Land cover/use change modeling with CLUE-S

Introduction and model structure
The Conversion of Land Use and its Effects modelling framework (CLUE) (Veldkamp and Fresco, 1996; Verburg et al., 1999) was developed to simulate land use change using empirically quantified relations between land use and its driving factors in combination with dynamic modelling of competition between land use types. The modelling approach has been modified and is now called CLUE-S (the Conversion of Land Use and its Effects at Small regional extent). CLUE-S is specifically developed for the spatially explicit simulation of land use change based on an empirical analysis of location suitability combined with the dynamic simulation of competition and interactions between the spatial and temporal dynamics of land use systems. More information on the development of the CLUE-S model can be found in Verburg et al. (2002) and Verburg and Veldkamp (2003).

The model is sub-divided into two distinct modules, namely a non-spatial demand module and a spatially explicit allocation procedure (Figure 1). The non-spatial module calculates the area change for all land use types at the aggregate level. Within the second part of the model these demands are translated into land use changes at different locations within the study region using a raster-based system. The results from the demand module need to specify, on a yearly basis, the area covered by the different land use types, which is a direct input for the allocation module.

The allocation is based upon a combination of empirical, spatial analysis and dynamic modelling. Figure 2 gives an overview of the information needed to run the CLUE-S model. This information is subdivided into four categories that together create a set of conditions and possibilities for which the model calculates the best solution in an iterative procedure.

![Figure 1. Overview of the modelling procedure](image-url)
Spatial policies and restrictions indicate areas where land use changes are restricted through policies or tenure status. For the simulation maps that indicate the areas for which the spatial policy is implemented must be supplied. Some spatial policies restrict all land use change in a certain area, e.g., a log-ban within a forest reserve. Other land use policies restrict a set of specific land use conversions, e.g., residential construction in designated agricultural areas or permanent agriculture in the buffer zone of a nature reserve. The conversions that are restricted by a certain spatial policy can be indicated in a land use conversion matrix: for all possible land use conversions it is indicated if the spatial policy applies.

Land use requirements (demand) are calculated at the aggregate level (the level of the case-study as a whole) as part of a specific scenario. The land use requirements constrain the simulation by defining the totally required change in land use. All changes in individual pixels should add up to these requirements. In the approach, land use requirements are calculated independently from the CLUE-S model itself. The calculation of these land use requirements is based on a range of methods, depending on the case study and the scenario. The extrapolation of trends in land use change of the recent past into the near future is a common technique to calculate land use requirements. When necessary, these trends can be corrected for changes in population growth and/or diminishing land resources. For policy analysis it is also possible to base land use requirements on advanced models of macro-economic changes which can serve to provide scenario conditions that relate policy targets to land use change requirements.
**Land use type specific conversion settings** determine the temporal dynamics of the simulations. Two sets of parameters are needed to characterize the individual land use types: conversion elasticities and land use transition sequences. 

*Conversion elasticities,* is related to the reversibility of land use change. Land use types with high capital investment will not easily be converted in other uses as long as there is sufficient demand. Examples are residential locations but also plantations with permanent crops (e.g., fruit trees). Other land use types easily shift location when the location becomes more suitable for other land use types. Arable land often makes place for urban development while expansion of agricultural land occurs at the forest frontier. An extreme example is shifting cultivation: for this land use system the same location is mostly not used for periods exceeding two seasons as a consequence of nutrient depletion of the soil. These differences in behaviour towards conversion can be approximated by conversion costs. However, costs cannot represent all factors that influence the decisions towards conversion such as nutrient depletion, esthetical values etc. Therefore, for each land use type a value needs to be specified that represents the relative elasticity to change, ranging from 0 (easy conversion) to 1 (irreversible change).

- **0:** Means that all changes for that land use type are allowed, independent from the current land use of a location. This means that a certain land use type can be removed at one place and allocated at another place at the same time, e.g., shifting cultivation.
- **>0 <1:** Means that changes are allowed, however, the higher the value, the higher the preference that will be given to locations that are already under this land use type. This setting is relevant for land use types with high conversion costs.
- **1:** Means that grid cells with one land use type can never be added and removed at the same time. This is relevant for land use types that are difficult to convert, e.g., urban settlements and primary forests. A value of one stabilizes the system and prevents that in case of deforestation other areas are reforested at the same time.

Land use type specific conversion settings and their temporal characteristics are specified in a *conversion matrix*. This matrix defines:

- To what other land use types the present land use type can be converted or not.

**Figure 3.** Illustration of the translation of a hypothetical land use change sequence into a land use conversion matrix.
• In which regions a specific conversion is allowed to occur and in which regions it is not allowed.

• How many years (or time steps) the land use type at a location should remain the same before it can change into another land use type. This can be relevant in case of the regrowth of forest. Open forest cannot change directly into closed forest. However, after a number of years it is possible that an undisturbed open forest will change into closed forest because of re-growth.

• The maximum number of years that a land use type can remain the same. This setting is particularly suitable for arable cropping within a shifting cultivation system. In these systems the number of years a piece of land can be used is commonly limited due to soil nutrient depletion and weed infestation.

**Figure 4.** Example of a land use conversion matrix with the different options implemented in the model.

### Location characteristics

Land use conversions are expected to take place at locations with the highest 'preference' for the specific type of land use at that moment in time. Preference represents the outcome of the interaction between the different actors and decision making processes that have resulted in a spatial land use configuration. The preference of a location is empirically estimated from a set of factors that are based on the different, disciplinary, understandings of the determinants of land use change. The preference is calculated following:

\[ R_{ki} = a_kX_{1i} + b_kX_{2i} + \ldots \]

where \( R \) is the preference to devote location \( i \) to land use type \( k \), \( X_{1,2,...} \) are biophysical or socio-economical characteristics of location \( i \) and \( a_k \) and \( b_k \) the relative impact of these characteristics on the preference for land use type \( k \). The exact specification of the model should be based on a thorough review of the processes important to the spatial allocation of land use in the studied region.
Most of these location characteristics relate to the location directly, such as soil characteristics and altitude. However, land management decisions for a certain location are not always based on location specific characteristics alone. Conditions at other levels, e.g., the household, community or administrative level can influence the decisions as well. These factors are represented by accessibility measures, indicating the position of the location relative to important regional facilities, such as the market and by the use of spatially lagged variables. A spatially lagged measure of the population density approximates the regionally population pressure for the location instead of only representing the population living at the location itself.

**Allocation procedure**

When all input is provided the CLUE-S model calculates, with discrete time steps, the most likely changes in land use given the before described restrictions and suitabilities. The allocation procedure is summarized in Figure 5.

![Figure 5. Flow chart of the allocation module of the CLUE-S model](image)

The following steps are taken to allocate the changes in land use:

The first step includes the determination of all grid cells that are allowed to change. Grid cells that are either part of a protected area or presently under a land use type that is not allowed to change are excluded from further calculation. Also the locations where certain conversions are not allowed due to the specification of the conversion matrix are identified.

For each grid cell $i$ the total probability ($TPROP_{i,u}$) is calculated for each of the land use types $u$ according to:

$$ TPROP_{i,u} = P_{i,u} + ELAS_u + ITER_u $$

where $P_{i,u}$ is the suitability of location $i$ for land use type $u$ (based on the logit model), $ELAS_u$ is the conversion elasticity for land use $u$ and $ITER_u$ is an iteration variable that is specific to the land use type and indicative for the relative competitive strength of the land use type. $ELAS_u$, the land use type specific elasticity to change value, is only added if grid-cell $i$ is already under land use type $u$ in the year considered.
A preliminary allocation is made with an equal value of the iteration variable (ITERu) for all land use types by allocating the land use type with the highest total probability for the considered grid cell. Conversions that are not allowed according to the conversion matrix are not allocated. This allocation process will cause a certain number of grid cells to change land use.

The total allocated area of each land use is now compared to the land use requirements (demand). For land use types where the allocated area is smaller than the demanded area the value of the iteration variable is increased. For land use types for which too much is allocated the value is decreased. Through this procedure it is possible that the local suitability based on the location factors is overruled by the iteration variable due to the differences in regional demand. The procedure followed balances the bottom-up allocation based on location suitability and the top-down allocation based on regional demand.

Steps 2 to 4 are repeated as long as the demands are not correctly allocated. When allocation equals demand the final map is saved and the calculations can continue for the next time step. Some of the allocated changes are irreversible while others are dependent on the changes in earlier time steps. Therefore, the simulations tend to result in complex, non-linear changes in land use pattern, characteristic for complex systems.

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