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Simulation scenarios of spatio-temporal arrangement of crops at the landscape scale

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ABSTRACT

The spatial and temporal arrangement of crops is a conspicuous feature of rural landscapes. It has been identified as an important factor in many environmental issues, such as the coexistence of genetically modified (GM) and non-GM crops, and the mitigation of soil erosion. This paper examines a scenario-based approach for rapid generation and screening of crop allocations that meet user's constraints without requiring mechanistic modelling. LandSFACTS (Landscape Scale Functional Allocation of Crops Temporally and Spatially) is a software application specifically designed to simulate such crop arrangement scenarios, whilst ensuring both spatial and temporal coherence with regard to the initial constraints. The software uses an empirical approach to allocate crops to fields (polygons in vector format) over a sequence of years, using a stochastic process (Markov chains) and rule-based constraints. Crop rotations are represented by transition probabilities complemented by other temporal constraints such as return period or prohibited sequences. Further spatial and temporal constraints on crop arrangement can be applied through separation distances, yearly proportions, and the application of statistical tests. The software outputs a crop allocation solution with a crop for every field for every year, respecting all user-defined constraints; the range of potential solutions can then be explored through multiple model runs. Metrics based upon the difficulty of obtaining such an allocation from the initial constraints are also generated. A case study is provided to demonstrate the use of combined agronomic and environmental criteria for exploring GM crop coexistence at the landscape scale.

Software availability

Name of software: LandSFACTS 1.6
Programming language: C/C++, Python 2.4
Libraries used: GEOS 3.0, SQLite 3.3, Qt 4.1
Inputs/outputs format: ESRI shapefile for the landscape, and ".dbf" format for other files
User interface: graphical interface, detailed documentation and tutorial with example datasets
Year of first availability: 2007
Availability: http://www.rothamsted.ac.uk/pie/LandSFACTS/ – free to use under the GNU Public licence, version 2
Subsequent versions: http://www.macaulay.ac.uk/LandSFACTS/

1. Introduction

1.1. Context

The complex inter-relationships inherent in environmental systems mean that a landscape-scale approach can have significant advantages when investigating issues such as soil erosion, water resources, disease and pest control, crop coexistence, and food safety. In agricultural landscapes, the spatial and temporal arrangements of crops have been highlighted as a crucial parameter that can exacerbate or mitigate environmental risks. For example, Joannon et al. (2006) found that by coordinating crop allocation between farms, runoff could be reduced by up to 13% in a trial catchment thus potentially decreasing soil erosion. Similarly, crop mosaics within agricultural landscapes can impact both positively and negatively upon biodiversity depending on species requirements for habitat (Ricketts, 2001; Wiens, 1976). When simulating

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the dispersal of genetically modified (GM) pollen and seeds at the landscape scale, Colbach et al. (2005a,b) demonstrated that the risk of gene flow between GM and non-GM related oilseed rape (*Brassica napus*) crops could be significantly reduced by combining an increasing spatial and temporal separation between GM and non-GM oilseed rape. Research to identify "optimal" crop arrangements and evaluate their real-world feasibility is usually an interdisciplinary activity that aims to integrate multiple social, economic, environmental and policy factors (e.g. crop prices, farm types, farm workload and infrastructure, climate, crop characteristics, soils and land capability). Alternatively, preliminary studies could focus on a more expediential scenario-based approach exploring the potential of multiple landscape arrangements through hypothetical crop allocation, based upon key constraints and the screening of unviable options. Such an alternative approach does not need to follow a mechanistic approach nor an optimisation process. Different environmental, economical or societal factors can potentially lead to a similar land-use allocation, therefore being able to produce scenarios with controlled crop arrangement, independently of their mechanistic origins, provides a means to assess a wider range of potential crop allocations.

The primary advantage of the scenario-based approach is that it allows rapid testing of a wide range of possibilities, and through the screening approach it can highlight particular options to investigate in greater detail. When considered in the context of scenario typologies (Borjeson et al., 2006; Mahmoud et al., 2009), the proposed methodology can operate either in an explorative mode (*What can happen?*) or a normative/anticipatory mode (*How can a specific target be reached?*), or even a combination of both. This combined approach is particularly relevant for evaluating potential landscape changes against acceptable environmental risks. Scenarios can therefore be used to both test the feasibility of potential regulatory limits, such as imposing separation distances between crops (normative scenario aiming for a specific crop spatial arrangement), and of altering crop rotations (explorative scenario investigating potential crop allocation under altered rotations). For example, by following this approach, the physical feasibility of specific separation distances between GM and conventional crops could be evaluated, before the economic and social implications of such policy measures are investigated only for those scenarios with a realisable spatio-temporal solution.

Scenario-based crop studies are often limited by two factors: (i) the lack of readily-available information on past or current crop allocation at the field level to characterise current agricultural systems, and (ii) the difficulty of creating coherent scenarios of crop allocation that meet multiple constraints (e.g. successions rules, spatial distribution, or target areas). National agricultural statistics may provide data from previous years that are aggregated at administrative levels, but still require downscaling to field scale. The use of aggregated crop information and the generation of crop allocation scenarios can therefore benefit by a co-ordinated modelling approach.

1.2. Existing modelling tools for crop or land-use arrangements

In agricultural systems research, models have been developed to create and optimise crop rotations either at individual field level (non-spatial) or at farm scale (spatial), including ROTOR (Bachinger and Zander, 2007), ROTAT (Dogliotti et al., 2003) and CropSyst (Stockle et al., 2003). Such approaches involve balancing nutrient inputs, control of pests/disease, or maximising yields against environmental conditions. By contrast, models such as SFARMOD (Rounsevell, 1999), PALM (Matthews, 2006), or FarmSAFE (Graves et al., 2007) have focused on the decision process leading to crop allocation and constraints on farm management (economic, social, policy, or environmental). In water quality research, crop allocations have been estimated using national statistics and expert knowledge (Klocking et al., 2003; CARROTAGE software from Le Ber et al., 2006; Mignolet et al., 2004) but this approach is not particularly conducive to investigate future alternative arrangements of crop patterns. In landscape ecology, the focus is often on the arrangement of habitats and land use (Hanski, 1999; Vanreusel and Van Dyck, 2007), with some studies also investigating the interaction of multiple landscape functions (e.g. nature conservation, agricultural profit, landscape character, etc.) by the spatial modelling of trade-offs between these functions using GIS tools (Groot et al., 2007; Holzkaemper and Seppelt, 2007).

1.3. An alternative modelling approach

Most of these existing models aim to develop an optimum crop allocation or land-use mosaic. This paper describes an alternative approach, which aims to allow the rapid generation of a range of crop allocations meeting specific targets, whilst recognising that these targets are often subject to negotiation and further iterative refinement. This approach is novel because it provides a generic method of creating landscape-scale scenarios of crop arrangement, both spatially and temporally, with direct control of the final landscape structure through the imposed constraints. The LandSFACTS software (Landscape Scale Functional Allocation of Crops Temporally and Spatially) is designed to facilitate and support this approach. Within the software, spatial and temporal constraints on crop arrangement utilise rules developed from existing agronomic or farming decisions such as the return period of crops (Dogliotti et al., 2003) and prohibited crop sequences (Klein Haneveld and Stegeman, 2005).

This paper describes the modelling approach, the inputs, outputs (Fig. 1) and processes used within LandSFACTS. The model evaluation is presented through the analysis of its conceptual model and fitness for purpose. The model is then demonstrated with a case study on the coexistence of genetically modified (GM) crops with conventional crops in a particular landscape context.

2. LandSFACTS description

2.1. Model overview

The LandSFACTS model allocates a crop to each field for each simulation year (referred in this paper as "*crop allocation*"). The

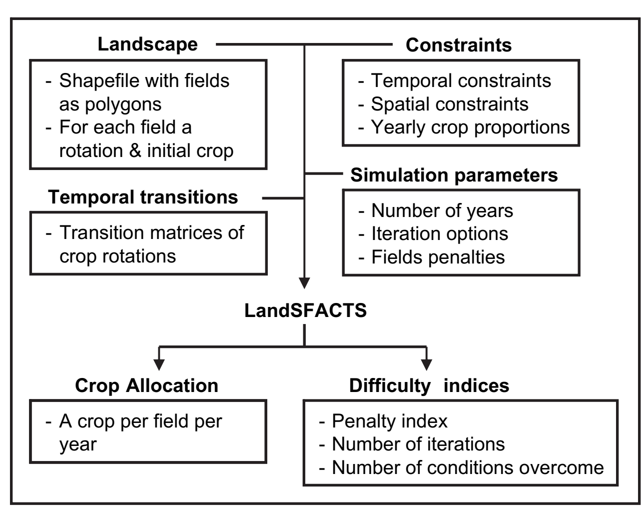

Fig. 1. Overview of LandSFACTS inputs and outputs.