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11.2 THE GIS AND REMOTE SENSING CONTRIBUTION TO THE ELABORATION OF SYSTEM HIERARCHIES IN FSR

Evaristo Miranda

Increasingly, the challenge of relating agriculture and farming to different land uses or landscape categories can be attacked using GIS and RS in both research and management.

11.2.1 Introduction

Land use and changes in land use are critical elements in FSR. Rural areas are markedly heterogeneous and many factors drive land use changes in both time and space[1]. In the agricultural frontier areas of the developing countries change is particularly intense and, in addition, one type of land use (annual crops, permanent crops, grazing lands, forestry) may be a feature of several different production systems within the landscape. This spatial and temporal diversity often precludes the application of the same technologies across the land-use type as a whole. To add a further dimension, technologies which are useful on an individual farm may be harmful when used more widely.

As a result, three important questions arise for FSR:

- How to establish the spatial distribution of production systems' at different scales?
- How to characterize the link between individual farming systems and different uses of land?
- How to evaluate the sustainability of the diversity of farming systems and the interactions between them in the landscape?

Historically, FSR has concentrated at the farm level of what is in fact a hierarchy of systems. Analysis and evaluation have widened recently, helped by new research tools. GIS and remote sensing (RS) techniques are proving valuable in establishing and monitoring systems hierarchies in which the farm is one important level. This contribution summarizes recent developments in GIS and RS methods, using examples from applications in the FSR-based systems hierarchy in Brazil. The methods were developed in a research programme executed by the NGO ECOFORCE (Research and Development @ http://www.ecof.org.br) with the technical and scientific collaboration of the

Environmental Monitoring Center (NMA-EMBRAPA, http://www.nma.embrapa.br) in the county of Campinas, in São Paulo State, Brazil.

11.2.2 Complexity and systems hierarchies

It has been acknowledged, historically, that farms are complex systems. FSR has tried to manage this complexity through its conceptual frameworks and models. This understanding of complexity is related to many factors; the non-linearity and asymmetry of the relationship among the components and its structure; the different levels of organization and constraints; the simultaneous existence of functional and structural boundaries; the level of uncertainty of systems indicators; the permanent state of evolution in systems' components and interactions between them; varied sources of perturbations which destabilize a range of parameters; the spatial diversity of the landscape and the interactions between the social, economic and ecological systems.

While the concept of systems hierarchies is helpful in understanding these sources of complexity, the establishment of hierarchical levels in FSR cannot be an arbitrary process. Research and rural development programmes[2] demonstrate a continuum of levels, their interactions and linkages. Scale is a central concern to those modelling dynamic multivariate structures that respond to the interactions between many levels of organization[3]. Generally speaking, FSR hierarchical levels are associated with spatial scales or organizational levels in agricultural production[4]. In FSR the early notion of hierarchy involved discrete levels: field, farm, watershed, valley, county. Hart, in 1985, presented a series of concepts on agroecosystems, based on this kind of hierarchical analysis[5]. His study led to many FSR applications in Latin America. Many researchers have considered the farming system hierarchy as nested, which requires that upper levels contain lower levels in a continuum of structures. However, research results can rarely be generalized, aggregated or disaggregated, from one level to another. In fact, in general, hierarchies which include farm systems are non-nested, with strong interactive tendencies. The levels are frequently a more convenient focus for research than the hierarchy, despite its explanatory power.

Computers are able to display structures in hierarchical levels without human value judgements[6]. In exploring typologies of farming systems, a process using clusters and multivariate analysis, employing only numerical criteria given by data sets is now well known. Some authors, such as Simon in 1962, suggest that hierarchical structure itself is a consequence of human observations[7]. Without raising questions of ontological reality, it seems fundamental for given levels in FSR to take account of hierarchical continuity and cohesiveness. Scale is one continuously varying function that can describe the continuum of levels and their interactions[8]. The available methods try to elucidate the process and the critical parameters for the different spatial scales and landscape units (land, property, hydrographic basin, community microregions, regions and county) using GIS and RS tools[9].

This contribution shows how GIS and RS are increasingly used in a complementary way to simulate farming systems strategies at the micro level; technologies for agriculture production systems, and at macro levels; public policy, politics and land use. Ongoing developments are improving the resolution available at several hierarchical levels. Increasingly the challenge of relating agriculture and farming to different land uses or landscape categories can be attacked using GIS and RS in both research and management[10].

11.2.3 GIS and RS: new techniques in FSR

GIS and RS techniques are proving their worth in helping to establish and monitor systems hierarchies in FSR. GIS offers sophisticated spatial analyses of the numerical descriptors of the farming system. Whereas FSR developed complex numerical models, GIS spatial analysis of production systems is limited to farm fields. The spatialization of productivity variables, of farm system typology parameters, or of the system's environmental impact on a given resource at several hierarchical levels (e.g. field, farm, groups of farms or region) widens our understanding and opens new horizons for FSR. GIS allows area, perimeter and volume calculations and a series of basic operations for quantifying the spatial expression of variables. GIS also allows qualitative spatial analysis, such as diversity, proper or improper land use, the simulation of alternative uses, the interactions between different uses and the probable impact of new agricultural technologies on the environment[11].

Spatial analysis of systems can occur at different hierarchical levels, however, it often demands information that is not readily available and sometimes does not even exist. Recently, the evolution of RS has made available series of spatial data on existing production systems and land use which have helped fill many of these data gaps. In the developing countries RS is frequently the only way to get these data due to the lack of census data[12] and the difficulty in reaching some rural areas[13]. Satellite imagery gives the researcher the means to evaluate land use and changes in use[14]. It also allows the researcher to detect the use of some technologies, particularly in soil conservation[15] and, importantly, to relate land uses and vegetation behaviour[16].

The terrestrial monitoring satellites represent an efficient instrument to characterize land use, measuring the spatial distribution of farms and land use in a very precise way[17]. Some farming systems can be identified from orbital images and the uses of RS in FSR have been increasing with the development of new imaging softwares and more sensitive sensors and satellites. In 1996 satellites can already observe detail smaller than $50 m^2$.

11.2.4 Remote sensing and FSR

The first LANDSAT satellite, originally called ERTS-1, was developed and launched by NASA in July 1972. Today about 300 satellites are available to monitor terrestrial ecosystems, agriculture and changes in land use. The interest in the use of RS in FSR is linked to three properties of orbital images: spatial resolution, temporal resolution and radiometric or spectral resolution.

Spatial resolution

This is important to the study of farming system based hierarchies. The orbital digital data's plasticity allows works at different spatial scales[18]. Agriculture can be analysed in different perception or hierarchical levels (local, microregional, regional, national), and each perception level can be at least partially associated with a cartographic scale in spatial terms. Local studies range from 1 : 1000 to 1 : 10,000, microregional studies from 1 : 25,000 to 1 : 100,000. Regional studies generally work with scales ranging from 1 : 100,000 to 1 : 250,000 and national or macroregional studies sometimes use spatial scales smaller than 1 : 1,000,000. The same image can be analysed from 1 : 1,000,000 to 1 : 50,000. Recently there has been remarkable development in the spatial resolution and scales of 1 : 25,000 and 1 : 10,000 can now be obtained, for example, from the IRS-C (India), SPOT 4 and 5 (France) and ORBVIEW (USA) satellites.

The LANDSAT TM image, used since 1985, covers an area of $34,000 km^2$ approximately and has a 30-m-pixel resolution. Agriculture can be studied hierarchically from scales based on the LANDSAT images which extend from 1 : 1,000,000 to 1 : 50,000. The French satellite SPOT 3 has a 10-m resolution and the Indian satellite IRS-1C has a 6-m resolution. Both these satellites offer stereoscopic views and their images are already available. The next generation of satellites will be even more accurate, providing resolution between 10 and 100 times better than the existing commercial satellites, formerly available merely as expensive aerial photos. As an example, the panchromatic sensor of the satellites QuickBird and OrbView will have a 1-m resolution at nadir and the multi-colour sensor will have a 4-m resolution[19].

The improving spatial resolution of the imagery allows ever better sampling plans in FSR. The distribution of land owners, the land uses and their localization can be mapped *a priori*. This is particularly important in areas where censuses are insufficient or non-existent. It is also vital in expanding agricultural frontiers such as the Amazon, or in areas where agriculture has a strong spatial dynamic, frequently expanding and contracting[20].

Temporal resolution

This defines the frequency of repetition in the image's coverage at a same point: 16 days for the LANDSAT, 23 for the SPOT. Remote sensing satellites are able to provide a monthly monitoring of agricultural and land use systems. If different orbital systems are combined, for example, LANDSAT, SPOT and IRS, a weekly monitoring can be obtained. At a finer level the NOAA/AVHRR satellites provide information on temperature[21], drought, fires and burnings[22], soils moisture[23] and vegetation activity at least four times a day. Thus orbital images can help monitor nutritional stress in vegetation, irrigation efficiency and even pest attacks.

In the last few years, the time between image acquisition by the satellite and availability to the user has been reduced to 1 or 2 months. The next generation of commercial high-resolution satellites will reduce this time still further as the images will be made available through electronic networks within hours. Several orbital systems have been working since the 1970s. The images obtained are preserved on files and made available through networks. This allows the reconstitution of land use evolution and the monitoring of dynamic phenomena, like deforestation[24], erosion, the expansion of the cultivated area and salinization.

Spectral resolution

This is defined by on-board instrument bands. The instruments' spectral range includes the panchromatic (PAN), the visible and the near infrared (VNIR), the short wave infrared (SWIR), the multiband thermal infrared (TIR) and the synthetic aperture radar (SAR). Satellites do not take pictures, but generate images. Those images are digital and can be processed digitally. Each part of the spectral range 'recognizes' different surface elements such as soil, humidity, vegetation, dust, etc. The combination of the several spectral bands through mathematical and statistical algorithms allows the identification and qualification of diverse cultures and the different kinds of land use[25].

The discriminatory power of the images is greatly superior to that of the human eye. While the eye distinguishes an average of 20 grey tones, hundreds of grey tones can be identified on a satellite image. This, for example, makes it possible to identify irregularities in photosynthetical activity that would be invisible to the human eye. Several vegetative stages can be identified on the same kind of plantation. Phytomass and productivity levels can be evaluated, on pastures, sugar cane and cereal fields. Different soybean varieties have been distinguished on orbital images, due to their differences in height and the insertion angle of the leaves. In the microwave field, the radar sensors allow imaging during the night and under any weather conditions[26]. In humid tropical regions with frequent cloud cover the radar images are of great help.

11.2.5 The use of GIS in FSR

The agricultural production cycle rarely corresponds to the time scales for the evaluation of environmental phenomena (pedogenesis, morphogenesis, loss of fertility, land compactness, acidification, biodiversity reduction, river obstruction). There has been little integration of environmental phenomena in the reconstitution of the history of production systems, or in the modelling of new ones. Strict numerical models are inadequate to show spatial realities. The spatial and temporal dynamics of land use, either on the farm or at regional level, are good examples of crucial hierarchical issues that are difficult to resolve without the use of cartographic methods. In FSR a spatial view can be acquired through the use of GIS.

GIS was born as a way to digitize cartography. Linked to the numeric data bank, a GIS is an efficient tool to characterize the spatial division of a great number of phenomena and their dynamics. GIS allows spatial analysis to be linked to maps according to rules archives/files, equations or logical sequences[27] and can then create new maps showing agricultural production cycles and the environmental impacts related to those cycles[28].

GIS have a different mathematical structure from the satellite images treatment systems, but there are interfaces between both. Cartographic data can be digitally confronted with the orbital images and vice versa. A great deal of software uses GIS in a variety of applications, the thematic and cartographic precisions vary for different studies. Many GIS are in the public domain and some versions can be very expensive to use. A GIS surrounding is convenient enough to analyse land-use maps of different periods and articulate them with the production systems.

Several routines of agricultural zoning are currently operational in GIS[29]. Land use planners are increasingly using it and, in FSR, it is contributing to sample planning, extrapolation of data and the multivariate and multilocational analysis of production[30].

11.2.6 GIS, RS and system hierarchies: an example

The work described in this contribution was carried out in an area of approximately 800 km^2 in Campinas county, São Paulo State, Brazil. The data were obtained during a multidisciplinary research project which included the survey of a sample of 100 small farms. The environmental and land use characterization was supported by RS and the integration of these cartographic results with the FSR survey data on the production systems was accomplished through GIS. The project used the 2.4 version of the GIS (GIS 2.4) of the National Institute of Spatial Researches (INPE). Four main methods based on GIS and RS use were developed and validated; mapping land-use capacity, characterization of present land-use systems, relationships between farming systems and land use and a hierarchical evaluation of agriculture environmental impacts.

Over 100 thematic and synthetic maps and orbital images were analysed and treated. Several themes were analysed at different hierarchic levels: farm, farm groups, watershed and county. It is impossible to reproduce these maps and images here, but the main methodological and operational results are discussed. These results were the object of several publications and are available on the Internet (at the URL, http://www.nma.embrapa/projetos/cmp/gis.html/).

Mapping land use capacity

There are several analogue methods of calculating land use capacity. The method used by FAO was adapted for GIS. The main steps developed and validated in the process were:

- Digitalization of the county limit.
- Digitalization of the contour curve map.
- Digital generation of the hypsometric map by the GIS.
- Digital elevation model (DEM) generation.
- Declivity map digital generation, by the GIS.
- Hydrographic map digitalization.
- Basins and sub-basins map generation and digitalization.
- Generation and adjusts of the pedological map, by fieldwork.
- Pedological map digitalization.
- Digital generation of the erodibility map, by the GIS.
- Digital generation of the hydric availability map, by the GIS.
- Digital generation of soils' phosphorus fixation capacity, by the GIS.
- Digital generation of free aluminum toxicity, using the pedology.
- Digital generation of the interchangeable bases availability map, by GIS.
- Digital generation of a chemical fertility map, using the pedology base.
- Constitution of an integration programme for generation of a land use capacity map.
- Digital generation of the agricultural land use capacity map.

Characterization of present land use

The characterization of present land use was carried out using satellite multispectral images (LANDSAT TM 5 and SPOT) and IBGE's (Brazilian Institute of Geography and Statistics) topographic charts in combination with fieldwork. The categories of land use were defined in the county. In the Campinas case 17 categories were identified.

1. Urban areas.
2. Water (lakes, irrigation dams and rivers).
3. Natural forests and woodlands.
4. Riparian forests.
5. Savannas.
6. *Capoeiras* (deforested areas, secondary vegetation).
7. *Pinus* plantations.
8. Eucalyptus plantations.
9. Sugar cane.
10. Citrus.
11. Coffee.
12. Fruit plantations.
13. Annual crops.
14. Natural pastures.
15. Artificial pastures.
16. Vegetable gardens.
17. Others (roads, rock, mines).

Digital classification methods were used to interpret the satellite images and the results incorporated in GIS. This information can be extracted at several hierarchic levels: farm, farm groups, basin or sub-basin, region or county. The main methodological steps developed and validated were:

- Preliminary definitions of the agricultural and non-agricultural land use categories in Campinas county.
- Images acquisition of the SPOT and LANDSAT TM satellites.
- Digitalization of Campinas county boundaries in GIS, and extraction of its area from the images.
- Migration of the corresponding digital records.
- Preliminary digital treatment of the satellite images to differentiate and limit the main land use categories.
- Terrestrial verifications in a diffused and concentrated way.
- Map making of agricultural land uses in a definite way.
- Vectoring the land use map and entry to GIS.

The relationships between farming systems and land use

Each type of land use can contain one or more production or farming systems. The existing production systems were identified and their technical coefficients quantified and the relationships between the use and production systems were established at a variety of hierarchical levels: camp, farm, farms groups, basin, region and so on. Every farm was geocoded in GIS and a data bank was created, articulating the land use and the production systems. The main methodological steps were:

- Land use inventory and elaboration of hypothesis about the existing variability between land uses and production systems.
- Preliminary identification of the main production systems, in relation to agricultural land use.
- Acquisition of a 100-farm sample using aleatory stratified sampling techniques.
- Hypotheses verification about the relationships between the production systems and the uses from the camp survey.
- For applications including more than one production system, definition of a complementary farm sample.
- Preliminary map making of spatial division of the main production systems interaction with land use.
- Farming systems technical coefficient quantification from the 100-farm survey.
- Final evaluation of the variability of main land uses across production systems.
- Technical coefficient quantification and assessment of the possible environmental impacts of the production systems.
- Data bank constitution, for 1 ha of each type of use identified in the fieldwork complemented with bibliographical data and discussions with researchers.
- Creation of a data bank of technical coefficients, production systems and possible current environmental impacts.
- Adequate polygon labelling of the present land use map to allow their association with the data bank (GIS).

Hierarchical evaluation of agricultural environmental impacts

The environmental impact map of the agricultural activities, based on GIS, was made by linking the survey data from the farming systems and the cartographic bases. The goal was to evaluate the impact of agricultural activities on the land, air, surface waters, fauna and natural vegetation. The impact of agricultural inputs was also evaluated. A final synthesis was drawn up for the ecosystems. The more recent data linking routines via GIS enables the evaluations for several hierarchic levels: farm, farm groups, basin, sub-basins, regions, counties or any other desired area. First, through GIS, the following maps are produced at several hierarchical levels:

- Nitrogen use (kg N ha^{-1} $year^{-1}$).
- Herbicide use (l ha^{-1} $year^{-1}$).
- Pesticide (l ha^{-1} $year^{-1}$).
- Synthesis map about chemical inputs impact.
- The use of burning for agriculture.
- Soil compactness.
- Run-off map.
- Soil loss.
- Land use stability.
- Land exposure period per year or bareness.

Second, the following synthesis maps are produced at several hierarchic levels:

- Farm system environmental impact on the land.
- Farm system environmental impact on the water.
- Farm system environmental impact on the vegetation.
- Farm system environmental impact on the air quality.
- Farm system environmental impact on the non-biotic systems.
- Farm system environmental impact on the biotic systems.

11.2.7 Conclusion

FSR's recent history shows new research themes and methods emerging. System hierarchies are a useful operational device to help deal with the complexity of farming systems. They can be addressed through GIS and RS which can be used independently or together in FSR. The results of the ECOFORCE and NMA/EMBRAPA application in Brazil demonstrate that GIS and RS can contribute to the improved elaboration of system hierarchies in FSR, reducing the costs and time required. The nature of the RS data allows the scale theme to be treated as a continuum across several hierarchical levels. At the same time thematic complexity gets adequate spatial treatment through the GIS. GIS and RS can contribute to FSR, from sampling to the extrapolation of results across space. New sensors are providing unprecedented data, with detail to 1 m and wide spectral resolution, and will widen GIS's application to FSR. The great challenge is not in GIS and RS development anymore but perhaps on the researchers' willingness to incorporate these techniques into their FSR toolbag.

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