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Exploring path-dependencies and spatial variability in landscape scale scenarios for ecosystem services assessments

Castellazzi M.S.[1] , **Brown, I.**[1], **Gimona, A.**[1], **Poggio, L.**[1]
[1] *The James Hutton Institute, AB15 8QH, Aberdeen, UK*
[1] *marie.castellazzi@hutton.ac.uk*

Abstract: Ecosystem services (ES) of landscapes evolve with landscapes themselves and with changes in their characteristics or uses due to human or natural causes. Land use changes may have immediate impacts upon the delivery of services in the short term (e.g. for food production), or longer term (e.g. sequestration of carbon by woodland due to a time lag of tree growth). The spatial location of land use changes also impacts on ES; e.g. woodlands might serve different roles for flood regulation depending on their location, through stabilising slopes against erosion or slowing water flow in flood plains.
The integration of high temporal and spatial resolution data with scenarios of land use change provides a dynamic platform with which to assess ES [Rounsevell et al. 2006]. Studies often only consider snapshots in time and spatially limited scenarios of land use change [Millennium Ecosystem Assessment 2006, Nelson et al. 2009, UK National Ecosystem Assessment 2011].
This paper proposes a simulation framework and tools for exploring spatio-temporal dependencies of land use change and ecosystems services. The LandSFACTS toolkit [Castellazzi et al. 2010a, Castellazzi et al. 2010b] allows exploration of stochastic realisations of land use changes within socio-economically defined scenarios. Land use changes are then dynamically assessed for impacts on ES such as carbon sequestration, and biodiversity.
The approach can be used to explore impacts of path-dependencies and spatial variability of land uses change upon ES. To exemplify our approach, a case study of woodland expansion in Scotland is used. Key findings show the sensitivity of certain spatial outcomes on key ES, such as the support of biodiversity through habitat networks. Conclusions are drawn with respect to the potential of such tools for informing strategic and regional planning, taking account of potential impacts between different ES.

Keywords*: scenarios; land use modelling; spatial variability*

1 INTRODUCTION

Ecosystem services (ES) are linked to the natural bio-physical landscape, but the services are strongly influenced by the way in which the landscape is used and managed by humans. Intensively farmed or built-up floodplains might impact upon downriver flood risk and potential pollution levels. The spatial localisation of woodlands might mitigate flood risk if placed on flood plains or decrease soil erosion by stabilising steep slopes. ES are typically evaluated as snapshots of a given landscape at one point in time [Millennium Ecosystem Assessment 2006, Nelson et al. 2009, UK National Ecosystem Assessment 2011]. However, landscapes are constantly evolving through natural progression (e.g. woodland maturing), and through human intervention and land use change. Global market prices, governmental policies or individual land manager decisions can significantly

and rapidly alter land uses from their current states. Climate change, with its uncertain direct and indirect impacts (e.g. land productivity), further exacerbates uncertainties on future land use changes.
To investigate the impact of potential future land use change upon ES, a scenario approach can be followed. The scenarios provide the framework on which to test sets of constraints on the landscape. The potential future landscapes can then be assessed for ES. Integrating the land use changes through time provides spatially explicit intermediary landscapes, on which ES responses can be tracked [Rounsevell et al. 2006].
An example of dynamic scenarios exploring pathways for woodland expansion in Scotland is presented below, along with two simple proxies for ES assessment.

2 CASE STUDY

After a long history of deforestation, Scotland reached a low of about 4% cover at the start of the 18th century [Forestry Commission Scotland 2008]. Active reforestation by the Forestry Commission led to an increase in woodland cover to 15.7% of Scotland by 2007. Current trends in woodland expansion are about 3,000ha/year for 2007-10 [Forestry Commission 2011]. Current Scottish policy aspires to further increase the woodland cover to support decreases in Greenhouse Gas emissions and support biodiversity. In 2006, an aspirational target of 25% woodland cover by 2050 was included in policies [Forestry Commission Scotland 2006]. However, this target is currently being replaced by a planned 10,000 ha expansion per year. Currently no restrictions are imposed on the spatial location of new woodlands, however, according to the Scottish Land Use Strategy, peatland and prime land should be protected for preserving carbon stocks and food security respectively [Scottish Government 2011].
The following land use change scenarios aim at the evaluation of the potential realisation of those policies on the Scottish landscape in comparison with current trends. Two succinct ecosystem services assessments were carried out to evaluate the scenarios: estimated carbon sequestration and woodland connectivity.

2.1 Land use scenarios tool: LandSFACTS

The LandSFACTS model [Castellazzi et al. 2010a, Castellazzi et al. 2010b] uses a non-optimisation approach to explore potential variability in space and time of land use changes. The model is based upon a stochastic process (random decision within given probabilities of land use changes) restricted by rule-based constraints on spatio-temporal patterns of land uses. Each run of the model provides one spatio-temporal realisation of land use change. Multi-running of the model provides a tool to explore the range of spatio-temporal variability between those realisations. A high degree of variability indicates the ease of implementation of the constraints tested, and a large degree of freedom in the actual implementation. The approach to modelling land use scenarios provides the means to study both path-dependency using dynamic scenarios (multiple time steps instead of snapshots) and spatial variability in the realisation of each path (cf. figure 1).

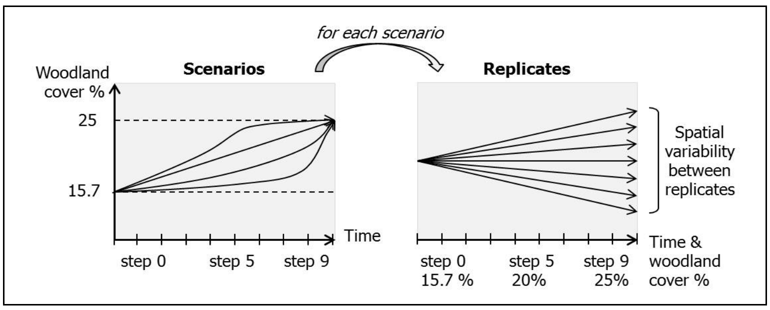

Figure 1: Scenarios for investigating path-dependency and replicates for exploring the range of potential spatial variability within a scenario

2.2 Landscape units and spatial restrictions on woodland expansion

The UK Land Cover Map 2007 [LCM2007; Morton et al. 2011] was used to define the spatial units and initial land uses. The LCM2007 represents the whole of Scotland in 2.11 million of polygons mapped at field resolution, allowing Scotland-wide model simulation with high resolution data.For this paper, the expansion of woodland is spatially restricted by two factors:

- Biophysical limitations: defined by current land uses (water, rocks, montane habitats, urban) and soil information (alpine and lithosols), (cf. figure 2 a).
- Current policy on the protection of peatland and future 2050 prime land [Brown et al. 2008], (cf. figure 2 b) and c).

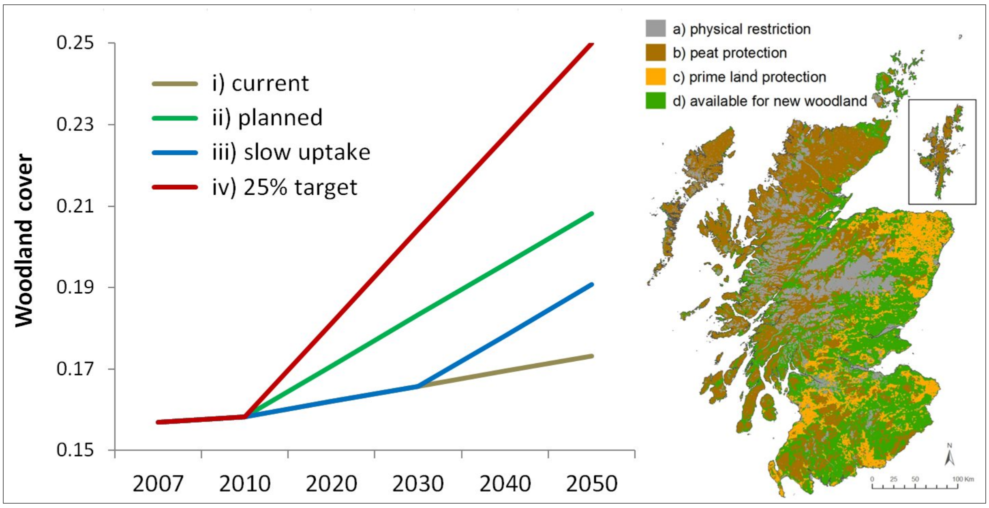

Figure 2: Four scenarios of woodland expansion: i) current trend, ii) policy planned rate, iii) slow uptake of policy, iv) 25% target. Spatial restrictions on new woodland localization in Scotland

2.3 Path-dependencies on woodland expansion

Four sub-scenarios were set up to investigate different trends for woodland expansion (cf. figure 2):

- current rate of 3,000ha/year,
- policy planned rate of 10,000ha/year,
- slow uptake of policy with current rate to 2030, then planned rate,
- 25% cover target by 2050.

The constraints on the rate of woodland expansion are set at ten year intervals, providing four time steps between 2010 and 2050 targets. The original land cover map dating from 2007 was updated to 2010 by simulating known woodland expansion. Each scenario was run 100 times to create as many replicates, i.e. 100 different spatial realisations of a given scenario.

2.4 Ecosystem assessment methodology

Land use changes over time are dynamically assessed for impacts upon carbon sequestration, and woodland connectivity. The carbon sequestration assessment is based upon a look up table of land use change to new woodland (cf. table 1). Woodland connectivity is evaluated by proxy by the number of woodland patches at 100m resolution using the Fragstats tool [McGarigal et al. 2002]. Due to time constraints, the Fragstats analyses were only carried out on 10 replicates for all scenarios and 100 times for the 25% target scenario to evaluate possible mismatches. These simple analyses aim to provide insight on how the rate of woodland expansion and spatial localisation impact on potential services.

Table 1: Estimated carbon sequestration look up table [Dawson and Smith 2007]

Land cover changed to woodland	Mean Net C rate (*10^6kg C/m2 /yr)
Arable and horticulture	8.5
Improved grassland	1
Rough grassland	2
Neutral, calcareous, acid grassland	2
Bog	-29.5

3 RESULTS

The land use change scenarios were simulated at Scotland-wide scale, however due to the high spatial definition of the datasets, results can be viewed in greater detail, such as the Tarland sub-catchment (cf. figure 3). For this preliminary paper, further results are only presented at Scotland-wide scale.

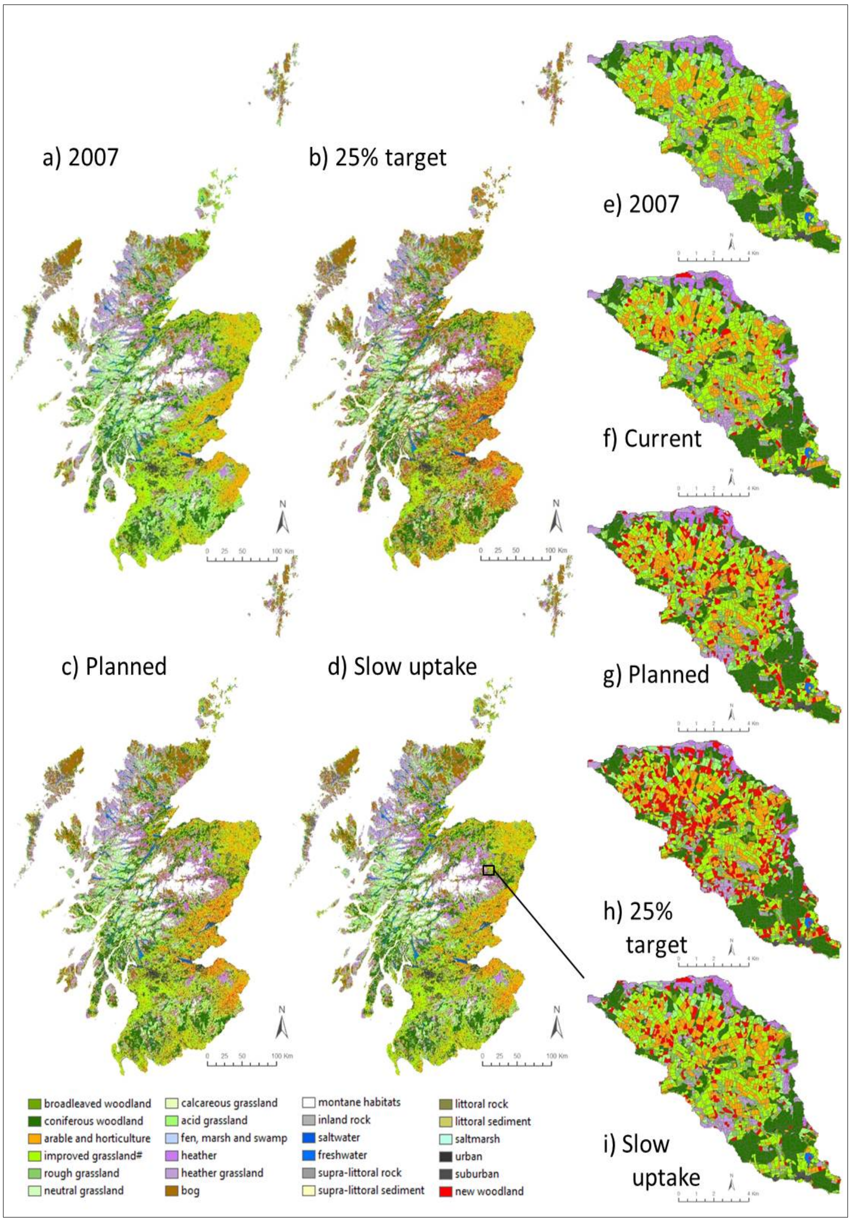

Figure 3: Realizations of the scenarios with zooms to the Tarland catchment

The four scenarios used the same spatial restriction on new woodlands, therefore the proportions of land use types being replaced by new woodland is very similar (cf. figure 4). Over all the scenarios, the mean contribution of land uses to new woodland is distributed as follows: 34.4 % from semi-natural grassland, 23% from improved grassland, 17.6% from bog, 14.5% from agriculture. The land use change of bogs to new woodland was due to differences in classification of datasets (soil dataset informed by 1988 land cover maps and the new land cover dataset, LCM2007).

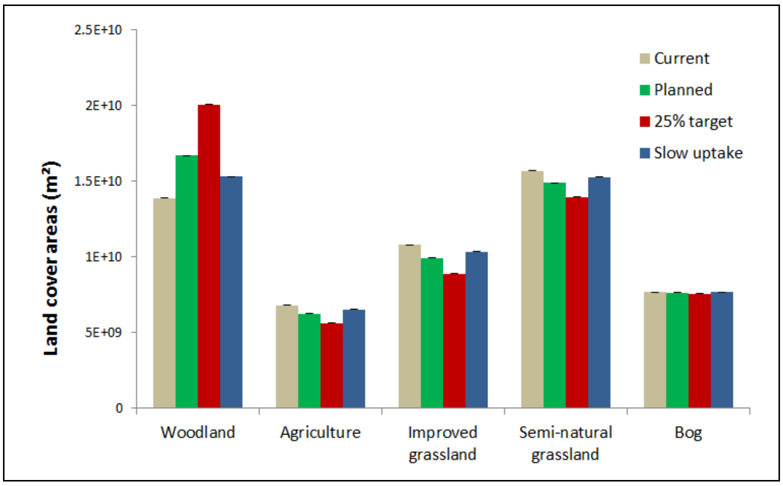

Figure 4: Land cover areas in the four scenarios in 2050 (median with minimum and maximum values as error bars, which are all within 0.99 and 1 of the median)

3.1 Carbon sequestration assessment

An estimation of carbon sequestration benefits for each scenario from 2007 to 2050 was carried out using the land use look-up table in table 1. Figure 5 shows the fluctuations in rates of carbon sequestration for each scenario. As expected, the rates follow the rates of woodland expansion. The variability between the replicates for any given scenario ranges from 3.6% to 14.4% of the median value.

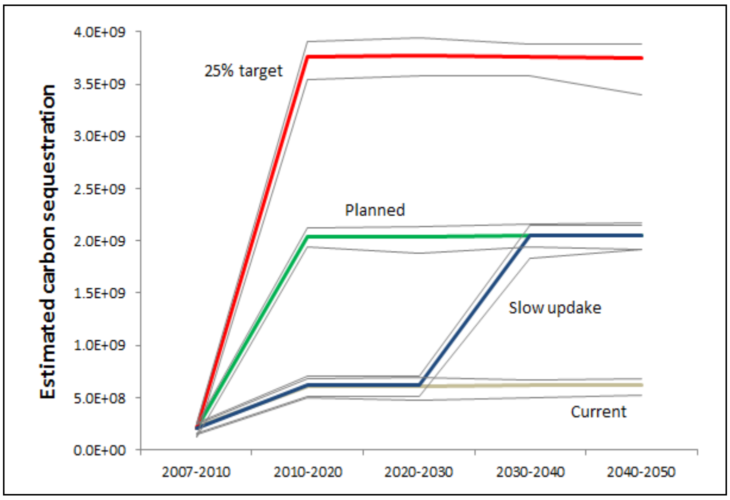

Figure 5: Estimated carbon sequestration (Mean Net C rate (*10^6kg C/m2 /yr)) for the four scenarios (median number over 100 replicates with minimum and maximum values shown in light grey lines).

3.2 Woodland connectivity assessment

The number of woodland patches was used as a proxy for woodland connectivity and its benefits on biodiversity. As expected, for each scenario, the number of woodland patches increases with the increase in woodland cover (cf. figure 6). However, the 25% target scenario reaches a peak in 2030, which is its equivalent to 20% woodland cover, followed by a decrease in the number of patches. The decrease in the number of patches indicates that despite the new woodland being randomly allocated within the landscapes' available areas, the new woodlands are now connecting already existing patches. This would indicate that by reaching at least 20% woodland cover in Scotland, woodland connectivity might be strongly increased even without more policy constraints, such as imposing new woodlands on land neighbouring existing woodlands. The Planned and Slow uptake scenarios seem to be close to reaching the 20% threshold by 2050, with at least 20 year lag time, i.e. 2070, before it would reach the same benefits as the 25% target scenario.

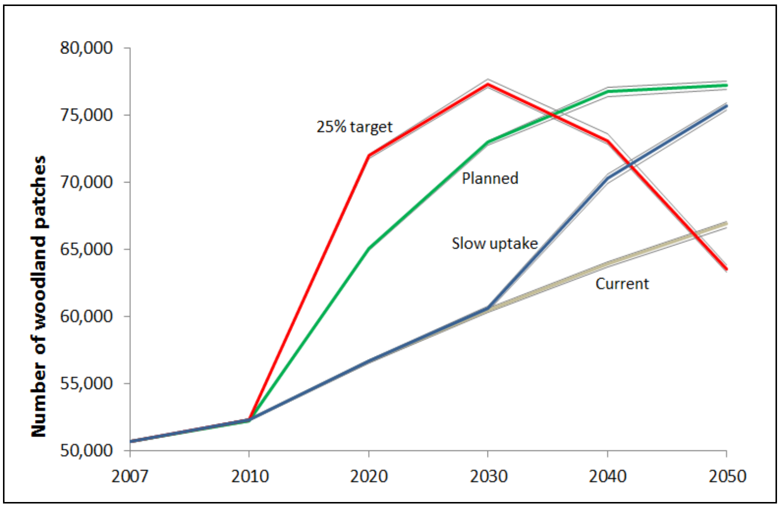

Figure 6: Number of woodland patches in the four scenarios (median over 10 replicates with thin grey lines of minimum and maximum values)

The 25% target scenario also had its 100 replicates analysed for the number of patches, and their frequencies were plotted against the frequencies for each simulated year (cf. figure 7). As expected the full range of values is not represented in the 10 replicates sample, thus analyses limited to 10 replicates of a scenario might overlook some extreme configurations of woodland patches. Further work is underway, to analyse a larger number of replicates.

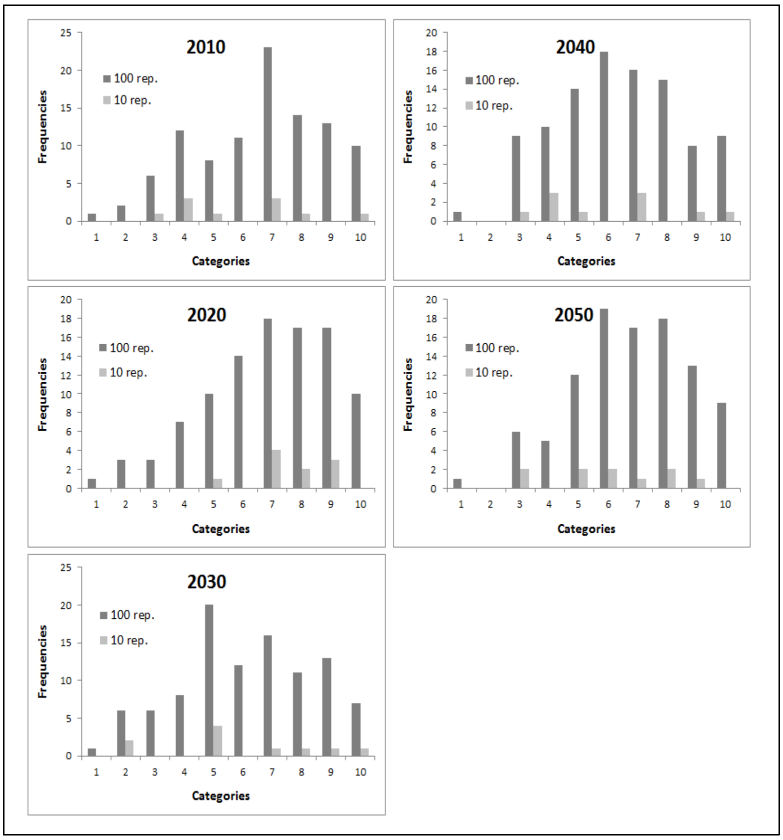

Figure 7: Distribution of the number of patches values between 10 and 100 replicates, for the 25% target scenario.

4 DISCUSSION

The scenarios mimicked four different potential trends for woodland expansion in Scotland from 2007 to 2050. One trend followed current rates of woodland expansion (3,000ha/year), reaching about 17% woodland cover by 2050, with little impact on the two estimated ES proxies. A scenario following current policy of 10,000ha woodland expansion per year, reaches nearly 21% woodland cover by 2050. Benefits for carbon sequestration and woodland connectivity were clearly visible in comparison from the current trend scenario. The Slow uptake scenario provided a mid-way alternative between the Current and Planned scenarios. This scenario might represent a “more realistic” realisation of policy, due to potential time lag between planning and implementing new woodland. The fourth scenario represented a 25% woodland cover target set for 2050, which had been set in 2006, before it changed to an aspiration instead of a target. This scenario shows strong impacts upon both carbon sequestration and woodland connectivity. Connectivity was particularly enhanced after reaching 20% woodland cover.

Variability between replicates of a scenario, and between scenarios, could be visualised and taken into account in the carbon sequestration and woodland connectivity assessments.

For the four scenarios, the spatial restrictions on woodland expansion were kept constant and considered that areas of peatland and all prime land would be protected from new woodlands. However, the productivity of the woodlands were not taken in account. The simulated new woodlands might not all be suitable for “wood production” or “energy”, and some locations might only support very slow growth which would be more suitable for biodiversity and/or recreational purposes. Further work is planned to rerun the scenarios with more refined definitions of the potential new woodland types.

Despite the simplicity of ES assessments presented, advantages of the general framework were shown for linking models of land use change with spatial and dynamic assessments of ecosystem services.

5 CONCLUSION

The methodology presented in this paper outlines an approach to explore spatio-temporal variability in land use scenarios for supporting dynamic assessments of ES. The approach has scope for the evaluation of uncertainties due to land use change. Taking uncertainty in land use change into account would provide tools to direct future land use changes towards more robust landscapes with respect to delivering multiple ES.

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