

A multidisciplinary modelling approach to analyse and predict the effects of landscape dynamics on biodiversity

Gauchere, C. (1); Martinet, V. (2); Bamière, L. (2); Sheeren, D. (3); Gibon, A. (3); Joannon, A. (4); Castellazzi, M.S. (4); Boussard, H. (4); Barraquand, F. (5); Inchausti, P. (5); Lazrak, E.G. (6); Mari, J.-F. (6); Schaller, N. (7); Houet, T. (8); Bretagnolle, V. (5)

(1) INRA, UMR AMAP, Montpellier, F-34000 France, cedric.gauchere@cirad.fr

(2) INRA-UMR 210 Economie Publique 78850 Grignon, France

(3) INRA UMR 1201 DYNAFOR Toulouse 31326 Castanet Tolosan, France

(4) INRA SAD-Paysage Rennes 75338 Cedex 07, France

(5) CNRS CEBC UPR 1934 79360 Villiers-en-Bois, France

(6) INRA Mirecourt LORIA F-54506 Vandœuvre-lès-Nancy, France

(7) INRA UMR Sad-Apt 78850 Thiverval Grignon, France

(8) CNRS UMR 5602, GEODE 31058 Toulouse Cedex 9, France

Abstract: Over the last 40 years, agricultural extension and intensification of land use have induced profound changes in distribution and dynamics of farmland biodiversity and in the functioning of European agroecosystems. Agroecosystems are mainly private properties, whose dynamics need to be better understood in order to preserve their biodiversity. Several French research teams have recently joined their skills in a multi-disciplinary project, BiodivAgriM, whose main goal is to test, validate, and predict the consequences of different scenarios of landscape changes on the distribution, abundance and persistence of biodiversity in agroecosystems. A central goal of this project is to generate a multi-purpose modelling platform which makes it possible to couple different spatially explicit models toward the same objective, and gather rather similar models toward the same generic object (i.e., the landscape). Such a modelling approach is a real challenge. The main knowledge provided by this project was that the disciplines involved were in various maturation stages, with respect to the modelling approach, to understand the impacts of agricultural practices on

biodiversity. Yet, a large panel of models is today available to address more specific questions, between human drivers and landscape, global incentives and landscape, or landscape and species. All of them are presently coupled or/and compared in order to qualify less ambitious yet relevant processes related to the landscape.

Keywords: integrated model; agricultural landscape; population dynamics; land cover; land use; biodiversity loss; farmer decision

Introduction

Over the last 40 years, agricultural extension and intensification of land use has induced profound changes in distribution and dynamics of farmland biodiversity and in the functioning of European agroecosystems (Donald et al. 2001, Benton et al. 2002). The intensification of Western European agriculture has involved several driving processes, i.e. i) the specialisation of agriculture resulting in simplification of rural landscapes (Benton et al. 2002), ii) the abandonment of less fertile farmland areas leading to an overall loss of landscape diversity (Bignal and McCracken 1996), and iii) the increase in the input of pesticides and fertilisers per unit area (Robinson and Sutherland 2002). These three processes have led to a degradation of habitat quality and a reduction in the amount of food resources, which are the ultimate causes of the observed declines of farmland plants, insects and birds across Europe (Robinson and Sutherland 2002, Gregory et al. 2004) at various spatial scales ranging from the plot to the regional level. Currently, there is therefore an urgent need to act in decreasing negative environmental impacts of agriculture, restore functional biodiversity and conserve threatened species.

Agro-ecosystems provide environmental services, such as quantitative and qualitative management of water, soil conservation, reducing emissions of greenhouse gas emissions, and conserving biodiversity. However these services must be evaluated and quantified only at spatial scales that are relevant to these functions, which greatly exceed the scale of a farm, i.e. environmental services occur mostly at the landscape level. Conversely, the farm scale remains a major level of decision and organization of agricultural practices (especially the spatial organization of cropping systems, crop rotations). The farm level is also the key level with regard to socio-economic decisions and land property. Consequently, the landscape structure of rural habitat, especially the mosaic of cropping systems, result from a complex interaction between environmental constraints and individual based decisions, and non-linear relationships in decision-making processes have been identified (Mottet et al. 2005, Soulard 2005).

Overall therefore, one of the major problems concerning the conservation of biodiversity in agro-ecosystems is to maintain habitats and their quality at the relevant spatial scale (i.e., landscape scale), while the relevant level for agri-environment regulations and policies is the farm level. This conflict is well exemplified by one key habitat in intensive cereal systems, namely grasslands. These perennial environments (meadows, fallow fields, but also hedgerows, forest fragments, roadsides, grass strips) are critical habitats for many plant and animal species, either as breeding habitats or as trophic resources (Newton 2004, Bretagnolle et al. 2010). While the farm level is a major driver of agricultural practices and

spatial organization of cropping systems, maintenance of biodiversity associated with these landscapes depends on the spatial arrangement of perennial community (partly outside crops) at the landscape level.

Agroecosystems being mainly composed of private properties, their spatiotemporal dynamics (as well as their drivers) need to be better understood in order to preserve farmland biodiversity. While the impact of the intensification of land use seems to be well understood for many taxa, the effect of change in the composition, structure and dynamics of landscapes induced by past and ongoing agricultural intensification is clearly much less understood (Burel and Baudry 2003). Nine French research teams have recently joined their skills in a multi-disciplinary project (“ANR BiodivAgriM”) whose main goal is to test, validate, and predict the consequences of different scenarios of landscape changes on the distribution, abundance and persistence of biodiversity in agroecosystems, including ordinary, functional and conservation dependant species that altogether constitute biodiversity. A central goal of this project is to generate a multi-purpose modelling platform allowing the coupling of different spatially explicit models toward the same aim, and gather rather similar models toward the same generic object. Such a modelling approach is a real challenge (Gaucherel et al. 2009, Gaucherel and Houet 2009).

This project is organised into four complementary and interdependent Workpackages (WP) aiming at: determining the landscape characteristics favourable to biodiversity at the species and community levels, including beetles, bees, grasshoppers, small mammals, weeds and several bird species (WP1); characterizing the processes, mainly socio-economical, influencing these landscape characteristics, not only at small temporal and spatial scales (WP2), but also at large temporal and spatial scales with the help of remote sensing analyses (WP3); and modelling landscape dynamics of agroecosystems according to the processes studied and the constraints and needs of biodiversity (WP4). Our aims are to model the social and economical processes that ultimately drive changes in agricultural landscapes as well as their impacts on farmland biodiversity, in addressing a wide range of questions that are rarely tackled by a single model or by a unique modelling platform.

Questions typically addressed by our current project concern for instance the efficiency of incentives and constraints policy on agricultural activities and whether they are able to generate landscape mosaics allowing biodiversity conservation. We also want to address how these policies will impact targeted species abundances, and this according to several scenario or system choices? How land covers and land uses constrain the dynamics and persistence of bird or small mammal populations? How land cover drivers such as crop rotations, irrigation, soil fertility and cropping systems constrain landscape structure? We therefore address a wide range of questions with the same model or the same modelling platform. At the initial stage of the project, we wondered whether several specific models or a global multi-model platform coupling the various models developed for each question would give the best answer.

Another issue concern space: most of our (sub-) models are spatially explicit models, since purely temporal models at one site are rarely realistic enough to assess the impacts of agricultural activities on farmland species. Recent studies have shown that it is crucial to model the patchy structure of a landscape and to explicitly consider the distances and neighbourhoods of landscape elements when studying questions of population dynamics and persistence in realistic landscapes, e.g. (Legrand et al. 2010). Our models also need to simultaneously consider several spatial scales and processes (e.g., daily movements,

seasonal strategies, inter-annual migrations) affecting the spatial distribution of individuals at different temporal scales. Finally, we aim to combine features of GIS (Geographical Information Systems, for space), of the DEVS (Discrete Event System Specification, for time) formalism or of the UML (Unified Modelling Language) approach to handle process algorithms.

1. Modelling approaches

A survey of available models amongst the teams involved in this project showed that each team developed already several functional (mechanistic) models to address specific questions related to landscape in biology, ecology, socio-economy, geography, and agronomy. We tried to summarise and organize these existing models, and propose a coherent scheme (figure 1). The main idea was to articulate models between the four components involved in the landscape-biodiversity topic: i) people (i.e., farmers in our case), building ii) the landscape (i.e. patchy mosaics) through crop rotation choices within each farm, iii) the animal or plant wild species populations that are impacted in the agro-ecosystem, and iv) the large scale (economical and ecological) incentives driving the landscapes through farmer decisions. These four components simultaneously interact through interfaces that are already modelled within different model types A1, A2, A3, and B1, B2, B3, where B models, unlike A models, consider landscape exogenous information, usually coming from larger scales (figure 1). We insist on the fact that if some model types (e.g. A1 or B2) are interdisciplinary (i.e. concerning the interface between two disciplines), many models and the overall project are multidisciplinary (involving more than two disciplines). A landscape model may often need socioeconomic and/or biophysical data to implement associated processes, in addition to the common algorithmic, spatial and temporal analyses skills used for their development (Gaucherel, 2009).

For example, models of type A1 consider the dynamics of landscape mosaics based on farmer's decisions. While A2 models analyse population dynamics based on the landscape mosaics, those of type A3 do so taking into account farmer decisions and their consequences in terms of changes in landscape structure. By contrast, models of type B1 simulate landscape mosaics taking into account large scale ecological and socio-economical incentives whereas models of type B2 do likewise but accounting also for farmer decisions. Models of type B3 simulate population dynamics by taking into account all other related factors (farmer decisions, incentives and landscape dynamics). The integration of this suite of models at the various interfaces has been one of the main challenges of our project.

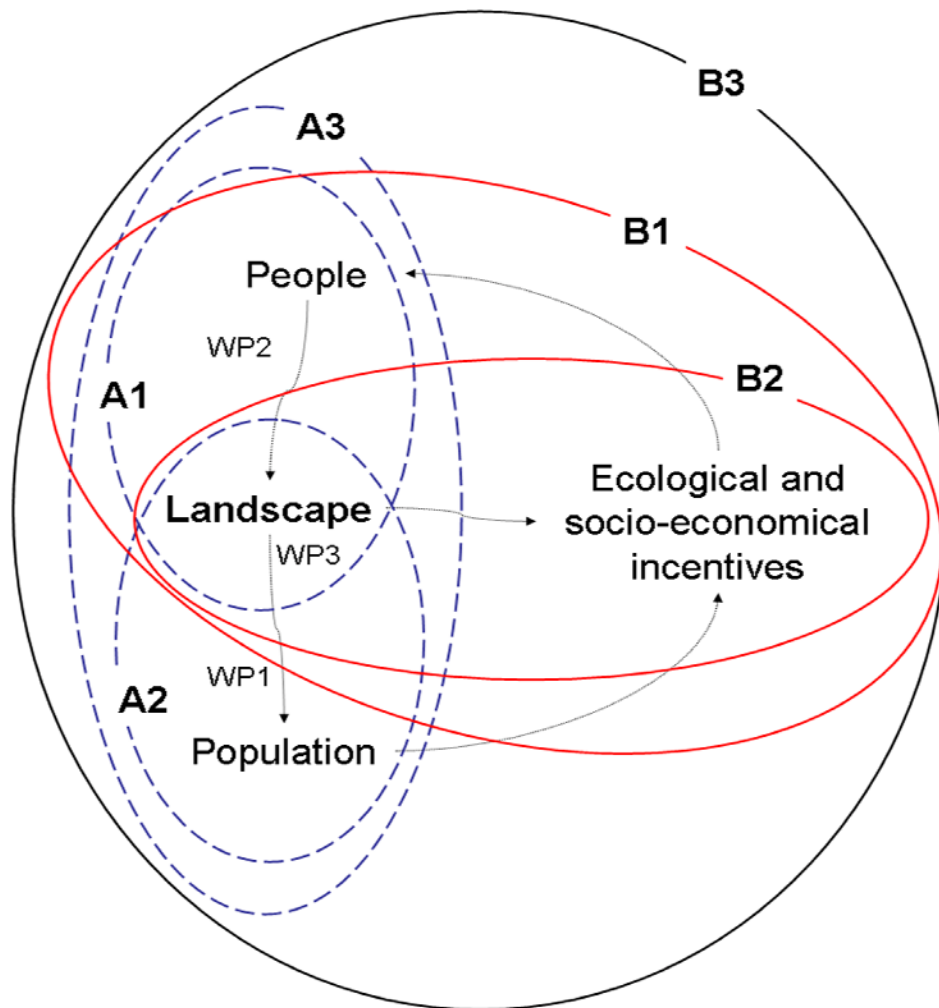


Figure 1: Organization scheme of the modelling approaches developed in the BiodivAgriM project.

It remains to be shown that an integrated modelling approach would be relevant for the scientific questions addressed here (i.e., integrate farmer level decision process to landscape level pattern of habitats), since such a platform would have many complex components that would certainly increase the number of model parameters and make difficult calibration and validation. Instead, we have pursued the three possible cross-studies between existing models. First, it has been possible to share data and knowledge for building a new interface model. This objective was relevant in collaborations between the modelling WP4 and the other WPs. Second, it has been possible to couple models. Most of these coupling are “weak coupling” (i.e. exchanging input and output files), instead of

“strong coupling” (with interacting codes, which is usually more difficult to implement). Third, it has finally been attempted to compare models, at least when they offer similar output types (for example A1 and B1 types, or A2 and B3 types). What follows is a brief overview of the interface models already developed in the BiodivAgriM project.

Economy: OUTOPIE is a spatially explicit mathematical model (B1 type) developed to analyse the optimal reserve design for species conservation (Havlik et al. 2008). The model structure corresponds to three spatial levels (field, farm and landscape) and is applied in a normative and in a positive ways. This model was applied to the Little Bustard *Tetrax tetrax*, a farmland species of very high conservation concern in western France (Bretagnolle et al. 2010) that needs patchy, and to some extent, randomly distributed grasslands within the farmland landscape. The location and number of grassland patches was addressed here as an incentive policy dedicated to reserve (of fields). We found that the environmentally optimal reserve, randomly dispersed across the zone, is the most costly one. The most effective contract structure is a digressive set of two payments enabling all the farms to enrol at least a small share of their land. A dynamic bioeconomic model of agricultural land-use and spatially explicit population dynamics (B3) has also been developed (Barraquand and Martinet 2009). It relates incentive policies level (subsidies to grassland) to the ecological outcome (persistence probability for the species) and describes the links between increasing conservation costs and a S-shaped ecological benefit function.

Techniques: APILand is a generic modelling toolbox (B1) making it possible to create and manage landscape elements. It is implemented as a Java® library (Boussard 2009). Since commercial GIS are deficient in managing time and scale dimensions, this library attempts to rely on an object-oriented design and development, benefiting of polymorphism, inheritance or composition properties. With the help of the UML language and a “design pattern” based approach, it becomes possible to design and handle landscapes composed of embedded elements, each having a complex spatiotemporal representation, and possibly managed or influenced by an agent with some specific rules. Another team proposed an innovative stochastic modelling method (B2) of agricultural landscape organization for which temporal regularities in land-use are first identified through recognized Land-Use Successions before locating these successions in landscapes (Lazrak et al. 2009). They built a time-spatial analysis on the basis of Hidden Markov Models through spatially explicit analysis of Land-Use Succession dynamics. This analysis assessed the relationship between the extracted agricultural landscape patterns and distributions of bird nests in the Niort area.

Agronomy: Multi-Agent Systems (MAS) are common modelling tools to address land use and land cover change issues. Some of us are presently developing such a model (A3), called SMASH (Gibon et al. 2009), to understand the relationships between ecological dynamics (spontaneous reforestation by ash trees) and farmers’ decisions on agricultural lands at landscape scale. In Pyrenean agricultural landscapes where almost all the land is subjected to ash seed rain, impacts of individual farmers’ decisions on spontaneous reforestation patterns were found to primarily result both from the nature of grass-harvest operations (hay cutting; herd grazing) applied at the parcel level in the course of the year and the cumulated yield of grass harvested year-round. Ash trees settlement at a grassland parcel is prevented by hay cutting, while in grazed-only situations it depends on grazing intensity. The modelling of farmers’ decisions therefore required considering their individual land management as hierarchical decision systems nesting a within-year

grassland management strategy at the parcel and the farm level (spatiotemporal arrangement of hay making and herd grazing operations at the set of parcels) and a long-term strategy for farmholding development driving change in the farmland area of the farmholdings. Preliminary results of GIS simulation of such rule-based scenarii clearly show that the spatial patterns of landscape reforestation are linked to the diversity of farm management strategies (priority to land-care or to labour efficiency), the size of the farmholdings and the respective lay-out of their parcels within the landscape mosaic.

The LandSFACTS software (A1) is specifically designed to meet the needs of environmental and agronomical research modellers requiring dynamical land-use maps (Castellazzi et al. 2007). This model may help to (i) set up scenarios of crop allocations, and (ii) fill out incomplete datasets (e.g., datasets missing field-specific data). In short, the software allocates crops to fields at the landscape scale to meet user-defined crop arrangements, including separation distances between crops, crop rotations, forbidden crop sequences, crop return periods, yearly crop proportions and statistical indexes of general crop spatiotemporal patterns. Finally, the DYPAL modelling platform (multi-object, A3) determinedly focuses on patchy landscapes driven by human decisions and/or natural forces (Gaucherel et al., 2009). The first objective of this approach is to provide a coherent mathematical framework, based on formal grammar, to derive landscape evolution rules. This is now achieved. The second objective of DYPAL is an application on specific landscape and population dynamics. The first part of the model highlighted that dairy and beef livestock production systems are more favourable to wild species than hog's production, with intensive dairy having higher landscape heterogeneities and extensive dairy higher grassland proportions and return frequencies. The second part of the model, presently coupled to spatialized population dynamics, has already shown how some specific landscape structures (for example with well distributed hedgerow networks) decrease the population extinction risk.

2. Modelling examples

We would like to give a brief illustration of what could be a A2-type model coupling, articulating a landscape model with a population dynamic model. Population dynamics of wild animals is currently tackled with either spatially implicit dynamics (island biogeography theory or niche theory) or with simplified spatially explicit dynamics (metapopulation theory or landscape ecology) (Caswell 1989, Kot 2001). These population dynamic models thus lack realism, in particular for complex and patchy rural landscapes. This context justified developing new modelling approaches to couple spatially explicit population dynamics and patchy landscape dynamics, in order to improve our understanding of biodiversity in changing rural landscapes. A preliminary approach has been proposed to quantify the effects of landscape structures on spatially explicit population dynamics.

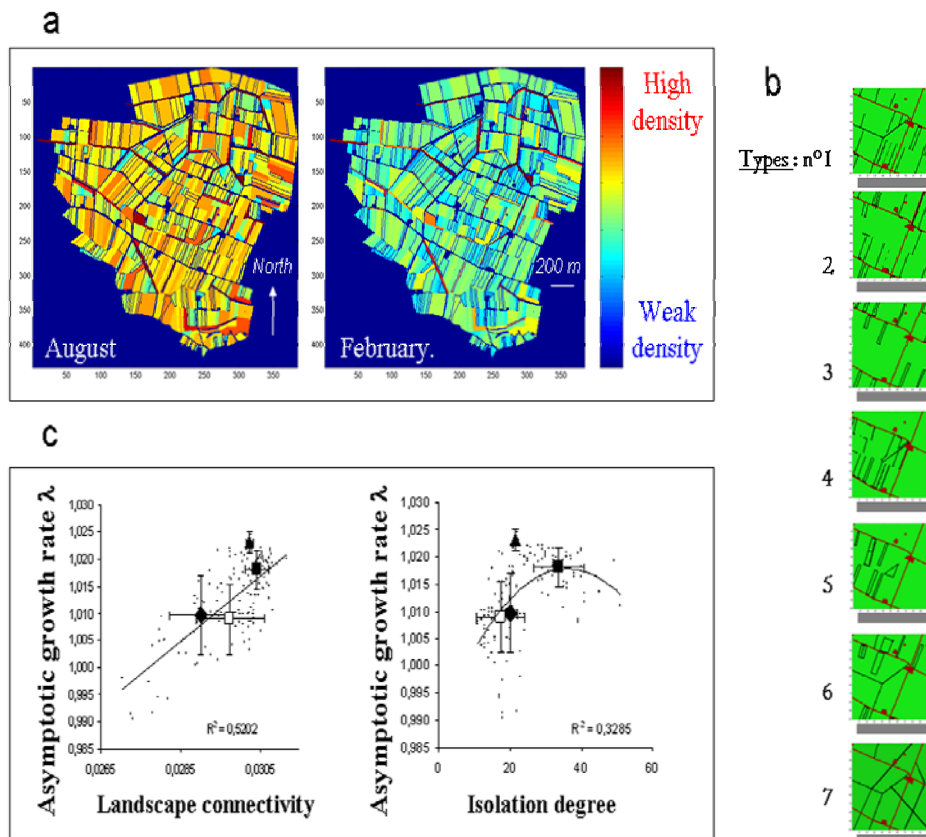


Figure 2: (a) Population density map in landscapes of polders that have a semi-natural habitat (dykes) density equal to 0,07; (b) Various types of semi-natural configurations with roughly similar densities simulated to welcome population dynamics; (c) Asymptotic population growth rates in relation with landscape connectivity and number of cluster of semi-natural habitats.

The population dynamics of *Pterostichus melanarius* (Coleoptera: Carabidae) in the polder landscape of the Bay of Mont St Michel (Brittany, France) has been modelled with a spatially explicit model (Rétho et al. 2008). This model results from the coupling of a matrix model of population dynamics with an explicit model of patchy landscapes, qualitatively validated with six years data. The use of indices describing the spatial composition and configuration of the landscape (composition density, connectivity and number of cluster) helped underlining the effects of its structure on the distribution and the dynamics of the carabid beetles, notably the effects of linear elements used as shelter by the insects during the wintering period. The results of this study highlight that the habitats usually considered as shelters for wintering also play a key role as well for the reproduction of the species during summer. We observed that, without fecundity in semi-natural habitat, an increase of their density could be harmful for the population viability. Moreover, the spatial arrangement of this semi natural habitat in the landscape has a strong influence on the population viability (figure 2): The connectivity as well as the spatial alternation of this habitat network can be an important factor to be considered in the conservation actions in the landscape context.

Conclusion

A main result already obtained by the BiodivAgriM project up to now is that the disciplines involved to simulate the impacts of agricultural practices on biodiversity, were in various maturation stages (at least with respect to the modelling approach). The ultimate goal, building an integrated modelling platform, was impeded by the fact that, on one hand, mathematical and computing scientists were ready with their tools, while on the other hand ecologists and socio-economists needed more time to improve their understanding of the processes involved. In addition, it seems that most successful and famous platforms (Linux, Grass, R softwares) were not initially planned as platform, and started from isolated initiatives later opened to a larger community. Despite these limitations, we already have a large panel of models addressing specific issues (e.g. between human drivers and landscape, global incentives and landscape, or landscape and species). All of them are presently coupled or/and compared between each others in order to address wider issues and to qualify them. These less ambitious modelling attempts seem to be a necessary preliminary stage before improving our comprehensive understanding of the landscape functioning in complex landscapes, such as farmland habitat.

References

- Barraquand F. and Martinet V., 2009. Agricultural land-use and biological conservation. in CNRS, editor. Symposium "Spatial landscape modelling: from dynamic approaches to functional evaluations", Toulouse 2008, June 3rd-5th.
- Benton T. G., Bryant D.M., Cole L. and Crick H.Q.P., 2002. Linking agricultural practice to insect and bird populations: a historical study over three decades, *Journal of Applied Ecology*, 39, p. 673-687.
- Signal E. M., and McCracken D.I., 1996. Low-intensity farming systems in the conservation of the countryside, *Journal of Applied Ecology*, 33, p. 413-424.

- Boussard H., 2009. APILand: An object-oriented library of landscape constitutive elements. Principles and handling examples with java. in CNRS, editor. Symposium "Spatial landscape modelling: from dynamic approaches to functional evaluations", Toulouse 2008, June 3rd-5th.
- Bretagnolle V., Villers A., Denonfoux L., Cornulier T., Inchausti P. and Badenhauer I., 2010. Alfalfa and the conservation of Little Bustards and other farmland birds in Central-western France, submitted to *Ibis*.
- Burel F. and Baudry J., 2003. *Landscape ecology : concepts, methods, and applications*, Science Publishers, Enfield, N.H.
- Castellazzi M.S., Matthews J., Wood G.A., Burgess P.J., Conrad K.F. and Perry J.N., 2007. LandFACTS: Software for Spatio-temporal Allocation of Crops to Fields. in Proceedings of 5th Annual Conference of the European Federation of IT in Agriculture, 1-8-2007., Glasgow, UK.
- Caswell H., 1989. *Matrix population models*. Sunderland, Massachusetts, USA.
- Donald P.F., Green R.E. and Heath M.F., 2001 Farmland bird populations Agricultural intensification and the collapse of Europe's, *Proc. R. Soc. Lond. B*, 268, p. 25-29.
- Gaucherel C., Griffon S., Misson L. and Houet T., 2010. Combining process-based models for future biomass assessment at landscape scale, *Landscape Ecology*, In press.
- Gaucherel C. and Houet T., 2009. Preface to the selected papers on spatially explicit landscape modelling: Current practices and challenges, *Ecological Modelling*, In press.
- Gibon A., Sheeren D., Monteil C., Ladet S. and Balent G., 2009. Modelling and simulating change in reforesting mountain landscapes using a social-ecological framework, *Landscape Ecology*, In press.
- Gregory R.D., Noble D.G. and Custance J., 2004. The state of play of farmland birds: population trends and conservation status of lowland farmland birds in the United Kingdom, *Ibis*, 146, p. 1-13.
- Havlik P., Bamière L., Jacquet F. and Millet G., 2008. Spatially explicit farming system modelling for an efficient agri-environmental policy design. in The 107th EAAE Seminar "Modeling of Agricultural and Rural Development Policies", Sevilla, Spain, January 29th -February 1st, 2008.
- Kot M., 2001. *Elements of mathematical ecology*. Cambridge University Press, Cambridge, UK.
- Lazrak E.G., Mari J.F. and Benoît M., 2010. Landscape regularity modelling for environmental challenges in agriculture, *Landscape Ecology*, In press.
- Légrand A., Gaucherel C., Baudry J. and Menard J.M., 2010. Long-term effects of organic, conventional and integrated crop systems on carabids, *Agriculture and Sustainable Development*, in press.
- Mottet A., Ladet S., Coqué N. and Gibon A., 2005. Agricultural land-use change and its drivers in mountain landscapes: a case study in the Pyrenees, *Agriculture, Ecosystems and Environment*, 114, p. 296-310.
- Newton I., 2004. The recent declines of farmland bird populations in Britain: an appraisal of causal factors and conservation actions, *Ibis*, 146, p. 579-600.
- Rétho B., Gaucherel C. and Inchausti P., 2008. Spatially explicit population dynamics of *Pterostichus melanarius* I11 (Coleoptera: Carabidae) in response to changes in the composition and configuration of agricultural landscapes, *Landscape and Urban Planning*, 84, p. 191-199.
- Robinson R.A. and Sutherland W.J., 2002. Post-war changes in arable farming and biodiversity in Great Britain, *Journal of Applied Ecology*, 39, p. 157-176.
- Soulard C.T., 2005. Les agriculteurs et la pollution de l'eau. Proposition d'une géographie des pratiques, *Natures Sciences et Sociétés*, 13, p. 154-164.