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Modelling land use change and its spatial variability for ecosystem services assessments

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Abstract: Ecosystem services (ES) assessments are relying upon scenarios to explore the impacts of potential land use changes [UK NEA 2011], and to explore the possible land use pathways leading to desirable ES targets (using a normative approach). The scenario framework acknowledges the high uncertainty inherent to land use changes [Goodwin and Wright 2010] and a stochastic approach to land use modelling would provide some useful support.
Moreover, for ES assessment, land use modelling needs to consider that i) some services are dependent upon fine land use mosaics (e.g. pollination, water quality), ii) decision-making is linked to spatial units, and iii) stakeholders should be involved in scenario development [MEA 2006]. To support these requirements, a vector representation of the landscape linked to decision's units (e.g. parcels) is deemed relevant; the recent availability of datasets such as LCM2007 [Morton et al. 2011] can support land use modelling at fine spatial scale on national extent.
This paper discusses the relevance of the LandSFACTS modelling tool [Castellazzi et al. 2010a, Castellazzi et al. 2010b] to meet the above requirements. The model provides potential land use allocations meeting all user-defined spatio-temporal constraints on land uses, for every spatial unit and for every time step. It is based on vector landscape, with each polygon being part of nested or overlapping groups representing decision units (land managers or administrative boundaries). The model is limited by its regular time steps, fixed polygon boundaries, and categorical definition of land uses. However, within those limits, its stochastic and rule-based process allows the exploration of the variability in spatial configurations, and thus provides the means to quantify spatial uncertainties. The spatial variability analyses can provide some useful support to the identification of bottlenecks; i.e. regions where constraints or policy might have higher difficulty to be implemented due to the spatial characteristics of the environment. Scenario examples at multiple scales from Scotland-wide to a sub-catchment are presented to discuss the use and limitations of the modelling approach for representing land use complexity for ES assessments.

Keywords: *vector; spatio-temporal; land use; stochastic model; uncertainty*

1 LAND USE MODELLING NEEDS FOR ECOSYSTEM SERVICES ASSESSMENTS

1.1 Ecosystem services and land use modelling

The delivery of ecosystem services (ES) is strongly linked to the landscape itself and its human uses. Land use and land management have the potential to enhance or hinder the quality and quantity of ES delivered. This strong correlation often leads to land use or land cover maps being used as proxies for the evaluation of ES [Castellazzi et al. 2010a, Nelson et al. 2009, Schroter et al. 2005]. However, often studies focus on a large scale assessment with low resolution, whereas some ES such as pollination or water quality are strongly correlated to fine spatial patterns of the land uses such as crops, although large distances might also be involved [Joannon et al. 2006, Lavigne et al. 2008]. The evaluation of initial state of ES is reliant on the representation of the current land cover/land uses. Land use change modelling provides virtual experiments on which potential or future land use patterns can be tested for their impact upon ES.

1.2 Scenarios of land use change

Experimentations on land use changes can be organised within a scenario framework to create coherent and internally consistent and plausible descriptions of a future state of land use change [Carter et al. 2007, MEA 2006, UK NEA 2011]. Scenario development also provides a participatory framework to involve stakeholders and incorporate their knowledge on local issues into the study. Land use change scenarios can explore the potential land use pathways leading to desirable ES targets (using a normative approach, e.g. outcome base). The scenario framework acknowledges the high uncertainty inherent in land use change [Goodwin and Wright 2010].

1.3 Non-optimisation and adaptive management

Classical approaches based upon optimisation of land use changes are de facto artificial, and restrict the range of simulated landscape compared to the real world. Optimality implies the adoption of a point of view through “objective functions”, which minimise/maximise specific variables such as economic wealth or productivity. By providing one “optimum”, an impression of a restricted degree of freedom might wrongly be communicated. Moreover, sub-optimal land use changes are overlooked and thus particular opportunities or risks are not considered, for example a sub-optimal land use change might be robust or less vulnerable to externally induced risks. This is particularly important due to the uncertainties in climate change impacts. Land use change modelling uniquely focusing on optimisation might often not be coherent with robust solutions as defined in adaptive management, where flexibility and sustainability are crucial [Holling 1978]. Adaptive management also acknowledges the need for stakeholders involvement and the importance on integrating local constraints. The integration of both top-down and bottom-up approaches would thus consolidate the validity of the scenario process. Top-down constraints are useful to represent policies and regulations, whereas bottom-up are required to integrate local limitations or opportunities such as land capability, existing industries, local knowledge, or cultural preferences.

1.4 Landscape representation

The landscape representation requires fine resolution to incorporate local constraints and to consider ES dependent upon small features. In this respect, a vector representation of the landscape can be deemed more relevant as it facilitates the identification and interpretation of the landscape by local stakeholders, mainly aided by the representation of linear features such as roads and rivers, but also of the land ownership parcels or field boundaries. Parcels can be considered as individual unit of land use decisions. Landscapes with broad coverage are also required to consider regional/national balance of ES. The recent availability of vector datasets such as Ordnance Survey MasterMap® - Topographic layer or Land Cover Map 2007 [LCM2007; Morton et al. 2011] in United Kingdom can support land use modelling at fine spatial scales (field level) at national extent. The level of details available is presented in figure 1.

This paper discusses the relevance of the LandSFACTS modelling tool [Castellazzi et al. 2010a, Castellazzi et al. 2010b] to meet the above requirements. An example of land use change scenarios and their respective impacts upon habitat connectivity is detailed. The analyses in this paper are only preparatory work to a future wider range of ES assessments.

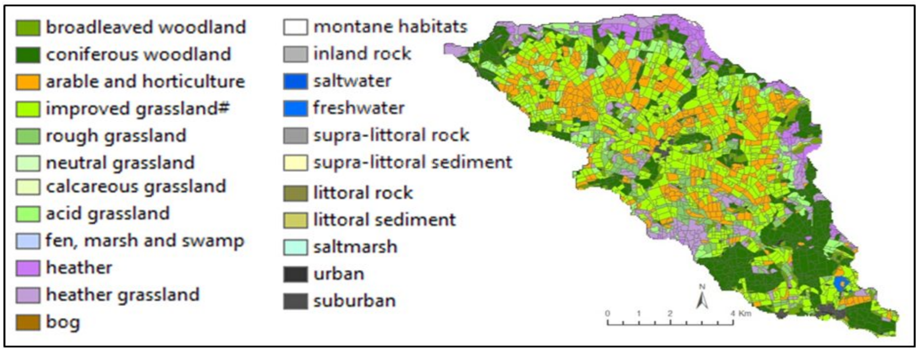

Figure 1. LCM2007 in Tarland catchment (Scotland).

2 AN APPROACH WITH THE LANDSFACTS MODEL

The LandSFACTS model was originally designed to model spatio-temporal patterns of crops within agricultural landscapes in the context of the coexistence between GM and non GM crops in European landscapes [Castellazzi 2010b, SIGMEA 2007]. The core modelling approach was relevant to land use modelling for ES. The model was further developed to meet more complex scenarios requirements (http://www.macaulay.ac.uk/LandSFACTS/), such as multi-scaling and temporal land capability . In brief, the model simulates a land use allocation to every polygon for every time step, by using a stochastic and rule-based approach. The simulated land use allocations all meet user-defined spatio-temporal constraints imposed on the landscape. Further details relevant to land use modelling are developed below.

2.1 Landscape: spatial units and land use classes

The model uses a landscape represented in vector format with polygons and with discrete land use classes. The model will allocate a class per polygon per simulation time step. The land use classes can be focused on individual crop varieties or incorporate broader definition such as forestry, semi-natural habitat and urban classes. The classes to consider can thus be adapted to the scenarios needs. The spatial units (polygons) can be 'virtually' grouped into 'management units' such as farms, cooperatives or estates. Those groups can be nested or overlapping each other.

2.2 Constraints

The constraints are linked to individual or group of spatial units ('management unit') or/and land use (LU) classes and simulation steps. The land use allocations simulated by the model meet all the constraints set up for the scenario; they define the normative scenario. The main constraints (cf. website for full details) are:

i) *temporal successions:* matrices of land use transition probabilities (Markov chains) [Castellazzi et al. 2008] complemented with rules on return period of LU, forbidden LU successions, and past allocation. They all can be defined per polygon or per group of polygons ('management units'). Current trends in land use change or crop rotations can be implemented through the transition matrices, strong temporal constraints such as return period of crops or minimum time before forest logging can be imposed through the other temporal succession constraints. The landscape can be initialised with a given landscape (e.g. current land use).

ii) *spatial locations of LU:* available LU per group of polygons and time step. The constraint permits to provide a land capability constraint for any given time step.

The land capability map can be used to include biophysical limitations (e.g. soil, current or future climate) or human infrastructure (e.g. irrigation, available processing plants).

iii) *virtual spatial linkage of LU:* group of polygons with identical LU for a given time step. This constraint provides the means to 'virtually' merge polygons and enforce a unique LU. This option is particularly useful to control fields merging and temporary subdivisions [Schaller et al. 2010].

iv) *LU area target:* LU cover proportions per group of polygons and time step. Target proportion of land use cover can be imposed per 'management unit' to simulate for example farm types, individual or administrative policies.

2.3 Stochastic & rule-based process

In the model, land use change is driven at each time step by a stochastic process through matrices of probabilities of land uses successions (Markov chains). In brief, the landscape is initialised with current land uses, if unavailable it is by a random allocation (cf. figure 2). This initial allocation is tested against all the LU constraints; if all are met, the probabilities in the Markov chain(s) are used to go to the next time step. If not all constraints are met, the current allocations are re-allocated for a given number of iterations using user-defined options (refused allocations are randomly changed using the Markov chains or user-defined substitutions rules). The iterations include a simulated annealing process to accept temporarily an allocation not meeting all constraints before a new reallocation.

One run of the model provides one land use allocation amongst many possible ones. The exploration of alternative realisations of scenario is considered in the following section on uncertainties.

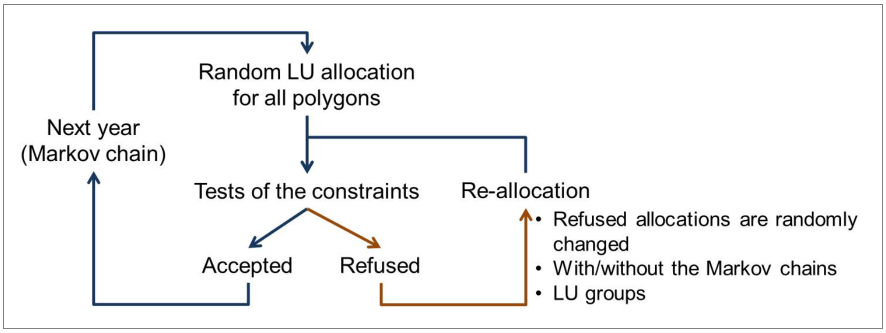

Figure 2. Model's algorithm (LU: land use).

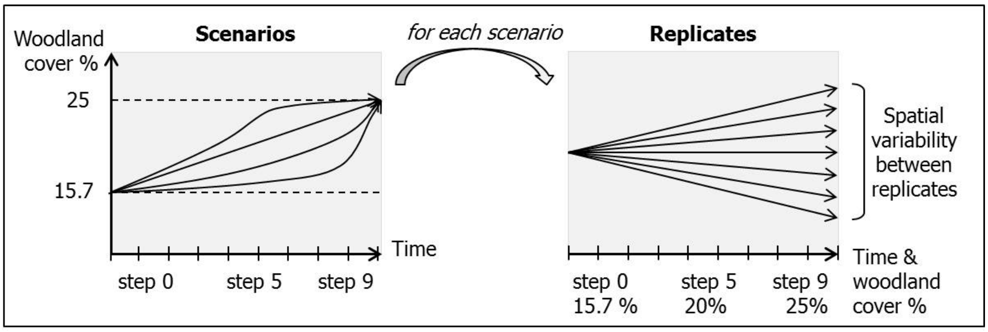

Figure 3. Scenarios and replicates for exploring path-dependency and spatial variability.

2.4 Uncertainty evaluation through stochastic modelling

The rule-based process of the model controls targets and defines pathways of the desired scenarios, whereas the stochastic process provide the support to explore the spatial variability of potential realisation of a given scenario (cf. figure 3). The combination of the two provides the means to explicitly consider uncertainties.

3 CASE STUDY

The following scenarios aim at exploring potential pathways to reaching governmental targets on woodland expansion in Scotland, and their impacts upon ES. In 2007, woodland covered 15.7% of Scotland, with an expansion rate of about 3,500ha per year for 2007-10 [Forestry Commission 2011]. The Scottish government set an aspirational target of 25% woodland cover by 2050 [Forestry Commission Scotland 2006], however this target is currently being replaced by a planned 10,000ha expansion per year.

3.1 Scenarios definition and input data

The Land Cover Map 2007 [LCM07; Morton et al. 2011] was used to define the spatial units and the land use classes on the whole of Scotland. The areas available to woodland expansion are defined by considering physical restrictions (woodland are excluded from rock, water, urban, montane habitats and alpine & litho soils), protected habitats (woodland are excluded from peatland) and land uses (woodland excluded from forecasted prime land for 2050) (cf. figure 4b).

Three trends of woodland expansion in 5 time steps until 2050 are investigated i) current trend (e.g. 3,000ha/year), ii) planned trend (e.g. 10,000ha/year), iii) linear trend to reach 25% woodland cover in 2050 (e.g. 18,378ha/year, cf. figure 4a). Each scenario was run 100 times. Woodland connectivity over time for each scenario was evaluated using the metric “number of patches” defined in Fragstats at 100m resolution [McGarigal et al. 2002].

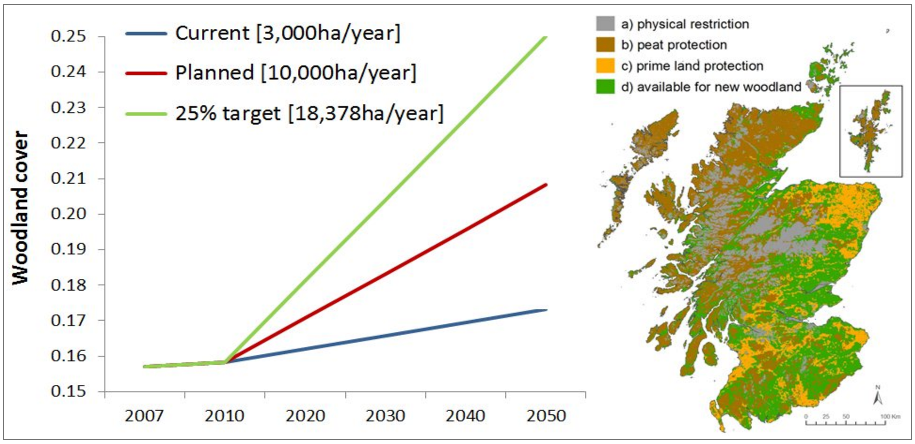

Figure 4. a) Woodland cover for three scenarios: current trend, planned trend, 25% cover target. b) Areas available for woodland expansion in green.

3.2 Results and Discussion: Land use allocations and uncertainties

The scenarios were simulated at the scale of Scotland. However the fine scale land use dataset allows to zoom to field scale and thus to investigate the impacts at a more local scale, an example of subset is presented for the Tarland catchment (cf. figure 5). This catchment is located at the limit between the lowlands, which are fertile land for agriculture, and the uplands, which are characterised by poor soils and extensive grazing. This catchment can thus provide a platform to study the interactions between the two environments.

In figure 6, the number of patches for the 25% target scenario reaches its highest value in 2030, i.e. at 20% woodland cover, before decreasing. The shape of the curve indicates that when increasing woodland cover beyond 20%, patches are becoming more connected, even when no rules where imposed on woodland aggregation. The same level of connectivity is reached in the “planned” scenario by 2050, i.e. 20 years later that if the 25% target policy was enforced. The measure of connectivity is limited, but provides an initial analysis. Due to processing time constraints, the connectivity analyses were only carried out on 10 out of 100 replicates, but after the right pane of figure 6, the values obtained are within the same range.

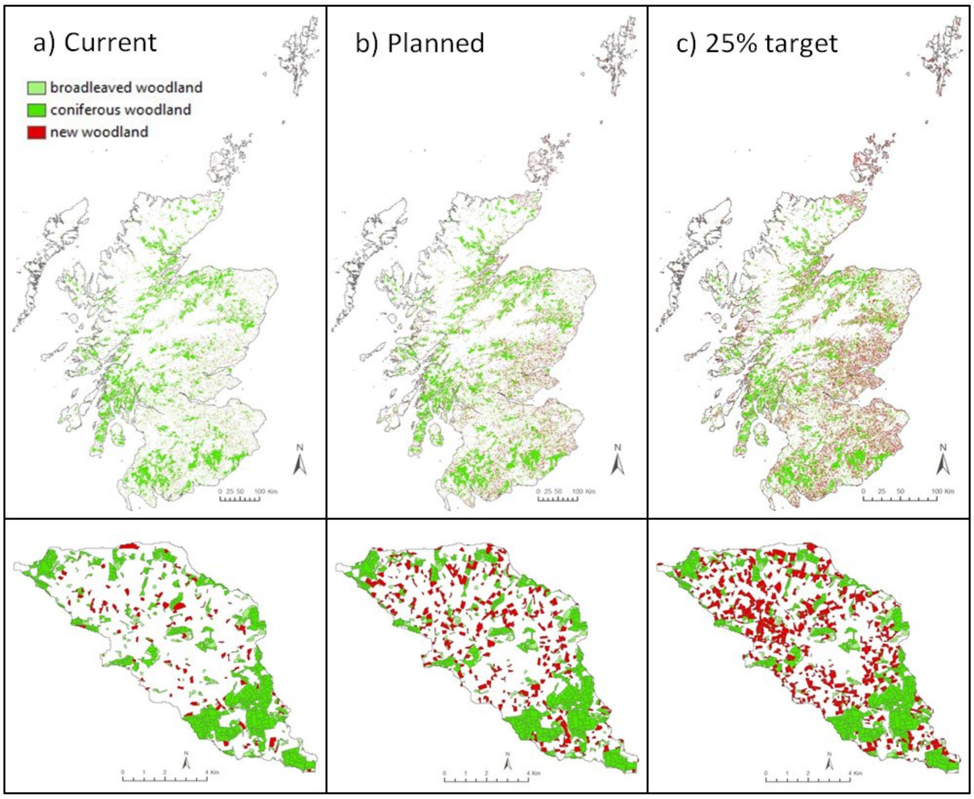

Figure 5. Examples of the three scenarios at Scotland scale and zoom to Tarland sub-catchment (one replicate for each).

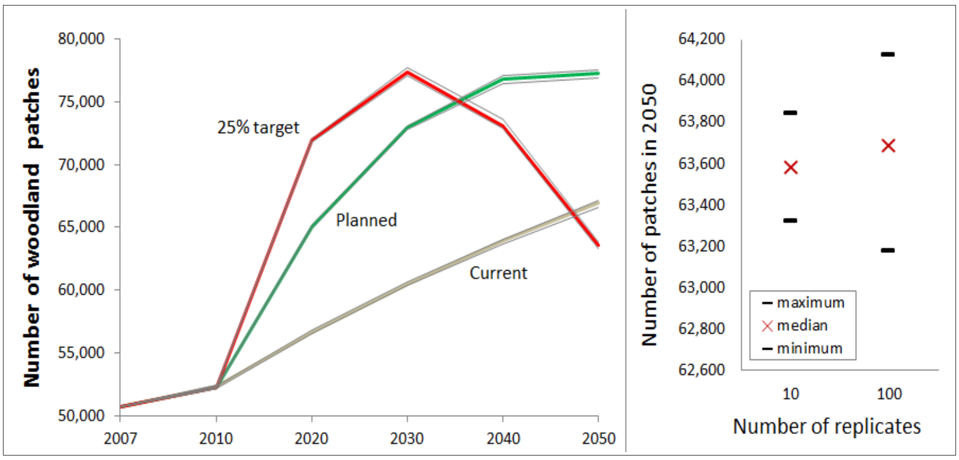

Figure 6. Number of woodland patches at national scale for the three scenarios (median number over 10replicates with minimum and maximum values shown in light grey lines). On the right pane, median with minimum and maximum values over both 10 and 100 replicates for the 25% target scenarios in 2050.

These preliminary scenarios ignore the woodland types (plantation, regeneration, native, coniferous or broadleaved) and the lag time required between plantation or regeneration until full growth; further work will aim at bridging this gap.

4 DISCUSSION ON THE APPROACH

The current model structure provides some advantages but also imposes some specific limitations to the use of the model for land use modelling.

The stochastic approach allows one to explore the variability in potential future landscapes, as shown in the example above. The approach explicitly acknowledges the uncertainty of the future and is used to illustrate the multiplicity of possible spatial realisations of the same policy objectives. The representation of the landscape in a vector format, provides the means to simulate land use change, while respecting the current characteristics of the mosaic of the landscape (e.g. field's shape and ownerships).

However, the landscape is still represented as a fixed 2D surface. In other studies, the dynamics of field's merging was investigated with an hybrid tool, APIlandsfacts, which is based upon APilland [Boussard 2008] and LandSFACTS. It was used to model dynamic field merging in the Niort region, France [Schaller 2011]. The fixed regular temporal step might represent anything from 1 year, 10 years or 1 month. It offers a simplistic representation of the landscape, by only considering regular snapshots through time, where land use changes can only happen at those regular steps. This is not sufficient for representing short-leaved, changeable transitional states, such as the length of time a field is bare between sowing and crop growth, which could have high impact on some ES services.

In the model, all simulated land use change will meet all the constraints set, i.e. the constraints define un-flexible limits for the range of potential landscapes. Thus, this range is sensitive to even slight changes in the constraints (different proportion of land use, or land capability). Sensitivity testing of the land use change to the constraints could be useful within the scenario framework to identify the controlling factors to land use changes in a given landscape.

5 CONCLUSION

In this paper, an approach for land use modelling was presented which would be relevant for ES assessments. The model could provide a useful alternative to classical optimisation modelling, as it recognises that the future is inherently uncertain and that notions of optimal criteria vary amongst stakeholders (e.g. an optimal solution now may not be optimal in the future). As detailed in this paper, its particularity lies in its stochastic process and non-optimisation, which are both most relevant when the exploration of sub-optimal landscapes are required. For every scenario, the model can provide multiple landscape mosaics with the same general land use patterns characteristics. Such a use can be linked to the generation of ‘neutral landscapes’ as specified in landscape ecology. It also provides a platform for integrating general top-down constraints with local constraints (bottom-up) through fine scale local characteristics or stakeholders involvement.

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