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Multi-Scale Modelling of Ecosystem Services – an Iterative Approach

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Abstract: Ecosystems are dependent upon the interactions between the natural environment and human factors. Each different ecosystem service is also associated with varying spatial scales related to their functioning and human benefits. Thus, key requirements for an ecosystem-based approach (EBA) are i) multiple scales, especially landscape scale, ii) flexible method for adaptive response and iii) stakeholders participation. Understanding complex inter-relationships between ecosystem functions and their services requires tools to handle change and uncertainty, notably scenarios and sensitivity analysis. We propose an iterative approach, which is multi-scale and user-focused based upon the LandFACTS toolkit to generate a suite of land use change scenarios. The complexity of the scenarios and knowledge of the ecosystem is evaluated and built up through an iterative procedure with stakeholders using spatio-temporal constraints on land use. This method has been used to link climate change impacts (direct and indirect) with climate change responses (adaptation and mitigation). An example of evaluating alternative scenarios of land use changes through EBA (e.g. for food security, carbon sequestration, woodland habitat network) is presented in this paper at two scales (Tarland sub-catchment and Dee catchment in Scotland, UK).

Keywords: ecosystem services; scenarios; land use change

1. INTRODUCTION

Landscapes are the reflection of the interactions between the natural ecosystem and human factors [Council of Europe, 2000]. Many landscapes of important natural and cultural values have been degraded and lost [Antrop, 2005; Hobbs, 2009], usually due to emphasis on resource production for human consumption (food, water, materials) at the expense of other ecosystem functions [Millennium Ecosystem Assessment, 2006]. To reverse the trend, multi-functionality of land use has been highlighted as having a strategic role for sustainable development, and should be integrated within land use planning processes. The ecosystem approach highlights the multi-functionality of the landscape and its land uses with ecosystem services operating at different spatial and temporal scales [CBD, 2001], their assessments requires to adapt the scale of study to the desired services. For example climate regulation is of global impact whereas pollination or habitat cover are of a more restricted impact; soil formation and soil erosion regulation are local. Multi-scale land use scenarios provide the means to assess the ecosystem services at their relevant scale. Past and future drivers of land use changes are constantly evolving due to economics, technologies, climate etc., therefore to explore potential land use changes and their impact upon ecosystem services a scenario approach is deemed more adequate than a forecasting approach [Veldkamp and Lambin, 2001]. Scenarios are not used to forecast the future, but to define a range of plausible futures independently from current probabilities of occurrences [Goodwin and Wright, 2010]. In the present study, the set up of the scenarios

are refined by the involvement of experts and stakeholders to evaluate and correct initial definition of the scenarios and potential adaptive measures. This iterative and interactive definition and involvement of scenarios facilitates stakeholder participation as good practice decrees [European Commission, 2010]. Instead of modelling stakeholder actions and interactions, the approach described in this paper focuses on providing potential scenarios and adaptive measures. In the literature, land uses are usually allocated on the assumption that profitability is optimised using modelling techniques such as rules [Rounsevell et al., 2006], cellular automata [de Nijs et al., 2004], linear programming [Holman et al., 2005] or empirical-statistical programs [Verburg et al., 2006]. In the present study, the land use scenarios are produced not as a result of optimisation of specific factors or metrics, but aim at exploring potential land use changes through an independent process, based upon key constraints.

Quantitative land use scenarios at local scales are usually downscaled from broad-scale or global economic models (i.e. top-down approach) and have been criticized as requiring a complementary bottom-up approach to strengthen their validity in strategic planning, Figure 1a [Ericksen et al., 2009; Verburg and Overmars, 2009]. Houet et al. [2010] have stressed the importance of representing the landscape at fine scale, such as farms and parcels in order to fully understand land use change. In this paper an alternative approach is detailed by modelling land use scenarios from individual land parcels (i.e. vector format) and using a combination of top-down and bottom-up approach for decision units and biophysical constraints upon the land (Figure 1b).

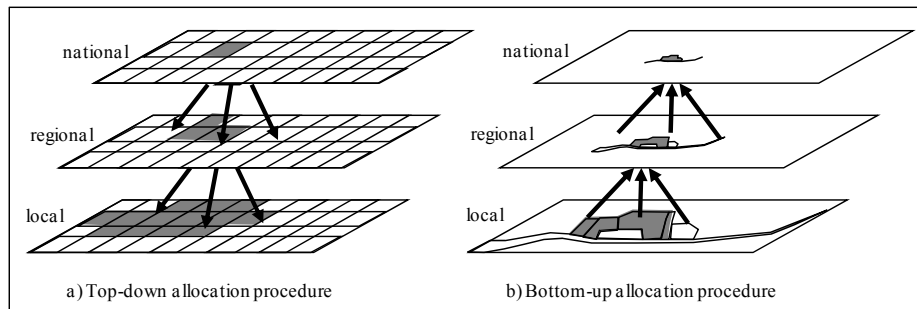


Figure 1: Top-down and bottom-up method to assess land use change

Firstly we highlight our approach for constructing scenarios of land uses for ecosystem services, before providing an example of one case study at two scales: sub-catchment and catchment levels.

2. METHODOLOGY

2.1 General approach

The approach used for constructing land use scenarios integrates current land use patterns, current and future biophysical constraints, and land use trends derived for example from policy targets (Figure 2). Scenarios are iteratively refined using a participative process to assess and adjust them to local socio-economic contexts. The flexibility of the method allows scenarios to be constructed at multiple scales from i) local scale using real land use units, i.e. parcels as polygons, complemented with current cropping systems (derived from agricultural statistics or farm surveys); ii) catchment scale using aggregated land use units or land cover as surrogate; or iii) regional scale using aggregated land cover and focusing on large scale policy targets. Multiple temporal scales can also be considered from yearly pattern changes (e.g. crop rotations) to longer term land use changes (e.g. targets for the year 2020 or 2050). The scenario's purpose dictates the spatio-temporal scales and the type and range of constraints to integrate within the LandSFACTS toolkit. Ecosystem services relevant to the scale of the obtained land use scenarios can then be assessed.

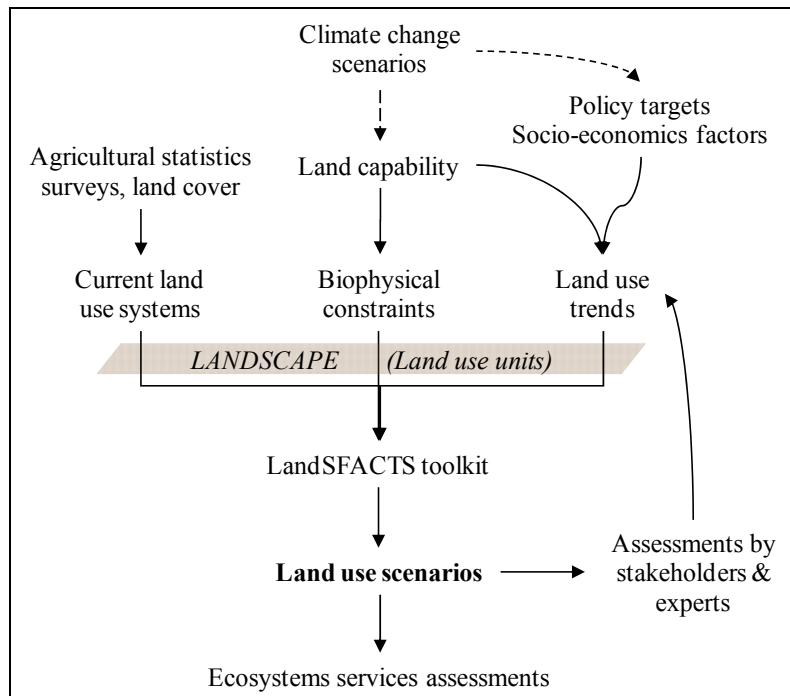


Figure 2: General iterative approach

2.2 LandSFACTS toolkit

LandSFACTS requires the translation by the user of scenario conditions (e.g. agricultural and socio-economic factors) into simple spatial and temporal constraints on the land use allocation (Figure 3). Spatio-temporal constraints include restrictions on the spatial extent of land uses, probabilities and rules on the land use successions [Castellazzi et al., 2008] and desired proportions of each land use per simulation time step. The categories of land uses to simulate are defined according to the scenarios, for example they can range from individual crops and species up to broad habitats. Simulation time step can be adjusted from one year to simulate yearly patterns of crops upwards to fifty years to study wider temporal patterns.

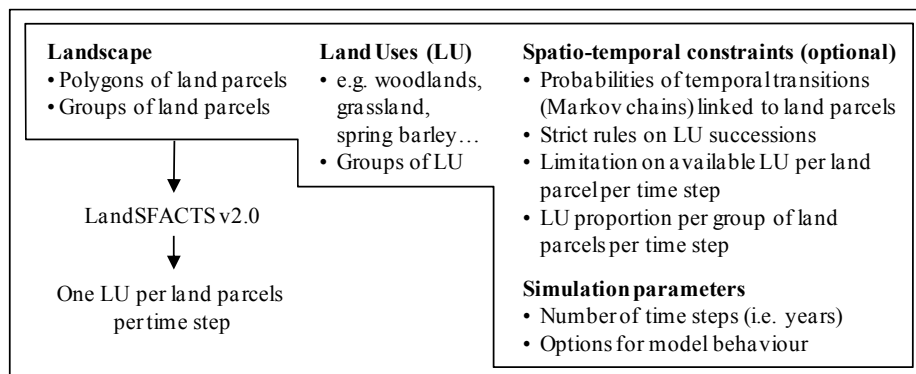


Figure 3: Inputs and outputs of LandSFACTS v2.0 model

The land use allocation for the land parcels is performed by the model using stochastic (Markov chains and simulated annealing) and rule-based processes [Castellazzi et al., in press]. Due to the stochasticity within the model, an allocation provided by a run of the model is only one potential allocation among many others. Therefore running the model multiple times is required for exploring the range of potential allocations meeting the scenarios constraints. The toolkit with its front-end, documentation and tutorial are freely available on the internet [LandSFACTS v2 website, 2009].

2.3 Assessing ecosystem services

For this paper, the final evaluation of ecosystem services has been restricted to i) climate regulation through carbon sequestration and ii) enhancement of natural ecosystem function through strengthened habitat networks. However, ecosystem services are not only evaluated in a post-processing role, but the initial scenarios constraints are also defined to enhance key ecosystem services. For example, in scenarios for woodland expansion, the spatial localisation of new woodlands is restricted to lesser-quality (non-prime) agricultural land in order to secure food production together with targeting of areas with high values for biodiversity and recreation.

3. CASE STUDY

3.1 Background: woodland expansion

The extent of Scottish woodlands was subject to several sharp decreases through recent history [Hobbs, 2009] mainly due to unsustainable wood production during the First World War and extended grazing and extension of heather moorland. To re-establish woodland cover in Scotland, current government policy aims to expand it from 17% up to 25% by 2050 [Forestry Commission Scotland, 2009]. This increase in woodland is also intended to contribute towards the governmental target of decreasing greenhouse gas emissions by 80%. Several financial schemes are available to support small scale woodland creation on agricultural land, and therefore currently marginal agricultural landscapes might be those most affected by woodland expansion (e.g. as EU “Less Favoured Areas” subsidies). Actual land uses patterns are typically driven by local factors, such as tradition, skills and demographics in combination with the availability of subsidies (e.g. EU LFA payments to counter risks of ‘land abandonment’). Thus bottom-up approach is required to set up scenarios [Verburg and Overmars, 2009].

This case study explores the implications of woodland expansion on ecosystem services through multiple scenarios. The case study is situated within the North-East region of Scotland on two nested scale study areas: Dee catchment and Tarland sub-catchment.

3.2 Land use scenarios on two scales

Woodland expansion will necessitate the loss of other land uses. To secure food production, current strategies suggests that new woodland should not be allocated on prime agricultural land. Current and future prime agricultural lands are identified through the Land Capability map for Scotland [Brown et al., 2008], which integrates climate, soil and topography constraints. Further ecosystem services related constraints on scenario parameters are derived from Gimona and van der Horst [2007] who mapped hotspots within the North-East of Scotland where new farm woodland would enhance habitats for key local BAP (Biodiversity Action Plan) species, visual amenities and on-site recreation potential.

Scenarios at the Dee catchment level are constructed using broad habitats units as defined by the national land cover map (LCM2000, [Fuller et al., 2002]), whereas Tarland scenarios are based upon “real” land use parcels from Ordnance Survey (OS) Mastermaps

polygon data (Figure 4). The basic spatial units used in the simulations define the type of scenarios that can be developed. At the Dee catchment scale, scenarios exploring the impacts of land cover changes upon ecosystem services are relevant; whereas at the Tarland sub-catchment scale, scenarios considering changes in cropping systems and implications on local land ownership can be investigated. The classification of the arable land in Tarland scenarios is further refined by considering detailed cropping systems. The current cropping systems are derived from agricultural census data (Integrated Administration and Control System (IACS) dataset), which records agricultural land parcels receiving subsidies in Europe. Land use conversions to new woodland are restricted to specific classes, e.g. conversions from current woodland, water bodies and built-up land are excluded.

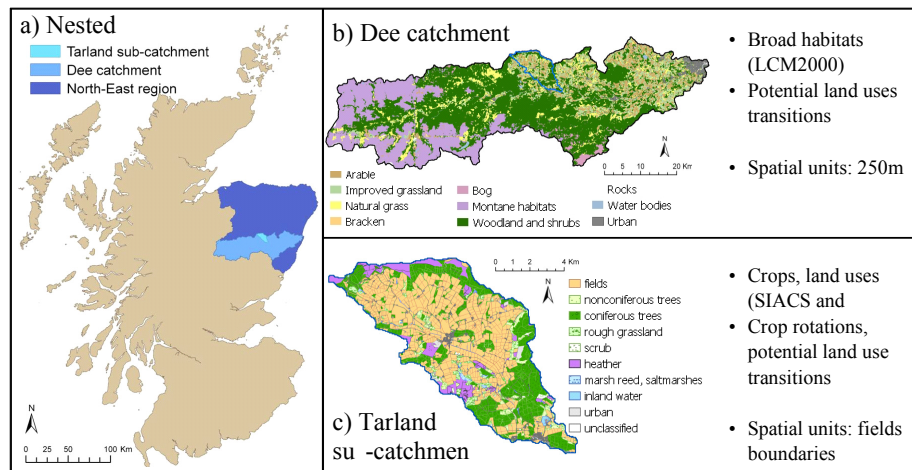


Figure 4: Case study on North-East Scotland

Here we report results from two scenarios for the Dee catchment: the first scenario integrates all the above mentioned constraints on spatial restrictions for new woodland; the second one imposes no spatial restrictions, Figure 5.

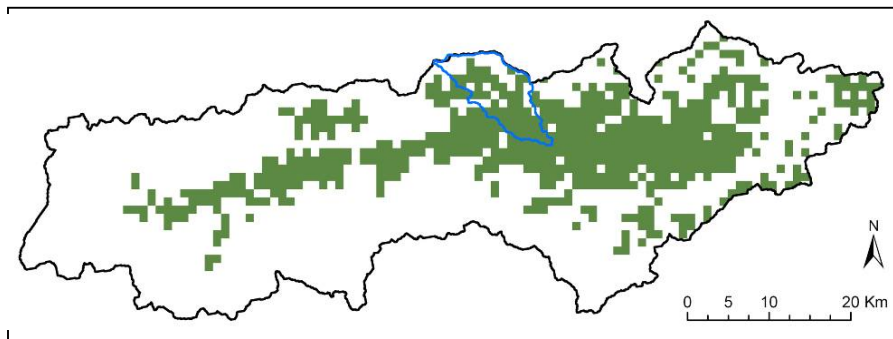


Figure 5: Spatial restrictions on new woodland in the Dee catchment scenarios

For the Dee catchment scenario, a policy target of 25% total woodland cover is imposed. From the 100 simulations of the Dee scenarios with spatial targeting, the range of new woodland covers is extracted for the Tarland sub-catchment (between 40.2% and 45.6%); those covers limits are then imposed as constraint for the Tarland scale scenarios, (Figure 6). This exemplifies the first iteration between the two different scales, which act to constrain and complement each other.

3.3 Assessing ecosystem services on two scales

At the Dee catchment scale, ecosystem services assessments were firstly concentrating on evaluating the impact of new woodlands on habitats networks and on carbon sequestration balance. For the same expansion in woodland cover, the spatial targeting of new woodland increases significantly the mean woodland patch area while decreasing the number of patches (Table 1).

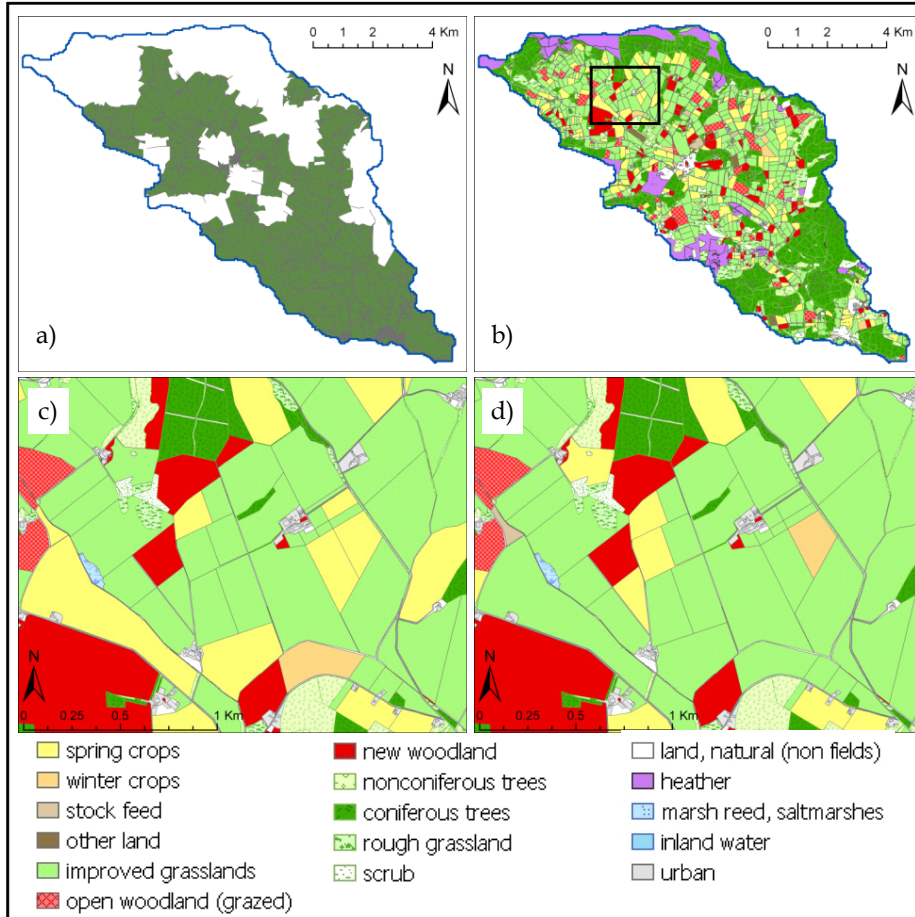


Figure 6: Example of cropping system scenarios in the Tarland; a) in green: land available for new woodland; b) one crop/land use allocation; c) close up for year 0; d) close up for year 1 (for display purpose, all sub-categories are not detailed)

Scenarios	Patch area (100 simulations)		Number of patches (100 simulations)	
	Mean	Standard deviation	Mean	Standard deviation
No spatial restrictions	21.73	0.54	2406.30	57.28
Spatial restrictions	59.69	2.13	876.09	35.91

Table 1: Woodland networks for Dee catchment scenarios

To assess the potential changes on carbon sequestration due to land use changes, a look up table derived from Dawson and Smith [2007] and Conant et al. [2001] was used. The net carbon sequestration rate calculated over 100 simulations of each Dee scenario is reported in Table 2. The spatial targeting of new woodland allocation induces land use changes which are more favourable to carbon sequestration, and hence beneficial for comparative

reduction of greenhouse gas emissions. The difference is mainly due to less arable and grassland being converted into woodland in the spatially targeted scenario than on the non-targeted one. In summary, newly-allocated woodlands in the Dee catchment could be targeted so as to also benefit food production, woodland habitats and recreation, whilst enhancing habitat networks and increasing carbon sequestration, i.e. a potential win-win situation.

Scenarios	Mean Net C rate (*10 ⁶ kgC/yr) (100 simulations)	Minimum Net C rate (*10 ⁶ kgC/yr) (100 simulations)	Maximum Net C rate (*10 ⁶ kgC/yr) (100 simulations)
No spatial restrictions	-351*10 ⁶	-645*10 ⁶	10*10 ⁶
Spatial restrictions	395*10 ⁶	-188*10 ⁶	1,027*10 ⁶

Table 2: Carbon sequestration potential for Dee catchment scenarios

At the Tarland sub-catchment scale, the detailed cropping systems provide the means to set up temporally coherent sets of crop allocations over successive years. The dynamic representation of the landscape is particularly favourable to investigate the impacts upon local biodiversity and ecosystem service issues such as soil erosion, water quality and flood risks. By allocating land uses to real spatial units (i.e. parcels), scenarios are closer to decision units. Detailed feedback and assessment on the scenarios constraints and their realisation could then be obtained by discussions with local stakeholders. This work is still currently under progress.

4. CONCLUSION

In this paper, we presented a multi-scale approach for construction and evaluation of landscape scenarios generation and evaluation with respect to ecosystem services. Some ecosystem services are currently only implicitly represented, but the approach aims at considering them more explicitly, in order to facilitate stakeholders understanding of the trade-offs between them. The development of the scenarios therefore provides a tool to facilitate stakeholders engagement, and to enhance the understanding of the interactions between land use changes and ecosystem services. In the approach detailed above, the multi-scale modelling is based on the use of the same tool (LandSFACTS) for every scale, with the land use elements, units and constraints adjusted to the scenario purposes. Simulating land use scenarios based upon vector representation of the landscape provides scenarios on “real” land parcels. The natural patterns of the landscape induced by the shapes of the parcel’s boundaries can thus be preserved. This realism helps local stakeholders to visualise more easily implications on land use changes. Moreover the inaccuracies and scale dependence induced by a grid-based model of the landscape are alleviated [Purtauf et al., 2005]. The iteration process allows feedbacks between large-scale simulations for policy makers, and smaller scale simulation more adapted for land managers. Iteration also provides an alternative to optimisation modelling of land-uses. Environmental, climatic and human factors are highly variable and an optimised or predictive approach does not facilitate the investigation of completely new or extreme situations. The refinement of the scenarios through iterations with stakeholders should facilitate the identification of land use changes that can deliver multi-functional benefits. Communication and engagement with experts and stakeholders could be facilitated by presenting land use scenarios in 3D visualisation including both specific famous views and “dog walkers” views [Dockerty et al., 2006]. Such work is planned using the Virtual Landscape Theatre [Miller et al., 2007].

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