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CHAPTER 33

Monitoring territorial dynamics by remote sensing and spatial modelling

Camille Jahel, Louise Leroux, Émile Faye, Karen Colin de Verdière, Pascal Degenne, Danny Lo Seen and Xavier Augusseau

The territory, defined as a geographical space as appropriated and perceived by individual or collective actors, evolves in space and time under the effects of natural and anthropogenic factors in an institutional, political and social context. It is therefore inherently dynamic. Planning and decision-making for territories consequently require a detailed knowledge and an objective representation of ongoing, expected or planned processes at different spatio-temporal levels of analysis.

This chapter provides an overview of tools for monitoring and modelling territorial dynamics. Without claiming to provide a turn-key solution to analyzing and understanding the spatial and temporal dynamics of territories, these tools can nonetheless be used as aids for decision-making for spatial planning. Remote sensing can help describe and quantify territorial dynamics, and spatial modelling can provide us a detailed understanding of the complex spatio-temporal processes underpinning these dynamics.

DESCRIPTION AND QUANTIFICATION OF TERRITORIAL DYNAMICS BY REMOTE SENSING

Use of remote sensing to characterize the organization of territories

In its broadest definition, remote sensing is described as the set of techniques and knowledge used to determine physiological and biological characteristics of objects using measurements made without direct contact with them. Thus, when applied to the Earth, remote sensing provides direct or indirect indicators on various biophysical parameters (e.g. leaf area indices, soil moisture indices, phenological metrics) to characterize the functioning of features on the Earth's surface. Due to their systematic and synoptic nature and their temporal repetitiveness, remote sensing data helps us expand our understanding of past and present dynamics at work on the territories. Their cost is constantly decreasing, thanks to an ever-growing supply of more and more useful images (satellite, aerial, etc.) and to the increase in the number of free or paid platforms for processing this data (e.g., eCognition Developer, ENVI, QGIS). The diversity of the available images generates a multiplicity of objects to be studied, ranging from the cultivated plot, through the use of new technologies like drones (Box 33.1), to the village terroir, with high or very high spatial resolution satellite imagery (in the order of 1 metre) such as from Pleiades or SPOT, to the level of the watershed with medium spatial resolution imagery (in the order of 100 metres) like MODIS or SPOT VGT. Different temporalities of change can also be assessed, allowing for seasonal or inter-annual monitoring of ecosystems.

In the countries of the Global South, for which cartographic and geographic information is generally lacking, remote sensing data is an important source of information to describe the organization of territories and measure their dynamics in regions that are sometimes difficult to access. For example, it is possible to map the forests in the Congo Basin (covering over 3 million km^2, i.e. five times the area of France) using satellites, whereas it would be difficult, if not impossible, to undertake a comprehensive mapping on the ground, with no road access within the forests (Box 33.2).

Box 33.1. Drones as tools for territorial development.

Émile Faye

Since they became available for civilian use, drones – remote-controlled, unmanned aerial vehicles – have become essential tools in several spheres (risk prevention, inspection of infrastructure, agriculture, environment, research, audiovisual disciplines). As noted by Watts *et al.* in 2012, drones today represent a real technological revolution for acquiring scientific data, especially in domains where *in situ* measurements are difficult using traditional means, or for which satellites and planes do not offer the same flexibility of use, or a sufficient spatial and temporal resolution. In fact, flying slowly at low altitudes, drones equipped with different sensors (visible, near infrared, thermal infrared and laser cameras, Figure 33.1A) can collect very high spatial resolution geo-localized images (of the order of cm^2/pixel). These images provide precise multi-spectral maps and digital terrain models for surface areas of several tens of hectares per flight. However, the steep learning curve, the limitations in processing the large amounts of acquired data, and increasingly strict regulatory constraints are hampering the adoption of these new tools.

Thus, CIRAD researchers, using these tools, have focused on identifying and characterizing agronomic, ecological and sociological processes at spatio-temporal scales and resolutions appropriate for studying territorial dynamics. Working at scales ranging from the plot to the agroecosystem as a whole, they study the effects of functional diversity of landscapes (composition and spatial configuration of agroecosystems) on yields and ecosystem services for pest control and plant pollination (at resolutions suited for observing insects). They use remote sensing tools on these high-resolution images to understand and model water stress and plant health (Figure 33.1B) in order to adapt irrigation and quantities of inputs to individual plants.

Finally, they analyze the dynamics of a village territory by comparing time series of land use maps obtained through drones (reduction of forest areas due to agriculture and urbanization). Drones are thus useful tools for describing, mapping, quantifying, understanding and modelling the functioning of agroecosystems at spatio-temporal resolutions relevant to the study of territories.

Figure 33.1. A. A hexacopter equipped with a camera and a thermal camera. B. A hyper-resolution mapping of the surface temperature of the canopy, only of sweet potatoes.

Using remote sensing to reconstruct territorial dynamics

Two broad types of analyses are generally carried out using remote sensing depending on the spatial scale under consideration: analysis of crop production trends at the regional scale (continental or sub-regional) and the analysis of changes in land use at a more local level (village terroir, watershed).

Based on vegetation index time series of type NOAA-AVHRR (10-day period and a spatial resolution of 8 km) or MODIS (bi-monthly, and a spatial resolution of 250 m), vegetation production trend analyses help identify statistically changes in the photosynthetic activity of plant covers and to make an initial diagnosis of the territories's functioning. These trends can then be interpreted in terms of improved vegetation production or vegetation degradation – but without any indication on the cause of these changes. For example, while satellite observation showed a general tendency of a recovery of Sahelian vegetation following the increase in rainfall over the past 30 years (e.g., Fensholt *et al.*, 2013), recent studies have, however, shown a tendency of plant cover degradation that could be the result of non-climate factors, either natural or anthropogenic (Box 33.3). Brandt *et al.* (2016) have, for example, recently highlighted a trend towards degradation of ligneous resources in the Baban Rafi forest in Niger and in the Zamfara reserve in Nigeria, which, according to the authors, is due to the selective felling of tree species and of the allocation of an excessive amount of newly cleared land to agriculture.

The main trends in vegetation are therefore the result of complex processes, combining both global and local factors. Analyses at the local scale, mainly concerning the characterization of changes in land use (or socio-economic land use), are therefore a key step in describing territorial dynamics. This involves a diachronic analysis of land use

Box 33.2. Satellite imagery for monitoring forest areas.

Karen Colin de Verdière

There is a very limited use of remote sensing technologies in the countries of the Global South because of the paucity of satellite data and the inadequate capacity to interpret and use them. At the Copenhagen summit in December 2009, the French Development Agency, in partnership with Airbus Defence and Space (a provider of satellite images), undertook to provide high-resolution SPOT satellite images, free of charge, to governments, research institutes and civil society organizations working for sustainable forest management in the Congo Basin. This initiative has helped boost the use of spatial data in Central Africa, strengthen the capacity of local actors to use these technologies and encourage the creation of national forest maps for an improved assessment of the effectiveness of anti-deforestation policies. Building on these results and achievements, a new project was launched in 2015, extending these benefits to three countries in West Africa (Guinea, Benin and Côte d'Ivoire). Its aim is to study past and present land-use dynamics and land-use changes in the savannah and degraded forest territories, using recent and historical high-resolution satellite imagery.

The Geoforafri project, funded by the French Facility for Global Environment (FFEM), is simultaneously promoting the adoption and the methodological and technical mastery of Earth observation satellite data in Central and West African countries by building capacity and user networks for these technologies.

In general, these interventions in an always-evolving high-technology domain require a significant public commitment to build image generation infrastructure that can be used by public and private actors, and robust systems to verify the interpretations. Training of national experts and their association with international networks is therefore essential.

(Based on Desclée *et al.*, 2014)

maps of a territory obtained from high spatial resolution satellite archives such as Landsat. At this scale of analysis, it then becomes possible to identify the part played by anthropogenic pressures in the dynamics observed. By analyzing land use changes between 1960 and 2010 around major African cities, Brinkmann *et al.* (2012) have, for example, highlighted an urban sprawl accompanied by an increase in cultivated area at the expense of forests. Thus, while remote sensing helps identify and describe areas with strong dynamics, it offers little information on the processes behind these changes whose detailed understanding is, nonetheless, essential for land use planning or for implementing resource management in these areas undergoing change. The use of spatial modelling then becomes necessary for an in-depth study of these processes.

Modelling territorial dynamics

Principles of models of territorial dynamics

The monitoring and assessment of territorial dynamics reveal changes resulting from ongoing, multiple and complex processes that researchers seek to understand and describe for better-informed decision-making. In this approach, modelling is often used as a methodology to formalize existing knowledge on the territory into a simplified description but one that is adequate to address a particular question. When models are built with computer tools, it is possible to carry out virtual experiments on these territories, such as testing hypotheses considered relevant for certain processes, or comparing and assessing different development scenarios of a territory according to previously defined criteria.

Box 33.3. Trends of and factors behind recent developments in plant biomass production in the Sahel: what satellite imagery tells us.

Louise Leroux

Which areas in the Sahel are undergoing a decline in crop production? In what way is the climate responsible for the observed dynamics? With looming climatic and demographic changes, these are some of the questions that must be answered in order to identify populations that are at risk and to propose ways of adapting to these changes. After processing information from time series on vegetation and climate, Leroux *et al.* (2016) have shown that there has been a tendency in some areas, such as the south-west of Niger, over the last 15 years, of a degradation of vegetation production, i.e., a potential reduction in agricultural and fodder production. The authors also showed that climate was definitely not the sole factor behind the observed degradation. By combining initial analyses carried out at a regional scale with local environmental, demographic and economic data, they highlight, map and quantify the degradation of the laterite plateaus with tiger bush around the city of Niamey (Niger). This degradation is mainly due to the overexploitation of timber resources to meet the city's increasing demand for fuel wood resulting from the increasing urbanization in West Africa (e.g., Brinkmann *et al.*, 2012; Leblanc *et al.*, 2008).

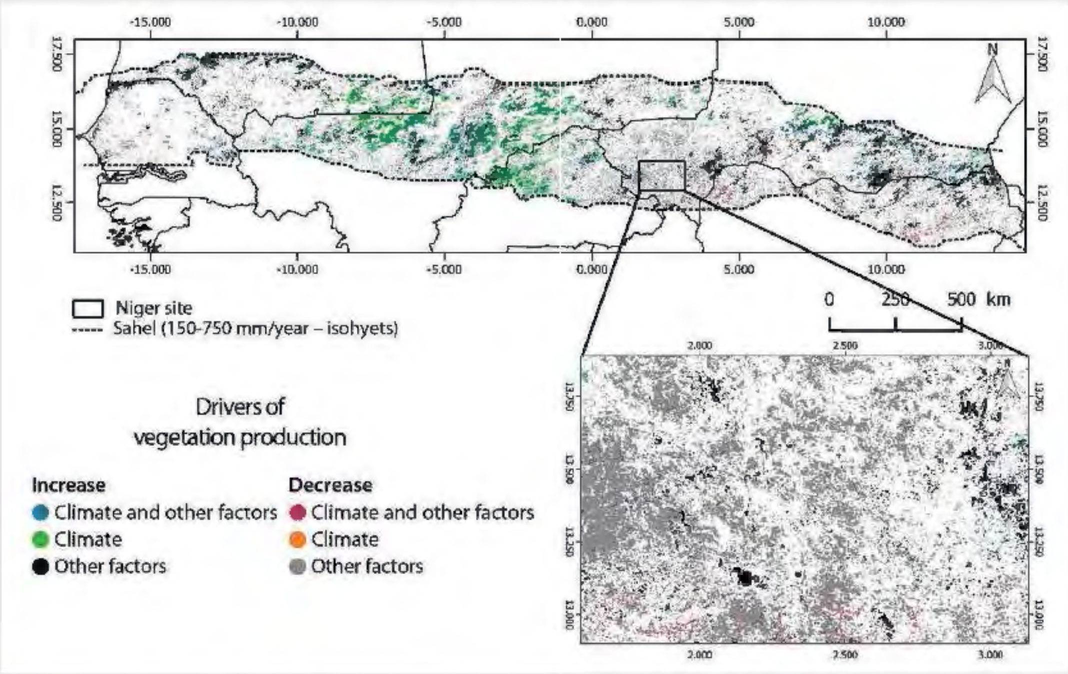

Figure 33.2 What are the factors behind the trends in plant biomass production in the Sahel?
Source: Leroux *et al.*, 2016.

However, constructing such models, i.e., modelling the processes behind territorial dynamics remains not only a technological challenge, but also a conceptual and methodological one. Processes are often dynamic and spatially distributed, interact at different spatial and temporal scales, and include human activities. Several disciplines are usually involved, including the geographical and agricnltural sciences, economics, social sciences, mathematics, and computer sciences, which makes modelling a means to integrate these disciplines (Schmidt-Lainé and Pavé, 2002). Although the lack of an integrative framework is keenly felt (Gaucherel *et al.*, 2014), scientific communities have started working together on Land-Change Science for studies on sustainability and on changes in the global environment (Rindfuss *et al.*, 2004).

Several modelling approaches have contributed to in-depth studies of territorial dynamics. Those that include the largest user communities are systems dynamics, cellular automata and multi-agent systems. In the systems dynamics approach (Forrester, 1968), processes are represented in the form of stocks (system variables), flows (exchanges between stocks) and feedback loops (where the result of an action is involved in steering the action). Thus, in the Spatial Modelling Environment (SME; Costanza and Voinov, 2004), space is divided into cells, each containing a stock-flow model, with the possibility of organizing or directing flows between neighbouring cells. In cellular automata, the geographical space is also divided into cells, each of which can be in a finite number of states. The state of each cell changes according to transition rules which take into account the states of neighbouring cells. This approach is mainly used in the study of urban dynamics (for example, Batty and Xie, 1994; Dubos-Paillard *et al.*, 2003). Multi-agent systems and cellular automata are centred on individuals. They originate from the concept of the agent, capable of communicating and reacting to an event, extended to the concept of agent, who has objectives to be achieved and can make decisions autonomously. They evolve in an environment they perceive, and on which they can act and draw resources from. Bousquet and Le Page (2004) explain the current state of the art of this approach applied to the management of ecosystems.

These approaches are now widely used to deal with territorial dynamics, but the inherent spatial dimension is not usually represented in a detailed manner. If it was, it would become difficult to process.

Taking interactions within the territory into account: the example of Ocelet

Systems dynamics modelling is often adapted to categories of problems for which we have an overall understanding of the exchanges in the system. The individual-based approaches are more suitable when the individual behaviours of a system's elements can be described, and the aim is to study the emergent properties resulting from these behaviours. The study of territorial dynamics requires the integration of knowledge from different disciplines, and it is often necessary to reconcile the local vision with the global vision.

One way of proceeding, which has not been implemented in the modelling families mentioned above, is to base the reflection on the interactions as common denominators.

The 'territory' system is then seen as a set of interacting entities sharing a part of the space, the evolution of the system being the result of these interactions. This entire process can be formalized using interaction graphs (a graph is a mathematical object consisting of nodes, with edges connecting these nodes): the nodes represent the territory's components and the edges represent the interaction functions (Box 33.4). A single concept serves to represent spatial, social, hierarchical or functional relationships. This facilitates not only the integration of points of view from different disciplines in the construction of territorial dynamics models, but also the simultaneous consideration of the different scales in which these interactions are to be considered.

This interaction graphs-based approach has been implemented in the Ocelet spatial modelling language (Degenne and Lo Seen, 2016) and the associated simulation platform, which stands out in this way from other modelling families. The concept of the interaction graph is central to this language, which is equipped with the tools required to import, export and process various types of geographical data. We thus have the means for including spatial relations with the other forms of relationships needed to simulate territorial dynamics.

The first experiment of modelling territorial dynamics, based on Ocelet and the interaction graph concept, was carried out in an island context on Réunion Island (Lestrelin *et al.*, 2017) where land is scarce and its availability an important issue, especially in peri-urban areas. Several models of land use dynamics were created to help characterize different scenarios of territorial dynamics using landscape simulation. Initially, these models integrated urban dynamics processes (urban planning, densification, social housing, and the appearance of urban sprawl) constrained by housing and infrastructure needs. They mainly generated indicators on the consumption of agricultural land. Agricultural dynamics processes (farm cycles, reconversion of wastelands, water supply for irrigated land, diversification) were added in the second phase. Cartographic outputs have highlighted the contrast between production areas that are especially vulnerable to urban pressure and those that remain stable in most scenarios. These models were most notably used to illustrate the possible interactions between different public policies. Boxes 33.4 and 33.5 illustrate the use of the Ocelet platform in very different case studies.

Box 33.4. Spatial modelling of runoff in the Saint-Gilles ravine watershed on Réunion Island.

Pascal Degenne

The French strategy for the integrated management of the sea and coastal areas in the southern Indian Ocean region resulted in an initiative by the West Coast Territories community to carry out a trial of such a strategy on its territory (Degenne et al., 2015). The many issues and subjects identified by the actors participating in the project (water resources, biodiversity, fisheries, agriculture, land, etc.) have been linked to processes (erosion, agricultural dynamics, irrigation, development of recreational activities, waste disposal into the sea, etc.), and these links have shown at what point the whole becomes a system. Some processes that were clearly seen to be integrators were modelled. For example, runoff is the link between land use, maintenance of ravines, various types of pollution, coastal flooding risk, and water quality in the lagoon and in the marine reserve.

Two complementary models were developed to simulate runoff. The first, by the Geosciences laboratory of the University of Réunion, was based on the HMS (Hydrological Modelling System) software application and relied on a spatial division of the watershed into seven sub-basins. In line with current knowledge, it successfully categorized, in order of magnitude, the hydrological characteristics of the watershed and its ravines.

Figure 33.3. Example of dynamic maps derived from the simulation of the model based on Ocelet during a rain event.

Animated cartographic rendering of the simulation of runoff in the Saint-Gilles ravine during a rain event. The colour and height of the cells are proportional to the flow calculated at each point.

The second component of this modelling work was created by CIRAD, and is based on the Ocelet language. This model is finely spatialized and allows the attribution of properties (rate of runoff, infiltration, sub-soil reservoir, drainage rate) individually to each cell of the selected section. The rendering of the simulations as dynamic mapping helped in characterizing the territory for the actors during workshops. This second model was also intended to be linked with models dealing with other subjects (flooding, land use dynamics) designed with Ocelet in the same territory, especially for testing highly localized measures envisaged to enhance infiltration.

Box 33.5. Spatial modelling of an agroecosystem's dynamics: case of the cotton production basin of western Burkina Faso.

Camille Jahel

Already undermined by significant intra- and inter-annual climate variability, the cotton production basin of western Burkina Faso has undergone a profound and rapid change over the past 15 years, due in particular to intense demographic pressure and to the implementation of development policies that favour export crops. Changes are visible at the landscape level: maize-cotton rotation has replaced the earlier cropping systems based mainly on cereals and legumes, and the landscape is close to saturation with a gradual conversion of the remaining dry forests into cultivation and a drastic reduction in the fallow period of the plots. Recent studies carried by Jahel *et al.* (2016) use the Ocelet approach to analyze the processes at different scales at the origin of this agrarian system's dynamics and to compare their respective influences in the changes recorded.

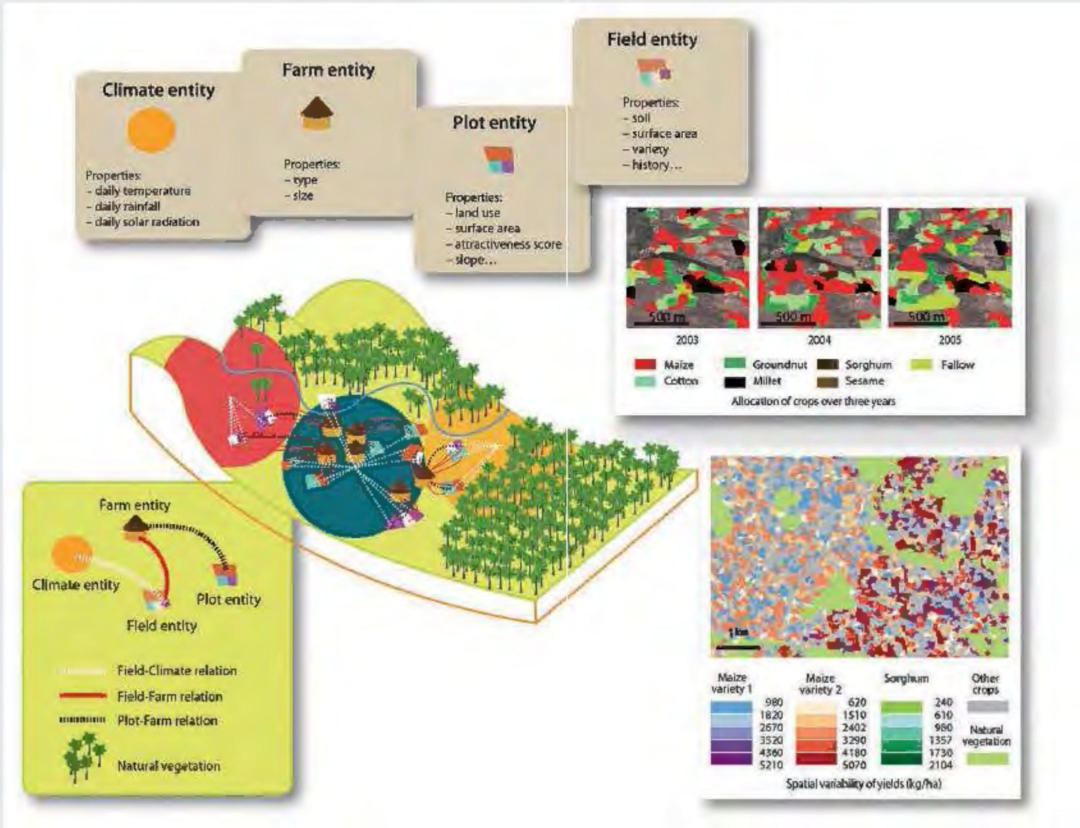

Figure 33.4. Schematic representation of the model's structure, modelled entities and examples of simulation outputs.
Adapted from Jahel *et al.* (2016).

Three main processes were modelled for the Tuy province (about 6000 km^2): extension of the cultivated area at the provincial level, crop rotation at the farm level, and cereal production at the level of the cultivated field. The evolution of the cultivated area is modelled every year and takes into account changes in farm size, the creation or disappearance of farms, natural population growth and migration. The annual crop rotation takes into account farmers' strategies in the context of their farms, which includes, in particular, the market price of cereals, cash crops and the relationship with the cotton sector. The SARRA-H crop model (Baron *et al.*, 2003) is used to model the daily cereal production for each locally characterized field using rainfall and climate data. The model was then used to assess quantitatively:
– the impact of the farmers' strategy to geographically disperse their plots to minimize climate risks;
– the importance of fallowing in a landscape where arable land is becoming scarce;
– the consequences of the farmers' limited access to credit to purchase fertilizers.

Conclusion

Remote sensing and spatial modelling are two complementary tools for analyzing and monitoring territorial dynamics at several scales. From drones to medium spatial resolution satellites, remote sensing offers many possibilities to characterize and measure territorial dynamics over a wide area and in an objective way, especially in areas with difficult access or where little data is available. The challenge then is to understand and analyze the observed and measured dynamics, which necessarily requires incorporating additional information from different disciplines (geography, agronomy, sociology, etc.). Modelling serves to link the dynamics observed and the different knowledge of the processes at work in the territory, by translating this knowledge into spatial rules that allow the reproduction, and thus the explanation, of the dynamics observed.

The combined use of these two tools then allows for retro-prospective and prospective analyses of the territorial dynamics at work, which are essential to incorporate into any territorial planning. However, while these spatial approaches contribute to improving the existing knowledge of, and studies on, territorial dynamics, they represent only one of the keys to understanding territories.

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