Modelling actors’ influence on land use change: a dynamic systems approach

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Abstract

In this paper we show how the dynamic behavior of human actors and their influence on land use change can be modeled to produce spatially explicit simulations of future land use. An actor-based dynamic systems approach is integrated with the existing APoLUS (Actor, Policy and Land Use Simulator) cellular automata land use model. Previous versions of APoLUS determined final total land use amounts, (land use claims), by entering estimated growth tendencies by hand. The values of actor state variables, representing the influence of actor behaviour on land use change, were also input at the start of a simulation and did not vary throughout the model run-time. The present paper overcomes these limitations by applying a dynamic systems approach to model both land use claims and the dynamic evolution of actor behaviour over time. We apply the modified model to the case of the Navarre region, Spain, for the example of land use dedicated to solar energy. Three different cases are considered: (i) the case of ‘actor statics’ (the actor variables are static parameters); and also ‘actor dynamics’ under two long-term regional economic scenarios: (ii) the ‘no-growth’ scenario (no long-term economic growth in the region) and (ii) the ‘growth’ scenario (exponential long-term economic growth in the region). Simulation results demonstrate the much faster development of solar energy in the region under study in both ‘actor dynamics’ cases, as compared to the ‘actor statics’ approximation, with regional economic growth further facilitating the solar energy development, as compared to the ‘no-growth’ scenario.

Keywords: policy implementation, Contextual Interaction Theory, actor dynamics, land use models, cellular automata, dynamic systems

1 Introduction

In the present paper, we apply an actor-based system dynamics approach to spatially explicit modeling of land use change for the case of solar energy in Navarre, Spain. The new approach we present is fully integrated into the existing Cellular Automata (CA) land use model and used to generate future simulations for the year 2050. The results of this integrated modeling exercise give insights for renewable energy (RE) implementation and highlight the importance of including realistic actor behaviour in policy relevant land use simulation models.

APoLUS (Actor, Policy and Land Use Simulator) is a free-and-open-source (FOSS) geographical computer model for the R environment, designed to simulate the effects of complex actor behaviour on land use. The model uses the CA approach described by White and collaborators (e.g. [10]) to simulate land use change based on the interaction of 5 key parameters, Neighbourhood (N), Accessibility (A), Suitability (S), Zoning (Z) and Actor Dynamics (D). The model was developed under the EU FP7 COMPLEX project to allow land use types that can be shown to follow an incremental cellular growth pattern (e.g. residential land, industrial land) and land use types that are strongly driven by the behaviour of actors like policy makers and planners (e.g renewable energy, irrigated cropland) to be modelled together. The influence of actors in shaping land use change is generally under-represented in many existing land use simulation models, which makes it difficult to study the spatial consequences of transformative economic or policy actions like renewable energy implementation or variation in crop prices. In the application described here, APoLUS is applied to the simulation of future land use configurations under different RE policy scenarios, thus serving as a policy evaluation modelling tool tailored to address the land-use related aspects of transition to low carbon economy. In its present form, prior to the developments described here, APoLUS links the spatially explicit CA geographical model of White and collaborators [8, 10], with a model of the influence of real-world actors on RE implementation based on policy implementation theory (see below Sec. 2) and sociological approaches (e.g. [6]). For a detailed description of earlier versions of APoLUS see e.g. [3].[1]

In APoLUS, the location and spatial pattern of land use in the CA model are determined at each time step by the D, N, A, S, Z parameters described above, in conjunction with a stochastic factor (ν). However, CA behaviour is constrained by assigning a total number of cells that can be allocated to any particular land use in a given simulation, known as land use claims.[2] Land use claims are normally determined exogenously, or by nesting the CA land use model inside a macro-scale model of factors likely to influence claims for any particular land use (e.g. population, economy, climate etc., see e.g. [9]).

In previous versions of APoLUS, actor state variables, on which the factor D in the transition potential was explicitly dependent, were time-invariant such that the characteristics of actors at the end of a simulation was the same as at the start of the simulation, while land use claims for different land use categories had to be explicitly specified by the user before the model run, by just entering the related numeric values.

Thus, the version of APoLUS described in the present paper includes two important advances:

1. Land use claims are now modeled as functions dependent on actor state variables.
2. Actor state variables, that were included in the previous versions of the model as time-independent (static) parameters, are now modeled within the dynamic systems framework (see [5]).

The rest of the paper is organized as follows. In Sec. 2, a theoretical model of actors' influence on land use allocation is presented, with a particular focus on the definition of actor state variables. In Sec. 3, we briefly describe the procedure of modelling land use claims in APoLUS as functions of time-dependent actor state variables. In Sec. 4, we provide some simulation results with the new version of APoLUS, based on one of the members of actor dynamics model family developed in [5] – namely, on one of the versions of linear actor dynamics model. Sec. 5 concludes.

2 Participatory Contextual Interaction Theory (PCIT) and definition of actor state variables

To understand the way actors can influence the implementation of policy actions like the expansion of irrigated crops or the development of RE installations in a given territory we draw on two existing theoretical approaches to policy implementation; Contextual Interaction Theory (CIT) (e.g. [1, 2]), and Participatory Action Research (PAR) (e.g. [6, 7]). CIT deals with the way actors' characteristics like motivation, cognition and resources will influence successful implementation, while PAR looks to help stakeholders implement their goals by focusing particularly on conflicts and power imbalances within the stakeholder community. The practical integration of these two approaches in the context of renewable energy policy in Spain and the Netherlands, which we refer to here as Participatory Contextual Interaction Theory (PCIT), is described in [4]. Under this framework we assume that the policy implementation process is driven by interactions of multiple actors, often with conflicting values, perceptions and goals. Actor properties might be described at quantitative level by characterizing each of N actors involved[3] (indicated by the subscript n, $n = 1, \ldots, N$) by the following five actor state variables (in the context of a certain policy goal – e.g. RE development):

1) *Motivation* M_n – the actor's degree of motivation to implement the modelled process for the relevant policy goal;

2) *Cognition* C_n – the actor's degree of awareness and knowledge that enable them to implement the modelled process for the relevant policy goal;

3) *Resources* R_n – the resources (monetary/non-monetary) at the actor's disposal;

4) *Power* P_n – the power of the actor with respect to other actors in the model;

5) *Affinity* A_n – the degree to which the actor is sympathetic towards implementation of the modelled process for the relevant policy goal. Unlike the previous four actor state variables, which are non-negative by definition, the affinity A_n might be of any sign: either positive (actor is in favor of action), or negative (actor is opposed to action), or zero (actor is indifferent to action).

Unlike in earlier versions of APoLUS, in the present paper, we explicitly model the dynamics of these actor state

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[1] APoLUS is an open-source, multi-platform model (freely downloadable from https://simlander.wordpress.com/apolus/) designed within the existing, popular and well supported R software environment (The R Project for Statistical Computing, URL: https://www.rproject.org/).

[2] Sometimes also known as *land use demand.*

[3] The total number of aggregate actors, N, should not be confused with the Neighbourhood parameter N appearing in the transition potential of the CA model (the latter will not be referred to in the remainder of the paper).

variables, using one of the members of actor dynamics model family developed in [5] – the linear actor dynamics model.

We should note that actor resources R_n are assumed to be exogenous, and are interpreted in economic terms. For instance, assuming for simplicity an exogenous long-term scenario of exponential growth of regional GDP of the territory under study ($\mathrm{GDP} \approx \exp(\lambda t)$), we might straightforwardly use this time dependence as a proxy of resource dynamics for all actors:

$$R_n = R_n(t) = R_{n0} \exp(\lambda t)\,. \qquad (1)$$

Obviously, in the 'no-growth' scenario (case of $\lambda = 0$ in Eq. (1)) the resources would be static, and Eq. (1) would be reduced to

$$R_n = R_{n0} \neq R_n(t)\,. \qquad (2)$$

3 Modelling the land use claims driven by actor dynamics

In the APoLUS simulations presented in Sec. 4 below we consider a set of global actors affecting the land use development in the Navarre region, Spain, and make the land use claims explicitly dependent on (now dynamic) actor state variables.

Specifically, we assume that the land use demand for the m-th land use category $D^{(m)}(t^*)$ affected by actors' decision-making in the end year of simulations t^* is given by a formula

$$D^{(m)}(t^*) = D^{(m)}(t_0) + \mu_m \cdot (t^* - t_0)\frac{F(t^*)}{F(t_0)} \qquad (3)$$

where $D^{(m)}(t_0)$ is the land use demand in the start year of simulations t_0, μ_m is a constant parameter determining the speed of land use claim growth (particularly, in a conventional model – see Case 1 in Sec. 4 below, and also Eq. (9) – strictly coinciding with the constant speed of linear land use claim growth), and

$$F(t) = \ln \Phi(t) = \ln \sum_{n=1}^{N} \Phi_n(t) \qquad (4)$$

where

$$\Phi_n(t) = \big(M_n(t) + C_n(t) + R_n(t)\big)P_n(t)A_n(t)\,. \qquad (5)$$

Explicitly, for the linear actor dynamics model in the 'no-growth' scenario (case of $\lambda = 0$ in Eq. (1)) Eq. (5) takes the form

$$\Phi_n(t) = \frac{b^{\mathrm{M}} + b^{\mathrm{C}}}{b^{\mathrm{A}}}\langle A_0\rangle^2 P_{n0}\left[\exp\!\left(b^{\mathrm{A}}\Delta t\right) - 1\right]^2 + \\ + \langle A_0\rangle\left\{\frac{b^{\mathrm{M}} + b^{\mathrm{C}}}{b^{\mathrm{A}}}A_{n0} + M_{n0} + C_{n0} + R_{n0}\right\}\left[\exp\!\left(b^{\mathrm{A}}\Delta t\right) - 1\right] + \Phi_{n0} \qquad (6)$$

where

$$\Phi_{n0} = \big(M_{n0} + C_{n0} + R_{n0}\big)P_{n0}A_{n0} \qquad (7)$$

is the initial value of $\Phi_n(t)$ at the start year of simulations. In Eq. (6) b^{M}, b^{C}, b^{A} are constant model parameters determining the speed of growth of individual motivations, cognitions and affinities, respectively (for further details, we address the reader to Sec. 5.1.3 and 6.2 in our earlier work [5]); subscripts '0' denote the initial conditions for actor state variables at $t = t_0$; the parameter Δ depends on initial conditions for power and resources and is defined as

$$\Delta = \sum_{n=0}^{N} P_{n0}R_{n0}\ ; \qquad (8)$$

and $\langle A_0\rangle$ is the initial weighted mean affinity.

Clearly, under the 'no-growth' regional economic scenario the function $F(t^*)$ appearing in Eq. (3) in the long term (asymptotically) grows linearly with time t^*. It follows then from Eq. (3) that the land use demand $D^{(m)}(t^*)$ itself is quadratic in t^* in the long term.

4 Simulation results with APoLUS

We performed simulations with the new version of APoLUS for the Navarre case study region (Spain), implying that the actor dynamics are affecting the land use demand for solar energy (SE) development. The cells allocated for solar energy development are indicated in yellow in the simulated future land use maps (Figure 1, left to right; the color scheme for other land use categories is specified in the legend for Figure 1) The start years of simulations (t_0) is 2012; the end year of simulations (t^*) is 2050.

Three cases are considered:

Case 1. Actor statics

In Case 1, all actor state variables are still static parameters (as in earlier versions of APoLUS). Then in the r.h.s. of Eq. (3) the function $F(t)$ is time-independent, as well; in particular, $F(t^*) = F(t_0)$, and Eq. (3) is reduced to a conventional model where land use claims linearly grow in time:

$$D^{(\mathrm{SE})}(t^*) = D^{(\mathrm{SE})}(t_0) + \mu_{\mathrm{SE}} \cdot (t^* - t_0)\,. \qquad (9)$$

Quantitatively, in Case 1 the land use demand for SE development in 2050 provided by Eq. (3) [or, equivalently, by Eq. (9)] is $D^{(\mathrm{SE})[1]}(2050) = 1365$ cells.

A fragment of land use map for year 2050 simulated by APoLUS in Case 1 is provided in Figure 1 (left).

Case 2. Actor dynamics, the 'no-growth' regional economic scenario

In Case 2, actor dynamics are driven by the linear model under the stylized 'no-growth' regional economic scenario. Broadly, this means, that no long-term regional economic growth is foreseen for the territory under study; technically, in Eq. (1) the growth rate λ should be set to zero ($\lambda = 0$).

In Case 2, the dynamics of the function $F(t)$ are provided by Eqs. (4), (6)-(7). Three of five actor state variables (namely, motivation, cognition, and affinity) are now time-dependent; the remaining two (resources and power) are still assumed to be static.

Quantitatively, in Case 2 the land use demand for SE development in 2050 provided by Eq. (3) is $D^{(\mathrm{SE})[2]}(2050) = 5000$ cells – a remarkably higher value than in Case 1.

A fragment of land use map for year 2050 simulated by APoLUS in Case 2 is provided in Figure 1 (center).

Case 3. Actor dynamics, the 'growth' regional economic scenario

All assumptions made for the Case 2 hold here as well, with the only exception that the territory under study exhibits long-term economic growth (the stylized 'growth' regional economic scenario), and in Eq. (1) the growth rate λ is set to 1 per cent per annum (λ = 0.01 year^{-1}).

Respectively, under the 'growth' scenario four of five actor state variables (namely, motivation, cognition, resources, and affinity) are now time-dependent; and only the fifth remaining variable, power, is still assumed to be static.

Quantitatively, in Case 3 the land use demand for SE development in 2050 provided by Eq. (3) is $D^{(\mathrm{SE})[3]}(2050) = 6529$ cells – a substantially higher value than in Case 2.

A fragment of land use map for year 2050 simulated by APoLUS in Case 3 is provided in Figure 1 (right).

5 Discussion and conclusions

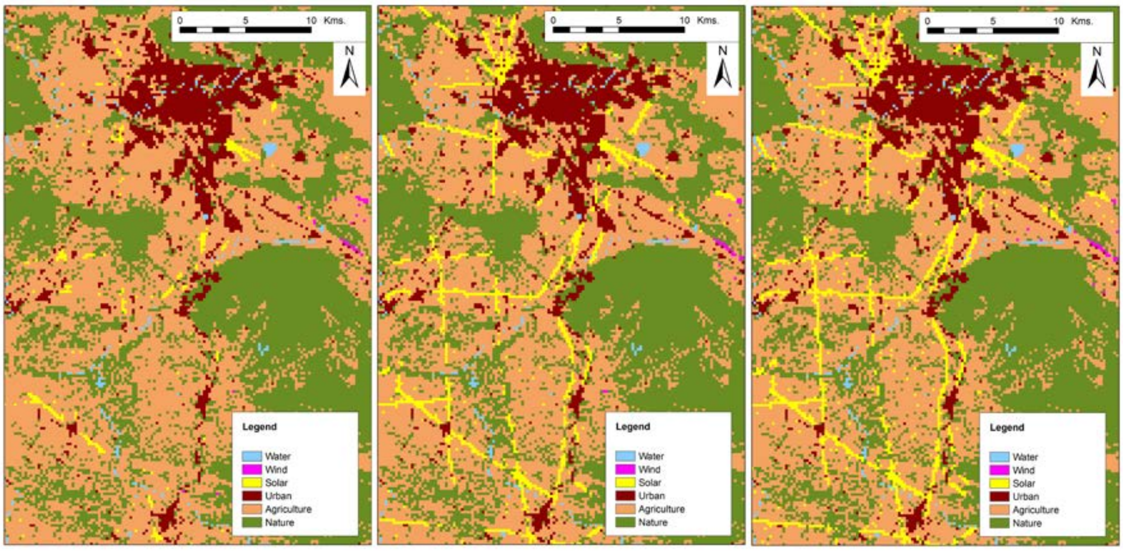
Simulation results provided by a new version of APoLUS model with land use claims made explicitly dependent on actor dynamics (in their turn, explicitly modelled within the actor-based dynamic systems approach) convincingly demonstrate the much more rapid advancement of solar energy in the model region under study, as compared with the case of 'actor statics' approximation (the assumption of 'actor statics' was adopted in earlier versions of APoLUS). Also, the simulation results reported show the sensitivity of projected land use change to long-term regional economic scenarios embedded in the actor dynamics model: indeed, the growth scenario corresponds to substantially faster development of solar energy than the 'no-growth' scenario.

The research has important implications for spatially explicit land use models as policy support tools. Policy makers are keen not just to know 'where' future developments are likely to occur, but also on what timescale they are likely to take place, given certain conditions. The timescale aspect is particularly important for the implementation of RE systems as a cornerstone of a low carbon energy future. The work discussed here shows one way in which spatially explicit simulations can be improved with respect to the timeframe of future developments.

Finally, the work presented here offers a means to link actors to land uses while retaining the simplicity of the CA modelling approach. Some land use growth patterns arise from a multitude of very complex factors, others may be more easily treated as responses to simple factors like economic incentives. The model presented here offers a means to deal with both of these types of behaviour at the same time.

As with a model of any nature yielding long-term simulations, a question might be raised on how 'sure' the simulation results are, given the quite distant time horizon (the end year of APoLUS simulations presented here is 2050). With pronounced dependence of simulations yielded by the new version of APoLUS described in the present paper on the details of actor dynamics description and on regional economic scenarios, we would be inclined to refer to the simulations presented here not as to 'long-term land use change *forecasts*', but rather as to 'long-term land use change

Figure 1: Land use change simulated by a new version of APoLUS model. Yellow cells correspond to solar energy. *Left:* Case 1 – Actor statics; *Center:* Case 2 – Actor dynamics, the stylized 'no-growth' regional economic scenario; *Right:* Case 3 – Actor dynamics, the stylized 'growth' regional economic scenario.



Source: Authors' simulations with APoLUS model.

projections' (in many respects the situation is analogous to *climate projections* yielded by global climate models and also strongly dependent on scenarios of emissions or concentrations of greenhouse gases).

It should be stressed that for exploratory simulations reported in the present paper we have (intentionally) chosen probably the simplest model from the actor dynamics model family developed by us previously in [5] – namely, a simple linear actor dynamics model. Other members of this model family demonstrate more versatile dynamic regimes, including strongly nonlinear dynamics. Embedding the more advanced actor dynamics models in APoLUS is, however, left for further research.

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