Ecological Informatics 40 (2017) 62–80

Contents lists available at ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf

Simulating spatially-explicit crop dynamics of agricultural landscapes: The ATLAS simulator

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A R T I C L E I N F O

Keywords:
Crop rotations
Crop phenology
Spatially-explicit
Landscape dynamics
Crop management

A B S T R A C T

The spatially-explicit AgriculTural LandscApe Simulator (ATLAS) simulates realistic spatial-temporal crop availability at the landscape scale through crop rotations and crop phenology. Intended to be linked to organism population dynamics, the simulator is developed in a multi-agent platform. The model relies on initial GIS inputs for landscape composition and configuration. Users define typical rotations and crop phenology stages to be included, according to their objectives. In the study, we present two applications to contrasting landscapes, where ATLAS is capable of simulating accurate composition (crop area) and configuration (crop clustering) dynamics. ATLAS has potential applicability to a range of contrasting agricultural landscapes. The benefits of such a simulator are the possibility to study the effects of various simulated management scenarios of crop spatial-temporal availability in relation to target organisms and/or specific ecological processes (e.g. pest, biological control), within a single model framework.

1. Introduction

Agroecosystems are characterized by high spatial and temporal instability, due to human management through agricultural practices such as crop rotations, and climatic conditions influencing crop phenology. Crop phenology can be defined as the timing of cyclic, climatically driven, recurring events (e.g. growth stages) of the plant. This high spatial-temporal variability of crops within agricultural landscapes has an important impact on the habitat availability for animal organisms; indeed, many depend on various resources to fulfill their life cycles (Gurr et al., 2016; Landis et al., 2000; Médiène et al., 2011). In particular, biological control of pests by natural enemies is dependent on a range of habitat availability within the agricultural landscape, and can be highly impacted by changes in the crop cover as new crops are introduced (e.g. Vialatte et al., 2006). For example, pests such as cereal aphids will rely on different crops as nutritional resources throughout the year (Vialatte et al., 2007). Hoverflies, which are natural enemies of cereal aphids, are strongly associated with pastures and forest elements as habitats within the landscape throughout the year (Alignier et al., 2014; Sarthou et al., 2005). Thus, better comprehension of the interactions between the agricultural landscape and these populations could lead to increase in the efficiency of biological control through landscape management.

Nevertheless, studying these interactions often requires observations and data gathering at large spatial and temporal scales. This can be costly and to conduct a full set of experimental studies at these scales can be challenging. Using spatially-explicit modelling can increase our knowledge on the system and allow us to explore the implications of events for which landscape-level experiments are not feasible. Many models aiming to study these interactions are based on artificial landscapes (Bianchi et al., 2010) that can be modified at will to study different theoretical scenarios. Realistic landscapes require mapping effort, and some models include this but remain usually static through time (Parry et al., 2006). In this paper we propose an agricultural landscape model that can easily integrate with dynamic models of organisms to better explore the effects of agricultural landscape dynamics on organisms.

Several models that simulate agricultural landscapes are already available. Models such as the Agricultural Production Systems sIMulator (APSIM; Holzworth et al., 2014) allow a highly detailed simulation of crop phenology through time, in a non-spatial context. Other agricultural landscape models such as LandSFACTS (Castellazzi et al., 2007, 2010), DYPAL (Gaucherel et al., 2006) or LUMOCAP (Van Delden et al., 2010), are on the other hand spatially-explicit and focus on agricultural practices, with the goal to explore the effects of crop

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http://dx.doi.org/10.1016/j.ecoinf.2017.05.006
Received 3 March 2017; Received in revised form 15 May 2017
Available online 30 May 2017

allocation from year to year across the landscape to help decision-makers assess potential impacts on the quality of agricultural landscapes through selected landscape indicators. These models are not intended to be linked to population dynamics and do not consider within-year crop dynamics such as sowing dates or crop phenology. Others, such as the Animal, Landscape and Man Simulation System model (Topping et al., 2003), are developed to study the interactions between organism (e.g. pest, natural enemies) population dynamics and the agricultural landscape and thus consider crop management and phenology at a highly detailed level. All these models have an agronomical approach, with the aim of reproducing detailed agricultural practices.

Most existing models described above are defined at the farm scale. When studying ecological processes, this could lead to spatial scale mismatches which express the fact that the levels of spatial organization in landscape management and the levels of ecological functioning only very rarely coincide (Pelosi et al., 2010). These mismatches constitute one of the main obstacles to the sustainable management of landscapes (Cumming et al., 2006). We thus identify a niche for a model reproducing realistic spatial-temporal dynamics at the landscape scale, without taking into account any social-economical level of organization. By simplifying agronomical practices we also aim at generating a model that can be applied across agricultural systems.

This paper presents the AgriculTural LandscApe Simulator (ATLAS) which is a new, open-source model available in the OpenABM platform (https://www.openabm.org/model/5416), capable of producing a realistic spatialized representation of agricultural landscapes through time with the aim of being linked to organism population dynamics. In particular, ATLAS takes into account both landscape composition and configuration, which are both known to influence population dynamics (Fahrig et al., 2011, 2015). This paper focuses on how crop elements of the landscape are handled in ATLAS. The model was developed to explore a large range of scenarios through the modification of agricultural practices and landscape heterogeneity (i.e. composition and configuration (Fahrig et al., 2011), which can lead to identifying how landscape changes may impact on population dynamics of agriculturally beneficial and harmful organisms.

2. Methods

2.1. The ATLAS model

The AgriculTural LandscApe Simulator (ATLAS) is a spatially-explicit model focusing on reproducing the general characteristic spatial-temporal patterns (composition, configuration and crop availability) of agricultural landscapes. ATLAS was developed in the GAMA modelling and simulation development environment (Grignard et al., 2013) with the following utilities. Firstly, the GAML language used in GAMA facilitates object-based programming, used to describe the behavior of each field. Secondly it allows the user to readily develop agent-based simulations for organisms that link directly to ATLAS. Thirdly, GAMA easily handles GIS data through built-in functions (for example direct spatial modifications on the different elements composing a landscape in terms of shape, placement and attributes). It is also possible to export the simulated landscape and any value of the simulation parameters describing the spatial entities as shapefiles at any moment in the simulation. The ATLAS model is available in the OpenABMmodel library (https://www.openabm.org/model/5416). To help define input data for ATLAS, we also developed an algorithm in R (Team, 2014) detailed in Section 2.1.3.3.

Here we present the ATLAS model using part of the ODD (Overview, Design concepts, Detail) protocol for describing individual and agent-based models defined by Grimm et al. (2006, 2010).

2.1.1. Overview

2.1.1.1. Purpose. The purpose of ATLAS is to simulate a dynamic agricultural landscape reproducing the same general crop pattern metrics as observed in the field in terms of configuration, composition and crop availability throughout the year. In the ATLAS model, landscapes are initialized using an ArcGIS shapefile, weather data and both user-defined crop rotations and phenology via a graphical user interface. The landscape is composed of patches which will each evolve individually throughout the simulation at a daily time step mainly following two processes: crops evolve through their phenology and crop fields evolve through crop rotations. It can be used to simulate a wide range of agricultural landscapes and can be interfaced with individual-based models developed for any organism that interacts with agricultural environments. This tool facilitates the spatial study of potential effects of landscape management scenarios on the interactions between landscapes and organism population dynamics. ATLAS also relies on a smaller number of parameters and inputs compared to other agricultural landscape models.

2.1.1.2. Entities, state variables, and scales. All entities, processes and variables are summarized in Fig. 1. In the ATLAS model, the environment is defined by a **Landscape**, composed of '**Patch**' agents (self-contained entities which represent real world objects). A patch is a spatial entity, simply a field, a forest patch, a hedgerow or another spatial entity of the landscape, and remains fixed in dimensions and location in space and time. Each patch is assigned a **Land use** (e.g. Corn, Forest, Hedgerow, Other…) which defines how the patch will behave throughout the simulation, and a **Land cover** (e.g. CoverWheat, CoverForest, CoverBareGround) which defines what cover is actually on the patch. Each land use can either be static or dynamic through time. Any land use can be defined in ATLAS, and the level of detail (e.g. Forest or Pine Forest and Oak Forest) can be represented, depending on the needs of the scientific question to be answered. A static land use will keep the same land cover throughout the simulation with no phenology considered (e.g. forest). On the other hand, dynamic land uses evolve through time either by detailed phenological stages (i.e. crop growth throughout the season) and/or by being part of a **crop rotation** (which is the practice of growing a series of dissimilar/different types of crops in the same area in sequential seasons). Land covers therefore represent the current cover of the patch and are assigned certain dynamic parameters (e.g. colour, height) which are important for the visualization of the evolution of the landscape covers, but can also have a specific impact on ecological processes (e.g. potential effects of hedge height on insect movement, (Lewis, 1969; Lewis and Dibley, 1970). **Crop rotations** are characterized by the user with a code name and a list of the succession of crops that occur in this rotation. A 'crop rotation' submodel is used in ATLAS to assign the user-defined crop rotations to field patches in the landscape based on several criteria (area, clustering) detailed in the Submodels section. All the parameters included in ATLAS are described in Appendix A (Table A.1).

When crop patches are assigned a rotation, the land uses assigned to the patch will change over time, following the sequence defined by the rotation. The crop land use class contains all the parameters that determine the crop phenology. For each crop, the phenology can be chosen to be very simple (only contain info on crop sowing and harvest dates) or more detailed if there is an important relationship between the study organism and the crop phenology. For example, if the crop's stages have an impact on the population dynamics by providing resources to individuals (e.g. flowering crop stage in relation to pollinators), then the crop should be phenologically detailed if the research question is such that those dynamics should be taken into account. In this case, the crop has a specific Boolean value ("isPhenologicallyDetailed" = True) and further parameters are then needed (i.e. info on crop stages and growing degree day thresholds, see Table A.1). Each patch growing a phenologically detailed annual crop contains a parameter that records the phenological state of the crop. Concerning detailed phenology, the current version of ATLAS only allows annual crops to be modeled (not perennial). Multiple crops within the year can be simulated in ATLAS.