important increase in MBT between 1990 and 2000, taking 912 hectares from broad-leaved forest (BF), and 96 hectares from mixed forest (BM). This increase has occurred principally in the north-west extension to the natural park (Figure 4). As MBT has continued to increase in the second period (2000-2006), this time from conifer forest (BC) (648 ha) and BM (137 ha), expansion of shrubland should be considered an important dynamic and also will be assigned to activity type function.

3. The vulnerability of this location to development of tourist infrastructure is evidenced by the construction of a 52 hectare camp site (IDR) between 1990 and 2000 in a zone previously given over to natural vegetation (VE) on the shoreline just to the north west of the national park (in a small pocket of land lacking natural protection related to the tourist resort of Matalascañas). A 53 hectare construction site is also in evidence. In the second period (2000-2006), 15 hectares of which had become urban fabric by 2006. It is clear that all types of urban fabric (TUC and TUD) as well as construction sites (ZC) and sports and leisure facilities (IDR) must be assigned to function activity types.

Land use demand:

Description	Spanish acronym	ha 1990	ha 2000	ha 2006
Continuous urban Fabric	TUC	407	407	451
Discontinuous urban fabric	TUD	6	6	6
Construction areas	ZC	53	53	38
Sports and leisure facilites	IDR	13	65	65
Permanently Irrigated land	TRP	419	369	351
Fruit and berry plantations	F	100	241	241
Crop Mosaic	MC	0	50	50
Shrubland	MBT	3307	4464	4939

Table 1: Land use demand for the 8 function activity types

On the basis of the observed LUCC dynamics (Table 1), land use demand was set for the 8 function classes.

Neighborhood rules:

The neighborhood rules (methods, step 6) are key to the transition potential computation which comprises the core of the CA model. To determine the neighborhood rules, relative values representing *persistence, attraction* and *repulsion* are applied to all land use categories with respect to the function categories in the model (Figure 3). These parameters are then applied by the model to each cell with respect to all other cells in its neighborhood, a total of 197 cells including the cell itself (up to 8 cells in any direction). As only the cells belonging to the function categories are have the ability to relocate within the model, neighborhood parameters must be set to establish their behavior, with respect to themselves (*persistence*) and other functions or non-functions (*attraction and repulsion*). The most intuitive way to explain this concept is in terms of a graph for each land use, having x representing distance in any direction away from a cell containing that land use and y representing *relative force of attraction* (RFA).

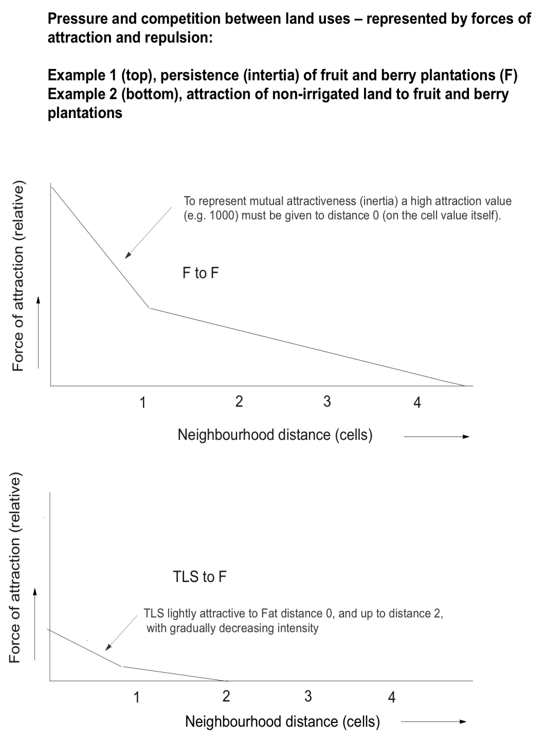


Figure 3: Examples of neighborhood rules

Other parameters, accessibility, suitability and zoning:
Three network layers were included in the pilot model, roads, irrigation channels and rivers. In the initial calibration, accessibility was applied only to the irrigated crops (TRP) and fruit and berry plantations (F) land uses, principally because these were the most important dynamics likely to be affected by accessibility conditions. Zoning parameters were established on the basis of the land use restrictions of the use and management master plan (PRUG), with highest and second highest level protected areas (reserve and restricted use) being designated strictly restricted (no occupation permitted by new land use), protected areas outside of these zones weakly restricted, and other areas, such as the buffer corridor, unrestricted for all anthropogenic land use functions. Non-anthropogenic land use functions (shrubland)

were allowed everywhere.

Technical calibration goodness of fit:

The goodness of fit of the technical calibration, depends on two key parameters, *quantity* and *location*. As we have seen previously, quantity is determined initially by the input demand for each land use, but ultimately by the amount of available land on the map relative to the ranking for that land use in the transition potential table; that is, even if all demand for one particular land use is not completely allocated, the model run may terminate anyway because all available locations have been filled with other land uses that scored more highly in the TP ranking. Although not all demand will necessarily be allocated, this is quite a satisfactory way to deal with real world pressure, competition and uncertainty. This makes it difficult to estimate the success of the technical calibration exercise solely in terms of *quantity.* A good basic starting point is to compare the cross tabulation for M1 and M2 with its counterpart for the simulated map (M1 and MS2); Table 2 (below).

	TLS	A	P	TPA	SA	BF	BC	BM	PN	VE	PDA	HZP	M	S	TUC	TUD	ZC	IDR	TRP	F	MC	MBT	LA	E	M	Total
TLS	3010																		19							3029
A		152																								152
P																										0
TPA				414																						414
SA					78																					78
BF						1630																				1630
BC							6510																			6510
BM								857																		857
PN									1378																	1378
VE										9364																9364
PDA											3879															3879
HZP												22994														22994
M													937													937
S														304												304
TUC															407											407
TUD																6										6
ZC																	53									53
IDR							54											13								67
TRP																			365							365
F	1					1			104										35	100						241
MC									50																	50
MBT	4					1001	24	21	3	90	13	1										3307				4464
LA																							6647			6647
E																								1369		1369
M																									7682	7682
Total	3015	152	0	414	78	2632	6588	878	1535	9454	3892	22995	937	304	407	6	53	13	419	100	0	3307	6647	1369	7682	72877

	TLS	A	P	TPA	SA	BF	BC	BM	PN	VE	PDA	HZP	M	S	TUC	TUD	ZC	IDR	TRP	F	MC	MBT	LA	E	M	Total
TLS	2985																									2985
A		152																								152
P																										0
TPA				159					48	73												17				297
SA					78																					78
BF						1720																				1720
BC							6581															33				6614
BM								782																		782
PN									1432	131																1563
VE										8950																8950
PDA											3892														14	3906
HZP				255								22995														23250
M													937													937
S														304												304
TUC															407											407
TUD																6										6
ZC																	53									53
IDR										52								13								65
TRP										29									325	3		12				369
F	30								55	15									44	97						241
MC																			50							50
MBT						912	7	96		204												3245				4464
LA																							6647			6647
E																								1369		1369
M																									7668	7668
Total	3015	152	0	414	78	2632	6588	878	1535	9454	3892	22995	937	304	407	6	53	13	419	100	0	3307	6647	1369	7682	72877

Table 2: comparison of cross tabulation results. Corine 1990 (M1) occupied the columns in both cases. M1 has been crossed with the first simulation attempt (MS2) at top, and with the real corine map for 2000, below.

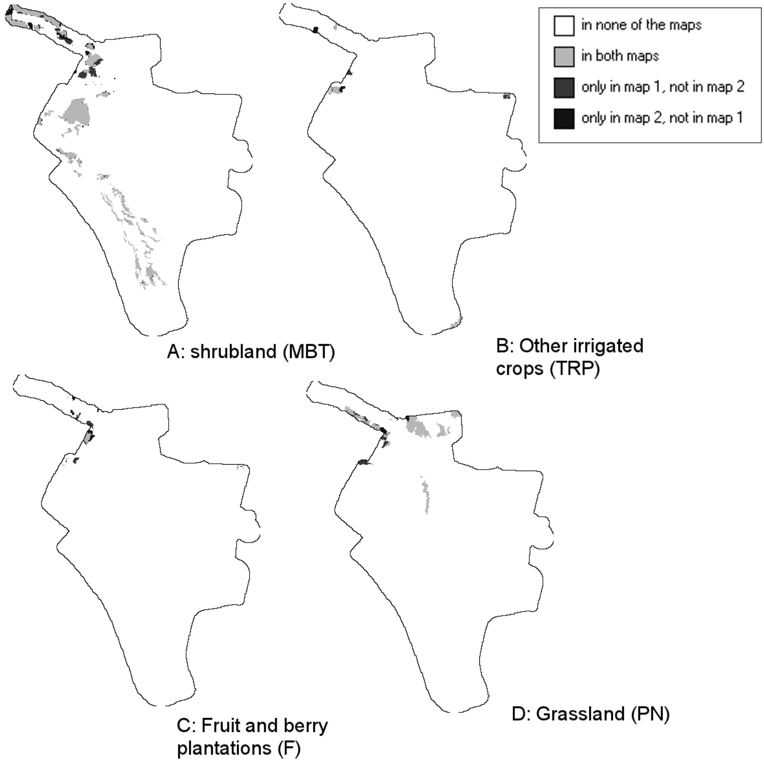
It can be seen that there are some early successes, and quite a few areas where the model has not performed well. For example, the expansion of the shrubland category

(MBT) over this time period has been adequately represented in terms of gains from the relevant categories in approximately correct proportions. Though there is clearly room for improvement, the model seems to be beginning to reflect the LUCC observed in reality. Turning to the expansion of fruit and berry cultivation (F), we can see, from the diagonal, that the inertia of this category (the RFA with respect to itself; Figure 3) is successfully preventing migration or occupation of existing F. The 141 new hectares required have been drawn from grassland (PN) and (TRP), again reflecting the real situation. However, while in the model the major part of the gain to this category has come from PN, in reality we can see that vegetation (VE) and non-irrigated land (TLS) have also contributed, something the model has been unable to reflect. In this case the adequate response would be to return to the neighborhood rules and try to establish a greater attractiveness for F at distance 0 for the VE and TLS columns. The loss of 50 ha of other irrigated land (TRP) has been correctly modeled with respect to F, which has gained 35 ha in the model against 44 in reality. But again, something is not quite right, as in the model it can be seen that TRP has not passed 50 ha to crop mosaic (MC), as happened in reality (MC has instead gained from PN) and has lost 19 ha to TLS, a vacant land category which should not have gained. This behavior, gain to a non-function category, is probably caused by the model seeking to obtain the correct demand for TRP (which has decreased over the modeled period) and allocating excess cells to the first available category (i.e. category 0, TLS). It needs to be remembered in these cases that the demand for vacant categories is invisible to the model. In this case, it is very likely that this unwanted behavior can be compensated for by making TLS more attractive to F, thus solving two problems at once. MC needs also to be made more attractive to TRP so that the model does not find itself with surplus demand at the end of the run. On this basis, further adjustments were made to the neighborhood rules, resulting in some improvements (Table 3).

	TLS	A	P	TPA	SA	BF	BC	BM	PN	VE	PDA	HZP	M	S	TUC	TUD	ZC	IDR	TRP	F	MC	MBT	LA	E	M	Total
TLS	2973																									2973
A		152																								152
P																										0
TPA				414																						414
SA					78																					78
BF						1634																				1634
BC							6512																			6512
BM								857																		857
PN									1446																	1446
VE										9357																9357
PDA											3874															3874
HZP												22988														22988
M													937													937
S														304												304
TUC															407											407
TUD																6										6
ZC																	53									53
IDR							54											13								67
TRP										1	1								363							365
F	34								85	2									20	100						241
MC	4					1				3	0	6							36							50
MBT	4					997	22	21	4	91	17	1										3307				4464
LA																							6647			6647
E																								1369		1369
M																									7682	7682
Total	3015	152	0	414	78	2632	6588	878	1535	9454	3892	22995	937	304	407	6	53	13	419	100	0	3307	6647	1369	7682	72877

Table 3: second comparison of cross tabulation results after adjustment of neighborhood rules.

With respect to *location*, once the quantity has been approximately correctly located by the iterative process described above (set neighborhood rules, output cross tabulations, adjust neighborhood rules, return to cross tabulations etc), the more intractable problem of *location* can be considered. The key to a workable *useful* model (see [16]) lies in the production of a visually acceptable simulation, where land use changes can be seen by model end users and stakeholders to have occurred in locations where available empirical knowledge suggests it is likely to occur.

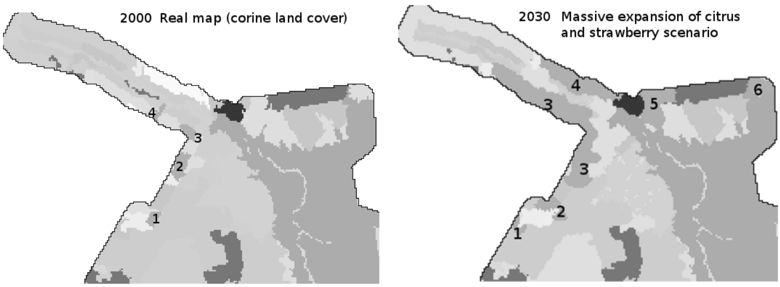


Map 2: Map Comparison results for 4 key land use categories. In the legend, map 1 refers to the real map for the year 2000, while map 2 is MS2, the calibration simulation for the same date.

The results of the model for MS2 (the year 2000) are shown above. Simple visual inspections were carried out in the Map Comparison Kit, a software application provided by RIKS for free download at http://www.riks.nl/mck/. Though the software does offer a range of techniques for statistical comparison of maps, in this case, the simplest, visual comparison method (per category comparison for each land use class) was used in this case to assess whether the simulation performance was broadly acceptable. The model shows success in some areas, for example (compare with Figure 2) in the area of extension to the park proper in the northwest corner the growth of new shrubland following loss of eucalyptus plantation has been simulated with a fairly high degree of success (MBT, map 2A). It can also be seen that the claims of success in terms of *quantity* (above) are not borne out with respect to *location*. Though new hectares of fruit and berry cultivation (F; map 2C) were simulated in terms of changes to and from the appropriate categories, the simulation did not choose the correct locations. This is probably because there were a large number of possible locations given neighborhood, accessibility and zoning rules relative to a small quantity of new F to be allocated.

Pilot simulation: massive expansion of citrus and strawberry

The final part of the *technical* modeling process consists in the application of the calibrated model to future scenarios. For this purpose a simple simulation was built on the basis of empirical knowledge of the evolution of the Doñana natural area and the results of cross tabulation analysis of land use changes. This scenario postulates an explosive growth of citrus and strawberry cultivation to a total demand of 2000 ha in the currently available locations by 2030 (Map 3). The simulation, which we have called *massive expansion of citrus and strawberry,* is extreme. However, although continued expansion of intensive cultivation in the zone immediately adjacent to the protected natural area is highly undesirable from the point of view of conservation, the historical tendency does indicate that further expansion is possible. It is very unlikely indeed that an expansion of intensive citrus and strawberry cultivation as great as that postulated in this scenario would or could take place, but sometimes *what if...* type scenarios may be important in communicating future threats or risks to stakeholders or testing resilience of zoning measures against hypothetical worst-case scenarios.



Map 3: Results of the massive expansion of citrus and strawberry scenario for the year 2030. Areas of fruit and berry cultivation are numbered. This highly unrealistic test scenario nevertheless illustrates the potential of the model to address real world questions of interest to natural resource managers, such as: what areas are most vulnerable to expansion of intensive cultivation?

Conclusions and future work to improve the model

At present, the work presented here has not attempted to integrate knowledge outside the realm of the technical accuracy parameters presented here by involving the stakeholder community in the model building process. It is generally accepted that decisions are likely to be implemented with less conflict and more success when they are driven by those who are likely to bear their consequences [17]. Though participatory work is ongoing, some stakeholder feedback has already been obtained [3]; in summary, stakeholders and researchers are in agreement that the model could be improved in the following ways:

1. Improved land use mapping. The corine land cover data used in the pilot study is too simplistic, future modelling work will employ larger scale land use/cover maps [3].

2. Accessibility maps were not included for all land cover types in the pilot model. Accessibility to infrastructures is likely to inhibit or stimulate LUCC, so including accessibility for a wider range of land use classes is likely to improve the model.

3, Suitability maps were not included in the pilot model. Physical suitability is important to avoid allocation of particular land use types in areas where they are not normally suitable (e.g. irrigated crops in mountain areas).

4. Study area does not take into account a large enough area to reflect all possible implications in the territory; the study area will accordingly be extended to include the whole of the hydrological catchment of the river Guadiamar (Map 1).

5. At present, the scenarios discussed are very simple, and currently not aligned with those developed for Doñana through participatory workshops by Palomo *et al* [18].

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