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Rearranging agricultural landscapes towards habitat quality optimisation: *In silico* application to pest regulation

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ABSTRACT

Modern agriculture suffers from its dependence on chemical inputs and subsequent impacts on health and environment. Alternatively, protecting crops against pests can be achieved through the reinforcement of regulation ecological services. Our work propounds a data-driven methodological framework to derive relevant agricultural landscape rearrangements enhancing populations of beneficial organisms regulating pests.

Building on spatialised entomological and geographic data, we developed a parsimonious reaction–diffusion model describing the population dynamics of beneficial organisms. Parameter estimation was carried out in a Bayesian framework accounting for uncertainty in the measurement.

Thousands of agricultural landscapes were generated under agronomic specifications dealt with as constraint satisfaction problems. Population dynamics was simulated on each landscape with the fitted reaction-diffusion model mentioned above, and two metrics of abundances allowed the assessment of the regulation performance of the landscape spatial arrangements. One metric is a mean field performance criterion assessing the regulation performance from the landscape composition only, the other is a spatial performance metric assessing the performance resulting from the whole landscape spatial configuration. The former is computed with a non-spatialised form of the population dynamics model, the latter results from the reaction-diffusion model of the population dynamics. Comparing these metrics enabled to quantify the impact of spatial arrangements, hence allowing arrangements proposals.

This framework was applied to the case study of a ground beetle species involved in the biological regulation of weeds. The arrangement proposals abides by the productive agronomic constraint that is the landscape composition, while they allow for significant habitat quality enhancement (or deterioration) for the beneficial organism (or a pest). Minor adaptations of our integrated data-driven approach would suit numerous situations ranging from the provision of enhanced ecosystem services to land management for conservation.

1. Introduction

A main concern in modern agriculture lies in reducing its dependence on chemical inputs and limiting its impact on health and environment. Alternative strategies for a sustainable agriculture converge towards the reinforcement of ecological processes suitable to protect crops against pests. Landscape has been described as a relevant scale to manage most pests and airborne plant diseases as numerous studies have highlighted the link between landscape complexity and biological control (Thies and Tscharntke, 1999; Bianchi and Van der Werf, 2003; Tscharntke et al., 2007; Chaplin-Kramer et al., 2011). Developing ecologically based agricultural production systems requires to identify and understand key pest suppression drivers. In particular, it is crucial to understand how the spatial configuration of landscape features impacts the dynamics of natural enemies and thus potential biological regulation services (Bianchi and Van der Werf, 2003). In this regard, rearrangement of the landscape in terms of habitat structure might efficiently contribute to pest regulation.

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Habitat management, that aims at conserving or enhancing beneficial organisms, can potentially improve pest management (Landis et al., 2000). Also, Jonsson et al. (2010) reviewed how habitat manipulation has improved biological control of invasive pests over the years 1998–2009, and discussed under what circumstances different types of habitat management are likely to be effective, and how the likelihood of success can be improved. Yet, most of the cited experiments had been conducted at a local scale (*e.g.* field scale). Studies at the landscape scale are rarer (SESAME, 2015), notably due to the difficulty to experiment at such spatial scale, thus emphasising the relevance of developing frameworks that enable *in silico* experiments.

Indeed, although landscape-scale effects on pest natural enemies in agroecosystems are numerous, as evidenced by many studies (Gämez-Virués et al., 2012; Veres et al., 2013), the underlying mechanisms are only partially known. In particular, we still have a limited understanding of the optimality in spatial and temporal arrangements of habitat structures, and even less of the management measures required to improve biological control (Gämez-Virués et al., 2012). Despite some recent papers heading towards that direction (Jonsson et al., 2014), landscape planning applied to agricultural landscape has not become a standard tool against pests and diseases. As a whole, landscape planning addresses the integrated analysis of land-use change in relation to socio-economic and biophysical driving factors (Verburg et al., 2002; Polasky et al., 2008).

In our study, we propose a data-driven methodological framework to derive apposite agricultural landscape rearrangements that might enhance pest regulation. As such, our framework is intended to be part of a landscape planning process coerced with other requirements and concerns, *e.g.*, for multiple pest dynamics or socio-economic factors. Our incentive is that, in order to cope with possible trade-offs between ecosystem services, we should (i) capture spatial dependencies of ecological processes underlying a given service and (ii) be able to provide many acceptable solutions, *i.e.* landscape rearrangements, enhancing the service under consideration. We addressed the first point by fitting a parsimonious, mechanistic and spatially explicit population dynamics model to observation data. Such a flexible tool allows to explore the effects of landscape management scenarios on the insect population and its seasonal field colonisation process. Secondly, combining a search heuristic and a constraint satisfaction problem, we generated candidate landscape rearrangements that abide by landscape composition constraints. Combining these two elements, we investigate the effects of the spatial configurations, looking for the best land-cover arrangements for each given composition (*i.e.* setting aside the non-spatial effects of the land-cover proportions).

We demonstrated the relevance of our data-driven approach by applying it to the case study of carabid beetles, an arthropod family involved in weed regulation through seed predation (Bohan et al.(2011)) and that was shown to depend both on local (field) and landscape characteristics (Trichard et al., 2013; Labruyere et al., 2015).

2. Materials and methods

2.1. Study area and experimental data

2.1.1. Study area and landscape characterisation

The study area (Fig. 1) consists in an agricultural landscape of approximately 130 km^2 located in north-western France (origin at 48° 29′ N 1° 34′ W.). This area, called "*Zone Atelier Armorique*" (*ZAA*), belongs to the International Long Term Ecological Research Network (ILTER, 2015) and, as such, its land-use has been assessed every summer over the last 25 years using aerial photographs, field observations and manual cartography. It is characterised by a SW-NE gradient of landscape structure—from hedged farmland, woodlands and permanent grasslands, to open fields (see Baudry et al., 2000 for more details). In 2010 (the season under study here), the *ZAA* comprised 36% grasslands, 38% cultivated areas (essentially wheat and corn in summer), 14% woodland, and the rest corresponded to roads and built areas. As it will be made explicit later, we focused our investigation on two sub-domains of the *ZAA*, hereafter referred to as Ω_1 and Ω_2 (Fig. 1), spanning respective areas of 3 km^2 and 2.3 km^2, and mapped at a 10-m resolution. In 2010, the landscapes Ω_1 and Ω_2 were characterised by 37% (resp. 54%) of grasslands, 47% (resp. 31%) of cultivated areas and 7% (resp. 5%) of woodland.

2.1.2. Sampling design of entomological data

The activity-density of carabid beetles was assessed using pitfall traps installed in 25 agricultural fields spread across the whole study area. In each sampled field, 3 pitfall-traps were set at random places within crop limits. Experiments were then carried out during five weeks between the 6th of May and the 8th of July

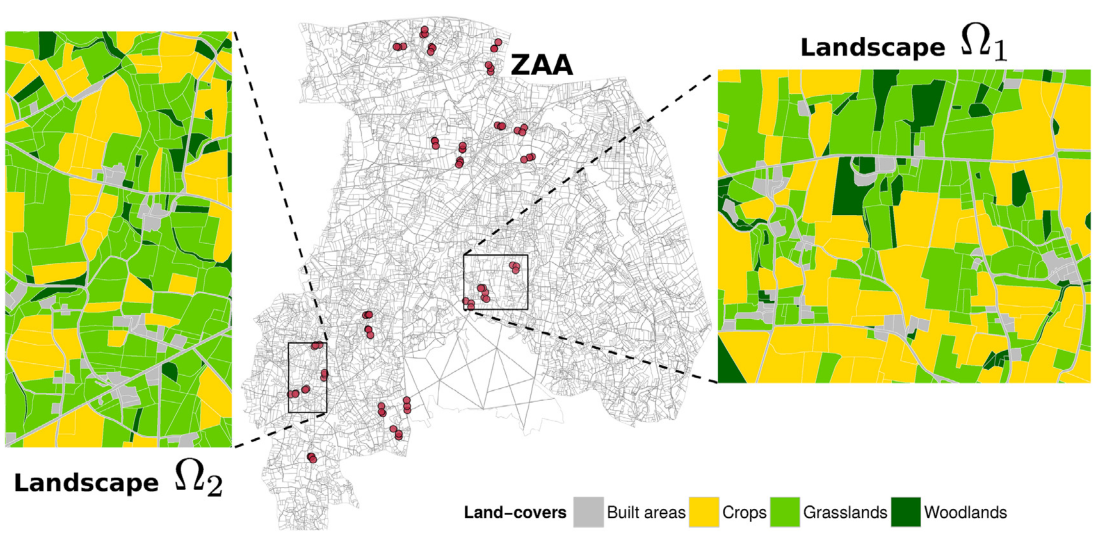

Fig. 1. Map of the study area showing the locations of the sampled fields (red circles), the sub-domains under investigation (Ω_1 and Ω_2) and the land-covers of interest (colour legend). (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

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