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Technical Report on **Improving the Use of GPS, GIS and Remote Sensing in Setting Up Master Sampling Frames**

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**Improving the Use of GPS, GIS
and Remote Sensing in Setting Up
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Acronyms and Abbreviations

ADG	Advanced Database Gateway
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
ASPRS	American Society for Photogrammetry and Remote Sensing
BRDF	Bidirectional Reflectance Distribution Function
BDS	<i>BeiDou</i> (COMPASS)
CAPI	Computer Assisted Personal Interview
CASI	Compact Airborne Spectrographic Imager
CSA	Central Statistical Agency (of Ethiopia)
DBMS	Database Management System
DFID	UK's Department for International Development
DGPS	Differential Global Positioning System
DTM	Digital Terrain Model
DTED	Digital Elevation Model
DVI	Data Vegetation Index
EBLUP	Empirical Best Linear Unbiased Predictor Estimator
EA	Enumeration Area
EIFOV	Effective Instantaneous Geometric Field of View
EUROSTAT	Statistical Office of the European Communities
FAO	Food and Agriculture Organization of the United Nations
FGDC	Federal Geographic Data Committee
FHQ	Flexible Histogram Quantization
FWHM	Full-Width at Half-Maximum
GAMM	Generalized Additive Mixed Model
GEOSS	Global Earth Observation System of Systems
GLONASS	<i>Globanaya Navigatsionnaya Sputnikovaya Sistema</i>
GIN	Global Information Network
GIS	Geographic Information System
GeoVis	Geographical Vector Interpretation System
GLCF	Global Land Cover Facility
GLCN	Global Land Cover Network
GNSS	Global Navigation Satellite System
GSD	Ground Sampling Distance
HRV	<i>Haute Resolution Visible</i>
ICT	Information and Communications Technology
IIFOV	Instantaneous Field of View
IGFOV	Instantaneous Geometric Field of View
ISODATA	Iterative Self-Organizing Data Analysis
JRC	Joint Research Centre (of the European Union)
km	kilometre
KOMPSAT	Korea Multi-Purpose Satellite
LCCS	Land Cover Classification System
LEO	Low Earth Orbit
LMST	Local Mean Sun Time
lvpl	Lineal-visual perception limit
m	metre
MARS Project	Managing Aquatic ecosystems and water Resources under multiple Stress Project
MSF	Master Sampling Frame
MTF	Modulation Transfer Function

USDA	United States Department of Agriculture
NASS	National Agricultural Statistics Service
NSSDA	National Standard for Spatial Data Accuracy
MAD-CAT	Mapping Device–Change Analysis Tool
MLP	Multi-Layer Perceptron
MSAVI	Modified Soil-Adjusted Vegetation Index
NE $\Delta\rho$ /NE ΔT	Noise Equivalent differential Reflectance/Temperature
NDVI	Normalized Data Vegetation Index
NSDS	National Strategy for the Development of Statistics
OLI	Operational Land Imager
PDA	Personal Digital Assistant
POPOLUS	Permanently Observed Points for Land Use Statistics
PPS	Probability-Proportional-To-Size
PSU	Primary Sampling Unit
RAIFOV	Radiometrically Accurate IFOV
RQI	Relative Quality Index
RS	Remote Sensing
RSME	Root Mean Square Error
RSS	Remote Sensing Survey
RVI	Ratio of Vegetation Index
SAC	Scientific Advisory Committee
SAR	Synthetic Aperture Radar
SAVI	Soil-Adjusted Vegetation Index
SDBMS	Spatial Database Management System
SNR	Signal-To-Noise Ratio
SRF	Spectral Responsivity Function
STM	Solid Terrain Model
SSU	Secondary Sampling Unit
TERUTI	<i>Territoire Utilisation</i>
UTM	Universal Transverse Mercator
WRS	Worldwide Reference System

Preface

This Technical Paper on **Improving the Use of GPS, GIS and Remote Sensing in setting up Master Sampling Frames** has been prepared within the framework of the Global Strategy to Improve Agricultural and Rural Statistics. The Global Strategy is an initiative endorsed in 2010 by the United Nations Statistical Commission. It provides a framework and a blueprint to meet current and emerging data requirements and the needs of policy makers and other data users. Its goal is to contribute to greater food security, reduced food price volatility, higher incomes and greater well-being for rural populations, through evidence-based policies. The Global Strategy's Global Action Plan is centred upon 3 pillars: (1) establishing a minimum set of core data (2) integrating agriculture into National Statistical Systems (NSSs) and (3) fostering the sustainability of the statistical system through governance and statistical capacity building.

The Action Plan to Implement the Global Strategy includes an important Research Programme, which addresses methodological issues in improving the quality of agricultural and rural statistics. It is envisaged that the Research Programme will devise scientifically sound and cost-effective methods that can be used as reference when preparing practical guidelines for country statisticians, training institutions, consultants, etc.

To enable countries and partners to benefit from the available results of the Research activities at an early stage, it has been decided to establish a **Technical Reports Series**, to widely disseminate existing technical reports and advanced draft guidelines and handbooks. This will also provide an opportunity to receive early and further feedback on the papers.

The Technical Reports and the draft guidelines and handbooks published in this Technical Report Series have been prepared by Senior Consultants and Experts, and reviewed by the Scientific Advisory Committee (SAC)¹ of the Global Strategy, the Research Coordinator of the Global Office and other independent Senior Experts. For certain research topics, field tests will be organized before the final results are included in the relevant guidelines and handbooks.

This Technical Report on *Improving the Use of GPS, GIS and Remote Sensing in Setting Up Master Sampling Frames* is the result of a comprehensive literature review on the subject, followed by a gap analysis and a development of innovative methodological proposals for addressing the various issues that arise.

¹ The SAC is composed of 10 renowned senior experts in various fields relevant to the Research Programme of the Global Strategy who are selected for a term of two years. The current members are: Vijay Bhatia, Seghir Bouzaffour, Ray Chambers, Jacques Delince, Cristiano Ferraz, Miguel Galmes, Ben Kiregyera, Sarah Nusser, Fred Vogel, Anders Walgreen.

This paper provides a detailed review of various geomatic tools used in the construction of Master Sampling Frames (MSFs), as the proper identification of the location of the territory's various constituent elements, and thus their georeferencing, is indispensable. The tools reviewed include digital cartography, satellite images and remote sensing, Geographic Information Systems (GISs), and Global Navigation Satellite Systems (GNSSs: in particular, GPS, GLONASS, Compass, and Galileo).

This Report specifies that the use of georeferencing or geolocalization tools (GPS and remote sensing) upon the many elements of an MSF, can enable, in combination with GISs – to exploit, among other aspects, the information's geographic component – connections to be made between the various aspects of a given sector. In particular, a spatial relationship can be established between the economic components (farms), the social components (households) and the environmental components (plots).

In addition, this Report indicates that remote sensing is a tool of particular interest when setting up an MSF, as it can be applied in the stratification of territory, in surface delimitation and in design optimization. Remote sensing is an important source of auxiliary information that can be used in sampling design or in estimation. GISs constitute a particularly important technology for setting up MSFs, as they can be employed in information digitization, area delimitation, stratification and definition of sampling units and sampling selection. GPS/GNSS can be useful for delimiting different surfaces (sampling units, boundaries) and for geolocating different elements of the frame. Also, GPS can be used to update maps.

This Report will form part of the Guidelines on Developing and Maintaining a Master Sampling Frame for Integrated Agricultural Surveys, which are currently under preparation.

The Technical Reports will be updated with the results of in-country field tests and country feedback and experiences, as these become available.

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The Technical Paper on *Improving the Use of GPS, GIS and Remote Sensing for Setting Up Master Sampling Frames* was prepared by Luis Iglesias Martínez, Luis Ambrosio Flores, Rafael García Rodríguez and Rogelio de la Vega Panizo, Associate Professors at the at the Universidad Politécnica de Madrid, with the guidance and supervision of Elisabetta Carfagna (FAO), Javier Gallego (JRC), and Naman Keita and Michael Rahija (FAO).

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Introduction

Setting up a Master Sampling Frame (MSF) involves the use of large amounts of information, from a variety of sources. Efficient methodologies for the capture, management, analysis and representation of this information are required with increasing urgency.

For a sampling frame to become an MSF in the rural sector, Vogel and Carletto (2012) propose that its construction bear in mind the following goals:

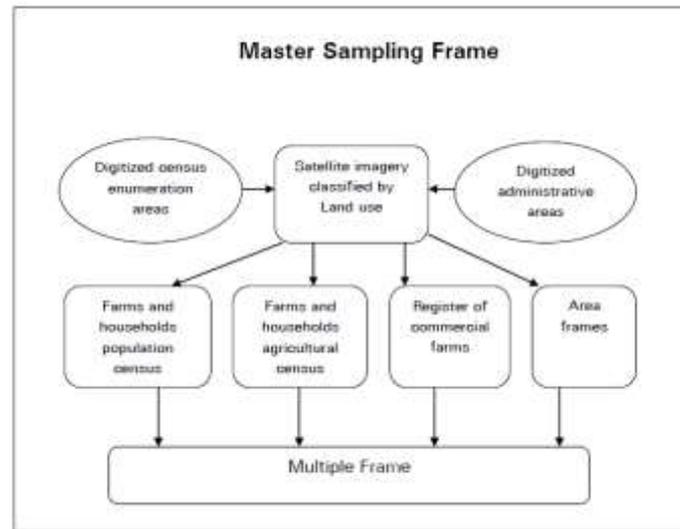
- the frame can become a survey basis for data collection activities relating to the agricultural statistics computed by all providers of the National Statistical System
- the frame can provide ways to connect households, farms, and land
- the frame can be made available to all institutions of the National Statistical System, for data collection purposes.

Vogel and Carletto (2012) suggest that an MSF can be constructed according to the following procedures:

1. Land classification using remote sensing
2. Georeferencing boundaries of administrative areas
3. Georeferencing census enumeration areas
4. List sampling frames for farms, households; area frames
5. Combining into multiple frames, if necessary

Figure 1 on the next page illustrates Vogel and Carletto's proposal (2012).

Figure 1 – The construction of MSFs



Source: Vogel and Carletto (2012).

As shown in Figure 1 above, the construction of an MSF requires that the location of the territory's different constituent elements be properly identified, which implies the need for their georeferencing. Therefore, the frame must be constructed using up-to-date geomatic tools, such as digital cartography, satellite images and remote sensing, Geographic Information Systems (GISs), and Global Navigation Satellite Systems (GNSSs: in particular, Global Positioning Systems – GPS –, GLONASS, Compass, and Galileo).

The use of georeferencing or geolocalization tools (GPS and remote sensing) for the various elements that make up an MSF, together with GISs that exploit – among other aspects – the information's geographic components, enable connections to be made between the various aspects of a given sector, by establishing a spatial relationship between the economic components (farms), the social components (households), and the environmental components (plots).

Remote sensing is a tool of particular interest in setting up MSFs, as it can be applied to territory stratification, surface delimitation and design optimization. Remote sensing is also an important source of auxiliary information, which can be used either in sampling design or in estimation. GISs feature particularly important technology for setting up MSFs, as they can be used for information digitization, area delimitation, stratification and definition of sampling units, and sampling selection. GPS/GNSS can be useful for delimiting different surfaces (sampling units, boundaries) and for geolocating different elements of the frame. Also, GPS can be used to update maps.

Remote Sensing

The purpose of using remote sensing in the construction of MSFs is twofold: on one hand, to obtain conventional cartography and thematic maps (land use) to assist initial territory stratification; on the other, to provide geographic information that can enable sampling unit delimitation, design optimization and improvement of estimates. Satellite images can also be especially useful when preparing the material required for fieldwork.

Geographic Information Systems

The construction of an MSF within a GIS is very useful for the subsequent processes of sample selection, material preparation, and field data collection, for the capture and handling of information, and for the treatment and analysis of this information at a later stage. When capturing information in the field, the possibility of storing all necessary information within an integrated digital format could be highly advantageous for its use on portable devices (laptops, tablets, GPS receivers). Indeed, this would enable a notable reduction in the time and costs of data gathering and processing.

Auxiliary information from remote sensing and other sources can be useful when planning MSFs. This auxiliary information, obtained from satellite imagery, censuses or inventories, can be included in the sampling design and estimation process, so that better samples and estimates can be computed.

Global Navigation Satellite Systems

Currently, several GNSS systems are available and in use (e.g. the United States' GPS – Global Positioning System – and the Russian GLONASS – *Globanaya navigatsionnaya sputnikovaya sistema*) or are being developed (e.g. the Chinese BDS – *BeiDou* Navigation Satellite System, also known as COMPASS, and the European Union's GALILEO).

The use of GNSS equipment to construct an MSF becomes necessary when some of the elements that compose the frame must be geolocated and digitalized. On the other hand, GNSS systems can be especially useful in field data collection, because the navigation utilities can guide surveyors to the precise positions where the data is to be acquired.

Geospatial technologies and sampling frames

Geospatial technologies can be extensively applied in setting up and exploiting sampling frames; territory stratification, optimization of sampling design and improved estimates are only some of the possible uses. In this Section, we review the literature on the various applications of geospatial technologies in a set of countries.

2.1. Using Remote Sensing, GIS and GNSS in setting up a Sampling Frame

Remote sensing, GIS and GPS can be applied extensively in setting up and exploiting sampling frames. As mentioned above, territory stratification, optimization of sampling design and improved estimates are only some of the applications that can be considered.

2.1.1. Remote sensing

Remote sensing is an important tool for agricultural statistics and is one of the main sources of auxiliary data, primarily because it is a method that enables the rapid acquisition of information over large geographic areas. Its use focuses on two important aspects: (i) sampling design and (ii) improvement of estimates. Regarding sampling design, remote sensing can be particularly useful in two phases (Carfagna 1999; Carfagna & Gallego 2005): (a) frame building and (b) design optimization.

2.1.1.1. Sampling design

a) Area frame construction

The use of remote sensing is of particular interest in area frame building. Traditionally, this process is performed on the basis of aerial photography, which, in some cases, have not been orthorectified. In particular, aerial photography continues to be used in area frames made of square segments (Carfagna 1999). For the operational construction of the country's area sampling frame for agricultural statistics, the United States' National Agricultural Statistics Service (NASS) has been using area frame sampling since 1964, and remote sensing since 1978 (Hale 1999; NASS & USDA 2009).

The use of satellite imagery presents certain advantages compared to the use of aerial photography. For example, satellite imagery is often more recent than the aerial photography available, since the photography may have been obtained several years before the construction of the frame. Also, satellite imagery usually features several bands or channels, which has been demonstrated to be useful in agricultural applications, especially in elaborating thematic maps through classification techniques (Delincé *et al.* 1993).

Stratification

In creating area frames, satellite imagery is mainly used in territory stratification (Carfagna 1999; Carfagna & Gallego 2005). When stratifying a population, the groups of individuals (strata) must be as homogeneous as possible, so that the variance within a single stratus is small. To this end, the stratification criteria, the number of strata, and the method followed in assigning individuals to each stratus must be determined. Territory stratification, normally according to land use levels, is the main utility in frame building. Several experiments have been attempted, without satisfactory results, to establish automatic classification algorithms for territory stratification. The MARS (Managing aquatic ecosystems and water resources under multiple stress) Project sought to develop algorithms for the automatic segmentation of panchromatic and multi-spectral satellite images, ultimately to automatically detect individual field limits. The algorithms developed did not provide results that allowed for adequate recognition of the boundaries between segments (Tsiligirides 1998).

Usually, the stratification process performed during area-frame building is executed by means of image photo-interpretation, using specific image management software such as the Italian informatics photo-interpretation tool POPOLUS (Permanently Observed Points for Land Use Statistics), used in the system for defining and stratifying the Italian statistical frame (*Consorzio Italiano per il Telerilevamento in Agricoltura* 2003). The Global Land Cover Network (GLCN) has developed informatics applications to facilitate the activities of land cover mapping (FAO-GLCN 2009), of the Land Cover Classification System (LCCS) (FAO 2005), the Geographical Vector Interpretation System (GeoVis), the Mapping Device–Change Analysis Tool (MAD-CAT), and the Advanced Database Gateway (ADG). This software has been employed to build the area frames in Ethiopia, the land cover classes of which were verified with GPS (Central Statistic Agency (CSA) of Ethiopia 2008). Morocco has developed an application to manage the updating of their area frames using satellite imagery (*application sig pour l'automatisation de la methode "d'échantillonnage à base areolaire"*) (Arrach and Tahri 2009).

Vibhute *et al.* have recently performed a review of the use of remote sensing and GISs in land use planning and decision support systems. They analyse the techniques employed by researchers to examine the use/land cover information in a given area (Vibhute, Anol & Gawali 2013). The main techniques include:

- Supervised classification. In these methods, it is assumed that prior knowledge for the classification of land (i.e. land cover types in specific sites) is available. The most useful classifiers of this type are the maximum likelihood classifier, the minimum distance classifier, the parallelepiped classifier and the mahalanobis classifier.
- Unsupervised classification. In this category of methods, there is no prior knowledge of the area to be classified. The two most common classifiers of this group are K-means clustering and Iterative Self-Organizing Data Analysis (ISODATA).
- Hybrid classifier. These methods are a combination of supervised and unsupervised classification.
- Fuzzy classifier. These classification methods are based on fuzzy logic.
- Normalized Data Vegetation Index (NDVI). These methods consist in calculating indices that exploit the differences in the spectral reflectance of plants, i.e. strong absorbance in the red part of the spectrum and strong reflectance in the near-infrared part.

The spatial, spectral, and temporal resolutions of the sensors are an important factor to consider for the activities of building or updating the area frames. Today, there is abundant satellite imagery, of different resolutions. As for the construction of an area frame, the most commonly used imagery has resolutions of 30 m (for Landsat, see Hale 1999) and 5-10 m (for SPOT, see Central Statistic Agency (CSA) of Ethiopia (2008); Arrach and Tahri (2009)).

The construction and maintenance of area frames has evolved, from adopting physical means (paper) to employing digital ones. The use of satellite imagery presents the additional advantage that its material is in an optimal format for digital storage and management in GISs.

Feature extraction

Feature extraction is the automated process of identifying physical objects from satellite and aerial imagery. This technology is used to update or create new elements in the mapping (Merchant & Narumalani 2009). Quackenbush presents an overview of the techniques for extracting linear features from imagery (Quackenbush 2004).

Recently, Turkera and Kokb proposed a methodology for the automatic extraction of dynamic sub-boundaries within existing agricultural fields (Turkera & Kokb 2013).

b) Design optimization

Remote sensing can play an important role in several features of sampling design. The use of information from satellite imagery can be particularly useful to optimize the size of the sampling unit, proposing the type of sampling to perform or fixing the number of stages to adopt (Carfagna & Gallego 2005).

I. Optimization of sampling unit size

What constitutes the optimal sample size has been addressed in several theoretical studies. The problem is usually approached on the basis of the fact that the most efficient sample size minimizes the variance estimator for a given cost; or minimizes the cost for a given variance. The sampling variance depends upon the variability between and within sampling units. Several authors have proposed alternatives to address this issue. Some have considered using the variogram function (Ambrosio, Iglesias & Marín 2003; Ambrosio *et al.* 2004; Carfagna 1997; Gallego & Carfagna 1995; Gallego, Feunette and Carfagna 1999).

The calculation of spatial variability functions requires possessing prior information on the variables of interest localized in space. The information available in previous studies may be insufficient to estimate the correlogram. In addition, it may be necessary to rely on autocorrelation functions for short distances, which are difficult to obtain from data. In these conditions, the autocorrelation functions can be derived from the information given by the satellite imagery (Carfagna & Gallego 2005). An important issue to consider is whether the photo-interpretation (classification) of the images and the variable of interest correspond perfectly (Carfagna 1999).

II. Selection of type of sampling and number of stages

Many authors have studied the behaviour of the spatial autocorrelation function, with the aim of evaluating the conditions in which systematic sampling provides more precise estimations than simple random or stratified sampling. A visual analysis of the correlogram function can be of particular interest when evaluating which type of sampling to perform, since it may offer information on the functions' concavity or on the presence of periodicity, and may suggest whether a stratified or a systematic sample should be chosen (Carfagna 2000). If the correlogram is a regular decreasing curve, a systematic sampling approach is adequate; however, if the curve presents a determined periodic structure, the sampling should not be systematic.

Additionally, a correlogram analysis could be useful in deciding whether two-stage sampling should be used, as well as for determining the optimal combination between the sizes of the primary and secondary units (Carfagna 2000).

2.1.1.2. Improvement of estimates

Several studies use remote sensing data to improve the estimates obtained from area sampling. In 2004, Gallego performed a fundamental review of the state of the art on land cover area estimation using remote sensing (Gallego 2004). He provided an overview of the different ways in which satellite images could be used to estimate land use. In terms of estimation, two application groups can be considered:

- A. Methods in which the basis of the estimation are remote sensing data, while ground data, usually obtained from spatial samples, are only used as auxiliary information. These estimates are obtained in the processes denominated “supervised classifications”, in which ground samples are used as training sites of the classification.
- B. Methods in which information obtained by remote sensing (exhaustive) is combined with information obtained from samples (accurate). These methods include regression, calibration and small area estimators.

Grace *et al.* proposed obtaining accurate estimates of cropped area for Guatemala and Haiti using an area frame sampling approach and very high resolution satellite imagery (Orbview and WorldView) (Grace *et al.* 2012). They use point-based interpretation for images taken during the major cropping seasons. Percent crop is evaluated using blocks of 5 x 5 km, upon which a regular grid of points spaced 500 m apart is superimposed. A Generalized Additive Mixed Model (GAMM) with a long link is used to estimate the cropped area, using geophysical and demographic data as independent variables.

Luiz *et al.* developed a method for estimating soybean crop area on a regional scale in the State of Rio Grande do Sul, Southern Brazil (Luiz *et al.* 2012). The proposed method (Geosafra) combines statistical sampling techniques with information obtained from satellite images.

For crop area estimation in Ukraine, Kussul *et al.* evaluated the use of various types of satellite images (MODIS, Landsat TM, AWiFS, LISS-III and RapidEye) combined with a field survey on a stratified sample of square segments (Kussul *et al.* 2012). The best results were obtained with neural networks classification (MLP: Multi-Layer Perceptron) and Landsat TM images.

Baig *et al.* propose applying area sampling frames and remote sensing to improve crop area estimation in a mountainous region of Pakistan bordering with Afghanistan (Baig, Suarez & Abbas 2011). Landsat 5 satellite images and sampling data were used in unsupervised and supervised classifications to obtain land use estimation. The results of this study were compared with those obtained by the Federally Administered Tribal Areas Secretariat of Pakistan. The authors concluded that the system presents an acceptable degree of reliability and accuracy.

Remote sensing techniques used in conjunction with a classical area frame sampling approach are also useful for assessing deforestation rates. Oduori *et al.*, using a semi-automatic tree detection algorithm, demonstrate the utility of the combined use of high resolution satellite imagery and spatial sampling for these purposes (Oduori *et al.* 2011).

Pradhan develops a GIS tool for crop area estimation based on frame sampling, remote sensing or a combination of both (Pradhan 2001). This tool aims to support crop forecasting systems at a regional level. The tool is useful in area frame design and in estimating the cultivated area of major crops.

Ambrosio and Iglesias proposed an Empirical Best Linear Unbiased Predictor Estimator (EBLUP) for estimating crop acreage in “small areas”, using ground survey and satellite images. The proposed estimator is compared with survey regression, synthetic regression, and direct expansion estimators (Ambrosio & Iglesias 2000).

Other methods for estimating land use are direct expansion and regression estimators. These are adopted by Deppe to establish forest area estimates within a test site area in the state of Rio Grande do Sul, Brazil (Deppe 1998).

2.1.2. Geographic Information Systems

The construction, management and maintenance of an MSF require efficient instruments for acquiring, processing and managing the information generated during the process. Most of the elements that are part of the frame, as well as the information to be acquired from samples, have a geographic component (location on the territory). Therefore, specific tools must be created for storing, handling and analysing such information. GISs have been developed since the mid-1980s. These systems consist of a series of physical elements (hardware), logical elements (software) and personnel, targeted at the acquisition, storage, processing and representation of geographic information for a given purpose.

The use of GISs in agriculture has important applications in contexts such as crop monitoring, management or precision farming practices and, of course, support to area frame surveys (Vibhute & Gawali 2013).

Most operational area frames have been developed into GISs (see Table 1 below). Projects are also introducing GIS applications aimed at the construction or management of information from sampling frames. The “*Direction de la Stratégie et des Statistiques (DSS)*” of the Ministry of Agriculture of Morocco has developed applications to manage works relating to area frame. One of these applications has the purpose of facilitating the updating of their area frames using satellite imagery (the *application sig pour l’automatisation de la methode “d’échantillonnage à base areolaire”*) (Arrach & Tahri 2009). Likewise, Pradhan developed GIS tools that assist area frame design, the selection of samples and the improvement of crop area estimation, combining remote sensing and sampling data (Pradhan 2001).

Sharifi and deMeijere (Sharifi & deMeijere 1997) developed an information system to support crop forecasting for major agricultural commodities in Iran. The system combines estimates from area frame sampling, remote sensing and growth simulation models.

Georeferenced data are the basis of a GIS. Three components of this data are of particular interest: the localized elements in space, the elements' attributes, and the relationships between the elements. Traditionally, georeferenced data have been assigned two components – a spatial component (location) and a thematic component (attributes). The spatial component can be of various types (points, lines, polygons), which coincide with the different type of area frames proposed, based on points, transects, regular polygons or polygons according to permanent boundaries. In designing GISs for the management of an MSF, it is essential to consider, in addition to the spatial elements, the attributes that each of those elements will have and the relationships that will appear between them. The functions of a GIS can fall within four categories:

1. Data acquisition/input
2. Information management (storage/maintenance)
3. Data analysis and processing
4. Presentation of results

The role of each function in the construction of an MSF will be seen in Sections A-D below.

A. Data acquisition/input

One of the main advantages of a GIS for information management is its ability to integrate information from different sources and having different formats (Carfagna 2013). Hence, vector and raster data can be integrated into a single system. As for the formats, GISs allow input of information from different remote sensing systems, airborne sensors (multispectral, hyperspectral, radar, and LIDAR), and scanned paper-based documents, as well as information acquired with topographic or GPS instruments.

The MSF is usually constructed on the basis of existing frames (list and area): therefore, the system must accommodate the use of all information generated previously. An important issue to bear in mind when treating existing geographic information is the reference system used by different sources of data. It is necessary to consider both the individual datum and the projection system. Since sample selection is usually performed in a manner that is proportional to the surface, it is recommended to use a cartographic projection that does not distort the land surface. The European Commission

recommends using the Lambert Azimuthal Equal Area (ETRS89-LAEA) projection, for statistical analysis and for map display purposes.

The system must possess tools that enable transformation from one spatial reference to another, such that all information can be adjusted to a common system.

The equipment for information capture may also differ. Typically, the information is introduced from digitalized cartography or georeferenced images, but GISs may also incorporate information from other types of peripherals such as cameras, personal digital assistants (PDAs), or tablet computers (Tablets) with mobile GIS technology and GPS for geolocation (Che *et al.* 2010; Chen & Xu 2008).

B. Information management (storage/maintenance)

A system is an entity that evolves and acquires new information continuously; thus, it is crucial that the information be up-to-date, and that a historical file of the information used previously be established. As the system's data and procedures increase, it becomes necessary to set up a system for information storage management.

C. Data analysis and processing

When building an MSF, the analysis and processing of information functions introduced into the system are especially important. The entire work scheme proposed by Vogel and Carletto (2012), displayed in Figure 1 above, can be implemented using GIS tools for information analysis and processing. Similarly, all the remote sensing methodologies proposed for setting up a Master Area Frame can also be applied using GIS tools. GIS tools that could be employed to construct a sampling frame include:

- satellite image classification using various classification methods
- spatial variability calculation (semivariograms and correlograms)
- spatial analysis
- projections and transformations.

In constructing MSFs, data linkage is one of the practical applications of GIS with the greatest potential for use. Its utility in integrating information from different sources has long been known (Longley *et al.* 1999). Mansour *et al.* have demonstrated the usefulness of spatially linking georeferenced data with GPS in population surveys, in which geolocation (addresses) is absent. They emphasize the potential for enhancing census data through spatial links with survey sources, and analyse the problems of spatially linking a georeferenced data set (Mansour, Martin & Wright 2012). The geographical linking of data from different sources can be a particularly useful tool in

constructing MSFs, although there are significant methodological issues to be addressed in this regard.

The integration of information from different sources has important advantages, including added value to data collection, costs reduction and greater consistency and accuracy of statistical outputs. Falorsi *et al.* have prepared a Technical Report on the Integrated Survey Framework, which discusses techniques for integrating data from different sources (FAO 2014).

D. Presentation of results

In the case of sampling frames, the functions for the presentation of results are crucial. Accordingly, once the frame is defined and the sample is drawn, the relevant graphical material for the fieldwork must be prepared. This material may be required in physical format (paper) as well as digital format, if field operations are to be performed with portable electronic equipment (PDAs or Tablets).

Portable hand-held devices may be particularly useful in collecting data. Combined with GPS, bar codes or transducers can facilitate data geolocation and reduce human error. If the information provided to the personnel in charge of the field data acquisition is correct, and the equipment available enables the target objects to be easily located, then timely data gathering is guaranteed. The data captured can be easily downloaded and even immediately sent through new mobile data technologies. The exchange of information can be bidirectional, with the field staff receiving the material and returning it, compiled, electronically. In addition, the entire process requires the information to be transcribed only once, which avoids possible errors due to multiple handling of the information.

The use of PDAs to capture field information has been tested in sampling frame construction projects in Ethiopia, although that project's main objective was the evaluation of GPS use for area measurement (Abdelwahab & Abdi 2008). Keita and Carfagna (2010) evaluate the use of portable hand-held computers as tools in agricultural statistics, concluding that this type of device enables faster data collection and improved data quality due to the fewer data input stages required. However, it is necessary to train the personnel who will use the equipment; this implies an additional cost for data capture.

2.1.3. Global Navigation Satellite Systems

As mentioned above, the construction of an MSF requires determining the location of its elements over the territory. The term “georeferencing” refers to the establishment of an element's location over the land surface, employing a specific cartographic projection and coordinate system. Georeferencing requires the use of tools that permit coordinates to be assigned to those elements. Among these tools, GPS has recently become a popular option.

In MSFs, GNSSs are mainly applied in:

- locating/navigating to points on the ground
- area measurement
- geocoding elements (i.e. households)

The location of points on the terrain during field activities for area sampling is usually performed by means of aerial (orthorectified) photography, topographic maps, compasses and GPS (European Commission 2003). Until recently, the use of hand-held GPS devices to locate points was not recommended, due to their low accuracy and elevated cost. However, today its use in locating sampling elements appears to be advisable, due to the technological advances that have enabled the improved accuracy and lower prices of GPS equipment.

As for area measurement with GPS equipment, Keita (Keita & Carfagna 2009; Keita & Carfagna 2010) evaluates the use of GPS instruments under different conditions (of a meteorological nature, or a canopy situation). GPS systems have enabled data collection that is more accurate and consistent than the collection possible pursuant to location or area estimation, using paper maps or a compass and distance measurement.

Palmegiani (2009) analysed the statistical relevance of measuring the surfaces of cultivation parcels using GPS compared to the traditional method using a compass and a meter. The author states, among other conclusions, that the measurement of cultivation parcels using GPS may have significant advantages in terms of reducing the costs of agricultural surveys.

The European Commission's Joint Research Centre (JRC) has defined procedures for the methodological validation of surface measurement using surveying instruments or remote sensing (Kay & Sima 2009).

Bogaert *et al.* (Bogaert, Delincé & Kay 2005) propose a theoretical framework for the area measurement of polygonal surfaces, which can be used to address errors in the area measurement of agricultural plots using GPS/GNSS devices. The measurement error of these devices is linked to the operator speed and acquisition rate. The authors propose acquisition rates and operator speeds for parcels up to 4 ha.

Aguilera *et al.* evaluate and propose the use of equipment based on GPS+PDA technology designed for agricultural or forestry surfaces (Aguilera, Jiménez & Meroño 2005). The equipment proposed can be used in multiple situations where the *in situ* collection of information is required. The accuracy of surface measurements depends on the surface of the parcels measured, with the relative errors being higher as the area decreases.

Geocoding is the process of assigning coordinates to elements that have a specific codification for their localization, e.g. postal addresses or administrative division codes (counties, provinces). In constructing sampling frames that include householders, the geocodification of the latter, which are normally identified by a code or a postal address, is a very important factor. NASS has proposed geocoding the centroids of the 9-digit zip codes associated with postal address households (NASS 1998). GPS devices are important tools for geocoding the elements of a sampling frame.

Until recently, remote sensing and GISs have developed along parallel but separate paths; however, the synergy between the systems is growing on a daily basis. This is why it is now possible to integrate remote sensing and GIS, and even GPS. This integration involves the concerted application of these technologies. Most GIS software now have tools for image processing, and the software for remote sensing analysis usually include GIS extensions (Merchant & Narumalani 2009).

2.2. Use of geospatial technologies for sampling frame construction – country examples

The construction of area frames for agricultural use is not recent. In the twentieth century, the United States' Department of Agriculture (USDA) and NASS computed statistics on the basis of this very methodology. The USDA sampling frames for agriculture (Fecso, Tortora & Vogel 1986; Holland 2012; Vogel 1995) consist of two elements: a frame list in which the farmer, the agricultural agents, and parcels are the sampling unit; and another area frame in which the territory is stratified and divided into blocks, which are in turn subdivided in segments, and delimited by permanent boundaries. These two frames are integrated into a multiple frame to exploit the efficiency of the list frame and the completeness of the area frame. The area frame was constructed using satellite imagery, digital maps, GIS software, and aerial photography.

This USDA area frame has served as a methodological basis for the construction of several other frames around the world. Table 1 below presents an overview of the area frames built in other countries.

In the American continent, the construction of area frames for agricultural purposes is clearly based upon the USDA system. Indeed, construction follows a territorial stratification according to land usage, employing either land use maps (Guatemala) or satellite imagery (Chile, Colombia, and Peru), and defined segments over permanent boundaries. The most recent area frames to be created (Chile) or updated (Guatemala) focus upon segments with geometric boundaries (squares). A sampling design based on area frames is stratified and probabilistic.

In Chile, an MSF was set up in 2012. Stratification was performed using land use data, aggregated at the EA level, obtained from the 2007 agricultural census. Multivariate statistical methods were used to classify Enumeration Areas (EAs) into strata. Sampling units were constructed, using square grids having sides measuring 500 metres each. Each sampling unit (segment) was assigned to the stratum in which the largest part of its area lied, and the strata limits were adjusted to those of the square segments.

In Guatemala, a new agricultural MSF based on a land use map was constructed in 2013. The stratification used land cover and land use maps created in 2005. The use of remote sensing imagery was discarded, because Guatemalan authorities were updating the maps of land use. Agricultural areas were stratified into four strata, according to land use intensity and field size. Segments with geometrical boundaries were used in all strata. GPS technology was used to locate the segments.

In Nicaragua, the current survey sample for agricultural statistics is based on a sample of points, or on an area frame with identifiable physical boundaries, within a strip of land parallel to the Pacific coast. The agricultural authorities have recently decided to build an area frame with segments of geometric boundaries, using the recent agricultural census, the older topographic map, and the 2002-2003 area frame with identifiable physical boundaries. Land use data aggregated at the EA level from the latest census is used to obtain 4 strata according to the percentage of cultivated land. Segments with geometrical boundaries are used in all the strata. GPS was used to locate the segments. Orthophotomaps are not available and it was decided to use Google Earth images instead [4].

In Uruguay, the agricultural census was used to set up a list frame of holdings. The cartographic material from the population and housing census was used to develop the agricultural census.

In Ecuador, a new MSF for agriculture was built in 2014, based on a land use map and with segments of geometric boundaries. Agricultural areas are stratified into four strata, according to land use intensity and field size. The stratification was performed using land cover and land use maps dated 2012-14. The use of remote sensing imagery for small area estimation is being considered.

Area Sampling Frames in Oceania

In Australia, a list frame is used for agricultural commodity statistics. Approximately every five years, the Australian Bureau of Statistics reviews the list frame's agricultural census base. (Australian Bureau of Statistics 2013)

In Fiji, the agricultural sampling frame was set up using the 2007 population and housing census. The stratification was performed using the intensity of cultivated land in the EAs as the guiding criterion. The sampling unit was defined by segments of physical boundaries having a size of 100 hectares (1 km² grid).

Area Sampling Frames in Europe

The Statistical Office of the European Communities (EUROSTAT) provides high quality statistics. Topics as diverse as farm structure, utilization of land, labour input, production and prices may be obtained from its agricultural statistics. Area frames, list frames and administrative records are used to compute these statistics (EUROSTAT 2013).

The Land cover/use (LUCAS) system was selected to provide harmonized statistics on land use and land cover across the European Union. This system is based on observation of points on the territory (EUROSTAT 2013). A two-stage sample design was adopted. The primary sampling units (PSUs) consist of cells of a grid that have a regular size of 18 km x 18 km; the secondary sampling units (SSUs) are rectangles (each 1,500 m x 600 m) located in each PSU. Each rectangle contains 10 sampling points. The sample contains approximately 10,000 PSUs, covering the EU's entire territory. The LUCAS observation is carried out at the SSUs' exact locations (Commission 2003).

Four countries of the European Union have systems different from the LUCAS system and that are based on specific area frames. Spain uses ESYRCE (Spain 2013), based on a systematic sample of cells of 700 m x 700 m. Bietapic stratified area frames (based on permanent boundaries) have been built for Andalusia's under cover crop-intensive zones.

France relies upon the TERUTI system. This is a two-level system, with a first level of square segments. 36 points, each 300 m apart, are observed within each square. In the case of basic observations, the observation of the point in the field covers a circumference having a diameter of 3 m; in extended observations, the circumference has a diameter of 40 m. This system is also adopted in Bulgaria, where it is known as BANCIK. In Italy, the POPULUS system consists of a systematic sample of points, which constitute a grid of 500 m x 500 m.

Area Sampling Frames in Asia

Projects for the implementation of area frames have been developed in Asia, in countries including the Philippines, Thailand, and Indonesia. In the 1980s, the Philippines developed a frame based on satellite imagery, orthophotography, and digital cartography for the Pangasinan area. Since 2006, it has been developing a project in Isabela on the basis of the methodology proposed by the EU's LUCAS system. In Indonesia, the area frame consists of blocks (PSUs) composed of squares measuring 10 km x 10 km. These blocks are, in turn, divided into 40 segments (SSUs) of 500 m x 500 m each. Four segments were selected within each block, employing a systematic aligned sampling performed in accordance with a distance threshold method.

Area Sampling Frames in Africa

The projects developed in Africa are of particular significance, due to the innovations that they have introduced to the building and updating of sampling frames. In Nigeria's Kaduna State, the frame developed in collaboration with the NASS consists of a territorial stratification in which the blocks are based on permanent boundaries. Points within the blocks are randomly selected. The fieldwork consists in locating the points with the aid of GPS equipment, and identifying the operators of the land under those points to collect information from the operators themselves.

Another possible method for creating sampling frames is to cross points of latitude and longitude (i.e. apply the Dot Sampling Method) over Google Earth images, as is done in Tanzania. The system features a regular point grid located directly on the website, and the observations are performed on the images on the screen. The estimations are made from point recounts that have a specific use.

In Morocco, a project to update area frames built in the 1980s has recently commenced. This frame update is based upon a territorial stratification that applies photo-interpretation to orthorectified XS images Spot 5 and 10m. An application for automatic stratus-building works has been developed (*application SIG pour l'automatisation de la methode "d'échantillonnage a base areolaire"*); this GIS application generates rectangular PSUs, which are split into in rectangular segments (SSUs), selected by means of SRS. These segments are also adjusted to natural borders.

Rwanda is another country that has recently implemented a multiple frame, based on an area frame supplemented by a list frame for large farmers (National Institute of Statistics of Rwanda 2012).

Multiple Sample Frames for Rural Statistics in Ethiopia

Ethiopia's Central Statistics Agency (CSA) is currently carrying out an MSF building project, in which existing frames to perform agricultural surveys are integrated with the frame used for Rural Households Surveys (Central Statistics Agency (CSA) of Ethiopia 2010). This project proposes integrating the EAs, defined upon a cartographic and georeferenced base during the execution of the population census, with land cover classifications from satellite imagery. The frame used by the National Integrated Household Survey is a list frame, formed by the EAs as PSUs and the households as SSUs. The PSUs are selected with probability-proportional-to-size (PPS) systematic sampling, and the SSUs are selected with systematic sampling.

The CSA has developed a National Strategy for the Development of Statistics (NSDS). One of its objectives is the establishment of an MSF for rural areas. This frame integrates existing list frames (the list of EAs from population and housing censuses, the list frame for collecting agricultural data, and the community list frame) with a new area frame, and is expected to result in more timely and accurate data.

The CSA, with the technical advice of the European Union and of FAO, has elaborated a land cover database that will “*provide a standardized, multipurpose product useful for environmental and agricultural purposes*”. SPOT imagery having a resolution of 5 m was used for territorial stratification, and MAD-CAT software was used for image processing.

A sampling frame was constructed on the basis of the EAs and the land cover map. The territorial stratification was based on the intensity of land use. The EAs (portions of territory in rural areas occupied by 150-200 households) were considered as PSUs; thus, they were digitized and georeferenced using cartography and GPS field data. The PSUs were selected with a probability proportional to size, and were then divided into segments of 40 ha each. Two segments were selected from each EA of the sample. The entire process was performed with IT support, a cartographic base, and digital databases.

In addition to frame construction, the project also includes activities such as (i) education and training of the personnel involved in any activity of frame construction (ii) field data production (iii) usage of Information Technology Systems (GIS and GPS) and (iv) treatment of the field data collected.

As part of the project’s final stage, the results obtained from the comparison of the estimations achieved with the proposed system with those derived with the frame list were validated.

An important aspect of MSFs is the implementation of GIS- and IT-supported activities to facilitate data collection, such as the use of GPS to identify segment boundaries, to delineate segments or to measure fields within segments.

As shown in Table 1 below, satellite images were used to construct area frames in most of the countries studied, except for Europe, where the use of orthophotography is still predominant. GISs have been introduced to manage information in all countries. GPS technology, instead, has been implemented only in newly established projects, or in those that are being updated.

Table 1 – Operational Area Frames

Country	Region	Sampling Frame	Type	Remote Sensing	GIS	GNSS	Ref.
American Continent							
USA		List	Farmers, agribusinesses				Holland 2012; Boryan and Yang 2012; NASS & USDA 2009.
		Area	Land use strata/block/segments' permanent boundaries	Satellite imagery	GIS software		
		Multiple frame					
Brazil		MSF Household Survey System	Census EA Frame				Pinto Bolliger 2012
		Multiple frame	Agricultural census (list frame)				
			Area Frame – EA Frame				
			List frame x Area frame				
Chile		Multiple frame (Area frame + list frame)	Stratified area frame/stratification by EAs, square segments (500 m x 500 m)	Satellite images and orthophotography used for stratification (land use intensity) and for field material	Digitalized cartography from 2007 Agricultural Census		Ambrosio Flores 2012
Colombia		Area Frame	Stratified area frame. PSUs and SSUs defined with permanent boundaries	Satellite images and orthophotography used for stratification (land use intensity) and for field material			Pérez Gómez et al. 1995; Colombia 2009; Colombia 2011.
Ecuador		Multiple frame	Area frame. PSUs ($\approx 10 \text{ km}^2$) and SSUs ($\approx 2 \text{ km}^2$) defined with permanent boundaries				Ecuador 2012; Ecuador 2009.

Table 1 – Operational Area Frames

Country	Region	Sampling Frame	Type	Remote Sensing	GIS	GNSS	Ref.
		Multiple frame	Area frame having segments of geometric boundaries of variable sizes between strata: 9, 36, 144 and 576 ha	Satellite images and orthophotomaps used	Digitalized land cover and land use map (2012-2014)		Ambrosio Flores 2014
Guatemala		Multiple frame	Stratified area frame, segments - dimension function of the strata (50, 25 and 6.5 ha)	Orthophotographic images for field material	GIS software used	Collection of tracks with GPS	Ambrosio Flores 2013
Honduras		Multiple frame	Stratified sampling, with replicas of segments within each stratum				Honduras 2010
Nicaragua		Point frame					FAO 1998
	Strip of land parallel to the Pacific coast	Area frame	Area frame with identifiable physical boundaries was built in 2002-2003	Satellite images and orthophotomaps used			Ambrosio Flores 2013
		Multiple frame (new, 2013)	Area frame with segments of 4, 6, 8 and 25 ha geometric boundaries.	Satellite images and orthophotomaps used	Recent agricultural census used for stratification		Ambrosio Flores 2013
Peru		Multiple frame	Land use strata/segments, permanent boundaries	Satellite images used for stratification and for delimiting PSUs	Cartographic material made from satellite images, orthophotos and vector files (GIS)		Peru 2010; Peru 2011a; Peru 2011b.
Europe							
European Union		Area Frame – List frame – administrative records					EUROSTAT 2013

Table 1 – Operational Area Frames

Country	Region	Sampling Frame	Type	Remote Sensing	GIS	GNSS	Ref.
European Union		Area Frame – LUCAS	Systematic area sampling in two stages: PSUs that are cells in a regular grid with size 18 km x18 km, and SSUs that are 10 regularly distributed points in a rectangle of 1,500 m x 600 m	Most recent ortho-rectified aerial photographs are used (where available)		GPS used for point localization	Gallego 2012; Bettio et al. 2002; Delincé 2001; Gallego 2004.
Bulgaria		Area Frame – Bancik	Systematic area sampling in two stages: PSUs that are cells in a regular grid with size 6 km x 6 km, and SSUs that are 36 points, arranged in a 6 x 6 point grid, each 300 m apart				Bettio et al. 2002; Arcaraz & Iotti 1998.
France		Area – TERUTI LUCAS	Systematic area sampling in two stages: PSUs that are cells in a regular grid with size 6 km x 6 km, and SSUs that are 36 points, arranged in a 6 x 6 point grid, each 300 m apart				Bettio et al. 2002 ; TERUTI 2010.
Italy		POPOLUS (Permanently Observed POints for Land Use Statistics)	Systematic sample of points on a regular of 500 x 500 m	Interpretation of orthophotography	Software photo-interpretation		Consorzio Italiano per il Telerilevamento in Agricoltura 2003; Italy 2007.
Norway		Area - AR18X18	Systematic sampling. Sampling unit of 1 x 1 km.	Aerial photographs			Stranda 2013

Table 1 – Operational Area Frames

Country	Region	Sampling Frame	Type	Remote Sensing	GIS	GNSS	Ref.
Spain	National (ESYRCE)	Area Frame	Spatial systematic sampling square segments (700x700 m). 3 segments selected by block (10 x 10 km). National Topographic Map at 1:50,000 scale	Material using orthophotography	Access planning segments is performed using mapping tools based on the Web, or GIS systems.	Collection of tracks with GPS	Spain 2012
	Andalucía	Area Frame	Stratified area frame/PSUs and SSUs (segments) permanent boundaries PSUs and SSUs (segments)	Photo-interpretation of orthophotography.	Frame building with GIS. Field material and data storage in GIS.		Ambrosio Flores 2006
Asia							
Indonesia	West Java Province	Area Frame	Spatial Systematic Aligned Sampling with a distance threshold. Square segments (500 m x 500 m). 4 segments selected by block (10 km x 10 km).		GIS Arc-View software was employed to extract sample segments		Mubekti & Hendrarto 2010
Iran	Province of Hamadan	Area Frame	Stratified area frame. Segments of 500 m x 500 m and 700 m x 700 m. (sampling rate 0.4 %)	Landsat imagery aerial photography used as base material		Hand-held GPS used in field work	Nematzadeh 2001
Philippines	Pangasinan (1980)	Area Frame	Random sample of 72 seg. ≈25 ha.	Landsat imagery aerial photography and topographic maps			Garcia & Esquivias 2012

Table 1 – Operational Area Frames

Country	Region	Sampling Frame	Type	Remote Sensing	GIS	GNSS	Ref.
	Isabela (2006)	Area Frame	Similar LUCAS	Landsat imagery, Google Earth imagery, NAMRIA topographic maps and NSO provincial/ municipality/barangay shape files.	GIS software and shape files	PSUs and SSUs were located using GPS and magnetic compass	
Thailand		Area Frame	Stratified area frame. Two-Stage Sampling. PSUs and define with permanent boundaries. SSU	Satellite images used for stratification(land use intensity) and for field materials	GIS software used	GPS used to prepare the information and locate the segments.	Thailand 2013
Oceania							
Australia		List Frame					Australian Bureau of Statistics 2013
Fiji		Area frame	Area frame with identifiable physical boundaries.		Population and housing census of 2007		
Africa							
Ethiopia		List	EA Frame from population and housing census				Ethiopia 2012; Ethiopia 2011; Tariku Abaye 2010; Gutu 2009; Ethiopia 2008.
		Community	EA Frame				
		Area Frame	EA Frame (PSU) and segments of size 40 ha (SSU)	Satellite imagery used for stratification	GIS software used	Maps and GPS are used to prepare the information and locate the segments.	
Morocco		List					Morocco 2011

Table 1 – Operational Area Frames

Country	Region	Sampling Frame	Type	Remote Sensing	GIS	GNSS	Ref.
		Area Frame	Rectangular PSUs, divided in segments (SSUs), selected with SRS. Segments adjusted to natural borders	Photo-interpretation on the orthorectified XS images Spot 5, 10 m	Frame building with GIS Generation of rectangular zones (PSUs)		Morocco 2011; Bouzafour 2000.
Nigeria	Kaduna State	Point Frame	Land use strata / block /random points	Satellite imagery used for stratification an block construction	GIS used for construction	GPS used for point localization	(Holland 2012)
Rwanda		Multiple frame	Area frame supplemented with list frame for large farmers				Rwanda 2008; Rwanda 2012.
Tanzania		Area Frame	Cross points of latitude and longitude	Google Earth	Web site		Jinguji 2012

Sampling Frames

A sampling frame can be defined as “the *set of source materials from which the sample is selected*” (United Nations 2005). Hence, the frame must be useful for the purposes of delimiting, identifying, and facilitating access to the elements of the population to be sampled. The frame can also include useful auxiliary information on the design of the sample selection procedure and the process of estimation (Ambrosio Flores *et al.* 2006; Groves 1989). Examples of frequently used sampling frames are list frames, area frames, and multiple frames.

An area frame is a partition or segmentation into sampling units of the territory in which a population is located (Ambrosio Flores *et al.* 2006), while a list frame consists of a list of the target population units (United Nations 2005).

As a general rule, there is no such thing as a perfect sampling frame: each of the types mentioned above has specific advantages and drawbacks. The construction of an MSF must be supported by consensual solutions on the frame in question, to enable the positive characteristics of each type of frame to be fully exploited and to minimize any drawbacks they might have.

The desired properties of a sampling frame are:

- Completeness – every individual constituting the population must be included
- Accuracy – exactness/correctness, i.e. devoid of errors; every constituent element is present only once
- Current – the elements must be up-to-date

In the interest of sample design, in addition to these properties, the frame should also contain auxiliary information useful to the design of the sample selection procedure and/or the estimation process. In addition, its elements must be correctly identified and ordered, so the random sample selection can be performed efficiently.

The main problems that arise in sampling frames are:

- 1) undercoverage – elements of the population under study are not within the frame
- 2) overlapping – a portion of a sampling unit (area) is contained in another sampling unit
- 3) overcoverage – the frame includes sampling units that do not exist in the population, or duplicates sampling units

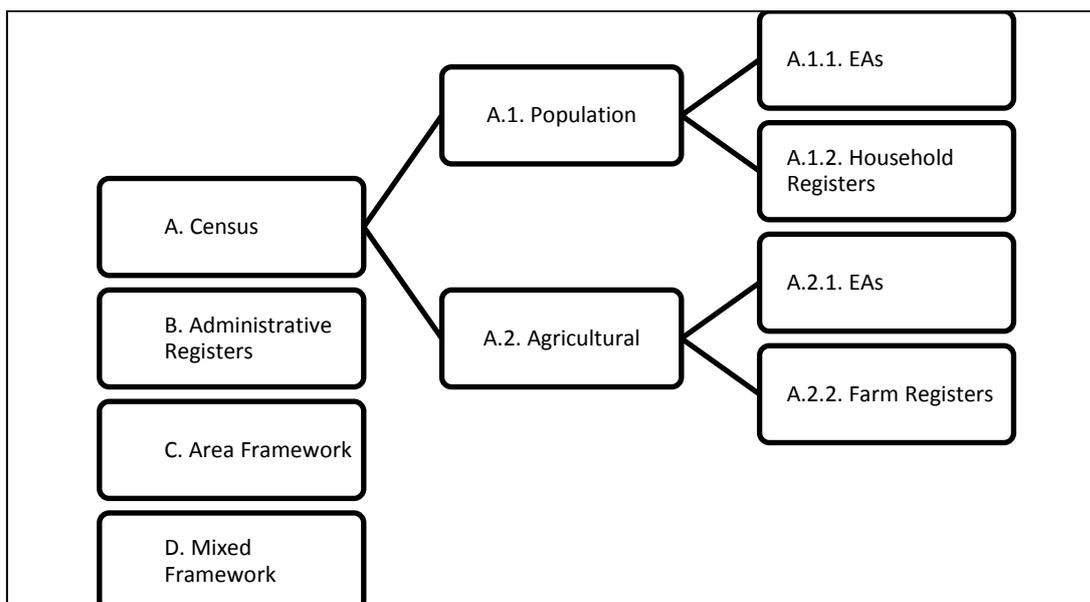
In multi-stage sampling, when a sample of Primary Units is divided into Secondary Units, from which a sample of farmers is selected, these problems can become generalized at the design level.

Traditionally, in agriculture, sampling frames have been built using information from different sources: on one hand, population and agricultural censuses, and on the other, agricultural administrative records. In recent years, specific Area Sampling Frames have been created to improve estimations within the sector.

3.1. Sampling frames used in agricultural statistics

As mentioned above, an MSF must be capable of acting as a basis for the performance of all surveys and censuses for a given sector (Carfagna 2013). The construction of a master sample for the rural sector requires the integration of crop and yield surveys (Agricultural Survey Samples) and livestock surveys with surveys on the rural environment's socioeconomic, demographic, and household health (Household Survey Samples) characteristics. Normally, a Master Frame is not started from scratch, because it is often built on the basis of previous statistical studies. The sampling frames that are usually used as a basis for MSFs are outlined in Figure 2 on the following page.

Figure 2 – Sampling frames used in agricultural statistics



A. Sampling frames based on information from censuses

A.1. Population censuses

A.1.1. Enumeration areas of population censuses

The conduction of population censuses is usually based on a hierarchical territorial division of countries (e.g. Country – State – Province – County), and on determining EAs, beginning from the lowest territorial level. These are the basic units for information collection, essentially upon the number of households or of inhabitants (World Bank 2010).

Frames based on this type of data would consist of a list of the EAs and the values added from the census. The use of this type of frame for agricultural statistical purposes usually occurs in two stages: first, PSUs are determined; then, these are often subdivided into lower units (individual households or groups), to achieve the SSUs.

A.1.2. Household records of population censuses

In countries that have the resources to improve the conduction of their population censuses, the elaboration process includes a record of the households within the EA. In this case, the frame may consist of the household list, including all the characteristics of each of these households.

A.2. Agricultural censuses

In some countries, the method employed to construct an agricultural census is similar to that used for a population census. Therefore, the information generated in census construction (the EAs and the information from each of these) can also constitute the Sampling Frame for gathering agricultural statistics.

A.2.1. Enumeration areas of agricultural censuses

Akin to population censuses, agricultural censuses are constructed in light of a country's territorial division, with the EA being the basic unit. Also similar to population censuses, a frame based on this type of data would comprise an EA list and the values added from the agricultural characteristics that could be gathered from the census.

A.2.2. Household records in agricultural censuses

Countries having greater economic means to conduct agricultural censuses can register the information relating to existing farms within each area. In this case, the frame can be built on the basis of a list of farms, together with the characteristics gathered directly from each household.

B. Agricultural Farm Records Based on Administrative Sources

In some countries, specific agricultural activities are reported in administrative records, such as livestock farming or agri-food industry records. In some cases, the records may be associated with tax levies. A list of registered individuals, along with characteristics of their activities, can be extracted from these records.

C. Area frames

An area frame is a segmentation or partition, provided in terms of sampling units, of a territory in which a population is settled. The segmentation is performed using maps, aerial photography, satellite imagery or any other graphical representation of the territory. For some time now, remote sensing techniques have been used to stratify the territory in broad categories, such as urban surface, agricultural zones (divided into permanent crops, growing areas, and grassland), forest and natural spaces, and wetlands. The population elements are identified solely on the basis of the segment to which they belong. The segments may consist of superficial units with permanent boundaries, superficial units with geometric boundaries (e.g. squares or rectangles), transects, grouped points within a regular geometry segment, or points on the territory.

D. Multiple frames

As suggested by the name, multiple frames are a combination of the other frames mentioned above. The purpose of these frames is to exploit the advantages presented by each of the constituting frames, and to reduce, as much as possible, any disadvantages relating to the use of a single type of frame.

The use of MSFs aims to improve coverage of the target population, reducing possible errors in this respect. Moreover, they enable the desired levels of precision to be achieved for a lower cost.

Some agricultural and livestock surveys use a multiple frame – a combination of list frames – for the large producers, and an area frame for the rest. Both frames used are independent, complementary and mutually exclusive.

To accomplish this, the entire area belonging to producers in the list frame must be removed from the area frame. It is essential to geolocate all plots of producers in the list frame, so that geospatial analysis techniques can be applied to establish the area frame to be used.

Table 2 below presents the behaviour of the aforementioned frames in terms of the desirable characteristics seen above.

Table 2 – Characteristics of sampling frames

Frame		Completeness	Accuracy	Currency	Auxiliary information	
Based on Census	Population Census	Only EAs	Yes	Yes	Yes	No
		With information captured within the EAs	Some households may be missing due to an absence of records or updates	No	May easily become obsolete	Unspecified valuable information on the agricultural sector
	Agricultural Census	Only EAs	Yes	Yes	Yes	No
		With information captured within the EAs	Some farms may be missing due to an absence of records or updates	No	May easily become obsolete	Valuable information for agricultural sampling
Administrative Records		Rarely complete, as individuals are not obliged to register. Potentially incomplete, depending on legislation	May contain significant omissions and duplications	May easily become obsolete	Valuable information, which, in the case of agricultural records, may be of interest for designing agricultural samplings.	
Area Frames		Yes	Yes	Yes	Little information. Remote Sensing can be an auxiliary data source.	
Multiple Frames		Combines the advantages of the composing frames, to minimize their drawbacks				

As shown above, the frames built from a territorial partition of superficial units (frames based on censuses, or area frames) present the property of completeness.

In the case of a census-based frame, the EA is defined as “the smallest geographic unit for which census information is aggregated, compiled and disseminated. An EA is defined by boundaries described on a sketch map or in a GIS database. These boundaries may or may not be visible on the ground. These units may also be referred to as census blocks or census tracks (United Nations 2009).

The EAs must: (i) cover the entire territory, with no gaps or overlaps (ii) be of a size that allows field operators to access and perform census work in the stipulated time (iii) be homogeneous in terms of land use and (iv) be built considering the need to supply information at superior aggregation levels, cover the needs for information at a small area level and respect the compulsoriness of maintaining personal confidentiality (Mokgokolo 2011).

Since area frames are based on EAs, they are divided on the basis of administrative divisions. In some cases, these divisions do not have permanent boundaries; the consequent frames may thus consist of units that are difficult to identify on the territory, which can hinder the capture of territory-related information such as surface measurement. Another factor to consider when establishing EA size is that, depending upon the number of households that the staff in charge of information collection can feasibly visit in the timeframe established for the census, some optimal surface discrepancies may arise in designs for agricultural purposes. In low-populated rural areas, EAs are large, from an agricultural point of view; in urban or suburban areas, the opposite is true.

When building area frames, the territory is divided into primary units and segments. Since these units and segments are elaborated for the purposes of sample extraction, its design is optimized for those aims. The dimensions and shape (for example, delimited by permanent or geometric limits) of the superficial units are selected on the basis of the purpose for which they are built. The superficial units that make up the Area Frames must comply with the following conditions: (i) they must cover the entire territory (ii) they must be of an adequate size for the execution of the statistical operations and (iii) they must be homogeneous in terms of their use.

The area delimitation of frames is performed on the basis of the cartographic materials available for the country (paper cartography, digitalized cartography, orthophotography, aerial photography, satellite imagery, etc.).

Generally, these frames are valid for long periods of time: their design remains useful throughout the years, unless territorial characteristics, such as land use or the superficial unit boundaries change.

Frames based on territorial partition are complete, accurate and up-to-date; but they often lack useful auxiliary information on the design process.

Frames based on lists (e.g. on administrative records or census information) usually have the disadvantage of being impossible to complete. This may be due to certain individuals not wishing or being obliged to register; or they may eventually become obsolete, due to a failure to update them.

The main problem with using this type of frame is that information is captured from households during census elaboration, which makes the frame obsolete when, for example, new households appear or existing ones disappear. Therefore, the results of the statistical operations performed with sampling frames tend to be increasingly flawed by the time the census is completed, unless a census updating policy is established.

Another disadvantage of these frames is that they may present data duplicities, which lead to inaccurate data.

The main advantage of these frames is that they contain auxiliary information that is useful to the sample design process. For example, the list frames created on the basis of population censuses often contain information on households; list frames generated in the construction of agricultural censuses contain information on farms. Since these characteristics are gathered during census elaboration, they are closely related to the purpose of agricultural statistics. The frame thus provides essential information upon the optimal sampling design for agricultural statistical purposes.

List Frames based on information gathered during the collection of data for population or agricultural censuses and administrative records are usually incomplete, inaccurate and soon become outdated; however, they often contain supplementary information that can be useful for the design process.

In this context, it is proposed to use multiple frames, to exploit the advantages offered by the two frame groups and to minimize their disadvantages. These frames are constituted by an area frame with a list frame, which thus complement each other. The area frame offers completeness, while the list frame contributes useful supplementary information that can be used for sample design.

3.2. Construction of MSFs

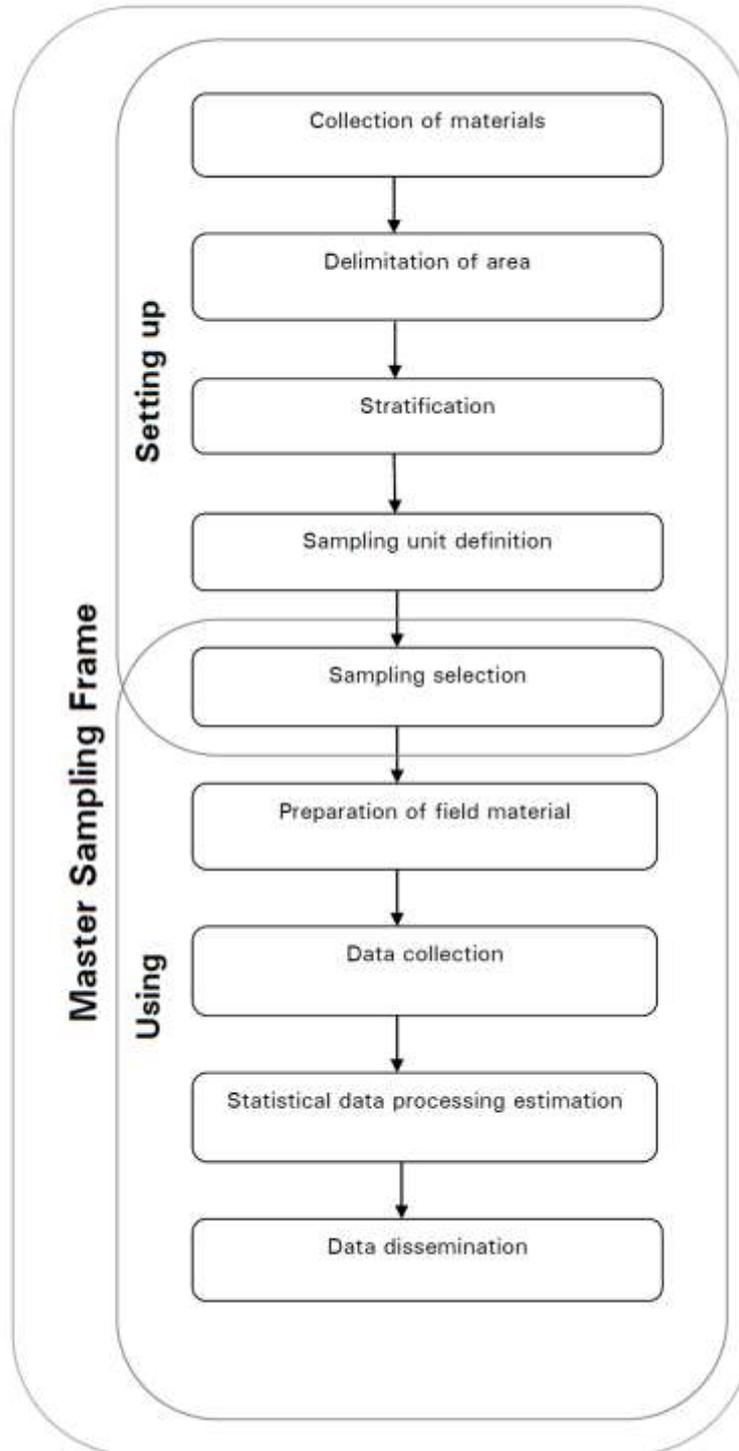
The construction of sampling frames is not a recent activity; indeed, such frames were already used in the United States in the mid-twentieth century. At first, these frames were constructed on the basis of paper cartography and aerial photography. The emergence of new geospatial technologies led to a technological revolution of the processes for statistics production based on sampling, such as the construction of sampling frames, sampling design, field data collection, and data analysis and dissemination.

The construction of an MSF for the agricultural sector requires a detailed assessment of the starting point, including an analysis of the following aspects (Vogel & Carletto 2012):

1. The current state of agricultural statistics (the set of core items being obtained, the methodologies used, the administrative records in existence, the statistical reports produced) and the current situation for agricultural and population censuses
2. The set of core items required by the country
3. The country profile for core items
4. The current conditions of the infrastructure necessary for the construction and operation of the frame
5. Determination of the appropriate sampling frame and sampling methods.

Once the situation has been analysed and an appropriate sampling frame has been decided, the MSF can be constructed. The stages of this process are presented in Figure 3 on the following page.

Figure 3 – Setting up the sampling frame



3.2.1. Collection of materials

The procedure for constructing a sampling frame begins with gathering the materials required and all the information available from previous frames.

The information required is essentially the following:

- a. Previously built frames (population censuses, agricultural censuses, administrative records, area or sampling frames)
- b. Available cartography, at least topographic maps, at different scales (usually 1:50,000 and 1:10,000). Other conventional maps are also recommended, e.g. of political divisions, roads, railroads, hydrography, etc.
- c. Aerial photography or recent orthophotography
- d. Satellite imagery
- e. Thematic maps (crops, land use, administrative boundaries)
- f. Digital Terrain Models (DTMs).

An important factor to take into account is the scale of the different materials considered, since these must be connected to the characteristics of the territorial elements under examination. In the case of agriculture, the size of a land parcel and of the farm are determining factors in choosing the scales to be used.

When gathering existing material, it is necessary to collect information from various sources (paper maps, digital maps, paper aerial photography, digital images, etc.), which may or may not be in digital form. Traditionally, frames were built using material in paper format. Currently, all information must also be available in digital format, to enable the process to be performed within IT management systems such as GISs. If the original information is not in digital form, it should be digitized.

Digitizing does not only concern the information's geographic components, but also the alphanumeric information of interest (e.g. in population censuses, data relating to households). Therefore, the processes of acquiring, and incorporating existing, information into the GIS requires planning and a significant allocation of resources.

The digitization of cartographic documents includes several processes. The first step is to convert paper documents to a digital media format: documents can be scanned for subsequent vectorization, or be digitized directly (e.g. using a graphics tablet). After obtaining the information of interest in vector format, it is necessary to verify the topology, to avoid duplication or gaps. The digital information thus generated must also be georeferenced.

Another aspect to consider is information updating. Cartographic production is not an immediate process, and requires significant resources. In developing countries, the cartography available may be obsolete. An alternative could be photogrammetric flights to obtain newer cartographic products, which could be either maps or orthophotography, although this option may not be feasible in these countries due to its high cost.

A low-cost alternative is the use of satellite imagery and remote sensing techniques as cartographic bases upon which to create the frame, because there are currently several satellite platforms that offer their products for low prices, or even for free. Satellite imagery is used for territorial stratification as well as for field material preparation, in those situations where the cartography available is not up-to-date. Given the spatial resolution needed for both purposes, it appears appropriate to use images having different resolutions (see Section 4.1, on recommendations for remote imagery).

The geolocation information of the elements that form the list frames (e.g. households or farms) must be detailed, or these elements must be geocoded. For this purpose, GPS/GNSS equipment are an essential tool, especially taking into account their ability to transfer the data collected directly to GIS databases.

The use of portable equipment (hand-held computers, PDAs, Tablets, etc.) to capture information during the development of censuses and surveys can facilitate the digitization of this information. It may be particularly interesting to integrate the GPS/GNSS equipment available with these devices. The possibility of directly transferring collected, georeferenced, information to GIS databases expedites the collection of this type of material, enabling the avoidance of processes such as format conversion, which can cause errors.

The use of GPS equipment for georeferencing frame elements can lead to errors if the elements to be geolocated are incorrectly identified. This is the case, for example, with georeferencing farm headquarters by means of GPS, if the coordinates provided actually concern another part of the farm.

In this respect, attention must be paid to the fact that in certain administrative databases or list frames, the location coordinates are associated with the farm's headquarters, and not with the land. This implies that in sample design, farm geolocations should be used with caution. Proper linking procedures must be established for integrating information from different sources, for multiple frames especially.

3.2.2. Delimitation of the area object of the frame construction

When building a frame for a particular territory, the area of interest should be delimited. If topographic maps are available, these will be used as the basis for the process; the natural or artificial terrain features will be used as limits, as they are permanent and easily identifiable. When no up-to-date cartography is available, satellite imagery could be used to delimit the zone.

Since statistical studies based upon a built frame require precise estimations at many levels, for example at the regional or municipal scale, the territorial marking limits must be established.

Assuming that the information is digitized, certain auxiliary information is essential to facilitate area delimitation. In particular, it is necessary to use cartography displaying distinct administrative demarcations and special interest areas, such as environmentally-protected zones. Satellite images of medium resolution and general mapping provide a good basis for area delimitation.

3.2.3. Stratification

Once the action area is delimited, homogenous broad-intensity zones regarding land use should be defined; this process is called stratification. It can be performed using thematic cartography or aerial photography, but due to the obsolescence of these materials and the current ease of access to satellite imagery, the use of remote sensing techniques is recommended.

In Section 4 below, recommendations are given concerning the sensors and satellite platforms that can be used in this stage, as well as the many stratification techniques available.

The number of layers to build is based on existing land uses, but generally, this number should not be excessively high. Usually, two extreme layers are set – urban strata and non-cultivated strata –in between which different levels of land use are defined on the basis of the agricultural activities performed therein.

The stratification process can be performed by means of image photointerpretation, or by applying automatic classification techniques to remotely sensed images.

Medium resolution satellite images are a first-order source of information for stratifying the territory, especially taking into account the possibility of accessing them for a low cost, or even for free.

Because satellite imagery is in digital format, and the treatment processes for remote sensing can be executed with GIS tools, stratification can be integrated into the system.

However, specific software may be necessary to perform remote sensing. GISs feature export/import and conversion tools that facilitate exchange between various software.

The determination of certain layers, such as urban or protected areas, is difficult to obtain by remote sensing. Therefore, such limits must be acquired from cartographic sources.

3.2.4. The definition of sampling units

The process for constructing sampling units depends upon the type of area frames considered (physical boundaries, square segments of points). Details of the steps to be followed for different types of frames can be found below.

The use of information from satellite imagery can be especially useful to optimize the size of the sampling unit, to propose the type of sampling to be performed or to establish the number of stages to be conducted.

A. Sampling frames defined using permanent boundaries

Usually, there are three stages to determining the sampling units:

- a. Delineation of PSUs and assignation, to each PSU, of a theoretical number of segments, taking into account the size of the target segment
- b. Selection of a sample of segments
- c. Division, of the PSUs having segments in the sample selected in stage (b) above, into SSUs.

Land surface is divided into polygons, denominated PSUs, defined by physical boundaries. A PSU is a portion of territory that contains a certain number of segments. A segment, or SSU, is a part into which a primary unit has been divided: it is, therefore, the final sampling unit. Only PSUs having segments in the sample selected in stage (b) are segmented.

The size of units (both PSUs and SSUs) is different for each stratum. The criterion used for size definition is the area in which data can be collected by a pollster in one day. This approach is consistent with that established to determine census EAs for population censuses. It is recommended that a segment contain no more than 20 plots, so that the segment size must be approximately twenty times the average plot surface. Segment size also depends upon the availability of permanent physical boundaries. In areas where agriculture is intensive, such limits are easy to find and segments may have a small size. It is recommended that primary units contain from 2 to 15 segments.

An alternative to the establishment of a new area frame is the use of the EAs of population or agricultural censuses as Primary Units. In this case, the size of the Primary Units may be inadequate for the purposes of agricultural statistics. As the size of EAs is established taking into account the number of households that the staff in charge of information can survey in the timeframe allocated to perform the census, this size may not conform to the objectives for frame construction relevant to agriculture. In this case, remote sensing is especially useful for stratification and PSU/EA assignment to a specific stratum, by simply overlapping stratification mapping and the EA map.

The superficial sampling units can be established using geospatial tools:

- a. Digitization of satellite images, orthophotography or digital mapping using the GIS' editing and digitizing tools
- b. Digitization of surface boundaries on the field, using GPS/GNSS equipment or hand-held computers having GPS/GNSS.

The first option appears more appropriate, since the use of the GPS/GNSS option requires apposite equipment and the necessary fieldwork can be very expensive.

After delimitation of the surface units, the topology must be constructed. This will enable an assessment of whether the area frame constructed is complete. Topological tools can detect unclosed polygons, lines digitized twice and other errors that could affect the completeness of the frame. Topology also enables a framework that is edited easily, preserving the desirable geometric properties.

GIS surface tools should also be considered. These are particularly useful for defining PSUs and for the subsequent selection of the sample in a PPS selection.

A special case is the construction of the sampling frame based on EAs built during the conduction of population or agricultural censuses. In this case, spatial analysis tools, such as the overlay layer, enables the stratification of sampling units by assigning the EA to a stratum; this, in turn, is achieved by overlapping the EA layer with remote sensing stratification.

GPS devices can be useful to delineate the surface units of a sampling frame (PSUs, SSUs, segments and plots). Given the high cost of collecting surface boundaries with fieldwork, the use of these techniques should be limited to special cases, such as the updating of information.

B. Sampling frames defined using geometric limits

Sampling units can also be defined with the following stages:

- a. Definition of the sampling units shape and size
- b. Coverage of territory with defined units.

In this case, each stratum is divided into square or rectangular segments of a certain size, depending upon its agricultural characteristics, in accordance with criteria similar to those used for area frames defined with permanent boundaries.

In some cases, primary units are delimited using geometrical limits and stratified, and then divided into secondary units or segments. For example, if maps using a Universal Transverse Mercator (UTM) grid are available, primary units can be built on the basis of a 10 km x 10 km grid and then, once stratified, segmented into sampling units of the target size.

GISs include tools for automatically designing geometric frames, square or rectangular, thus enabling the geometrical dimensions of these elements to be defined depending upon the characteristics of the stratum. This is an advantage of using maps with overlapping meshes, such as UTM grids, without being limited to predefined geometries, e.g. a 1 x 1 km square.

C. Sampling frames defined using points

Often, systematic sampling is used to select a sample of points; the stages outlined below can be used for constructing a point sampling frame:

- a. Mesh step selection
- b. Random selection of the starting point
- c. Systematic selection of points.

In these frames, a systematic grid of points is used. The application of a systematic procedure to determine the location of points ensures a good distribution of the sample upon the territory.

To set up a frame based on points, the mesh size must be defined. The step may be equal or different in the two coordinate axes, so that the mesh may comprise either squares or rectangles. The next step is to define the starting point over the terrain; then, the remaining points are selected by placing them at distances that are multiples of the chosen mesh step distances.

Several GIS tools are available for the input, management and representation of point elements. For example, from a file containing the coordinates of a point, it is possible to import points, and to represent them directly superimposed upon cartography or images. Therefore, the frame can be designed with simple tools such as Excel sheets and then imported into the GIS. Also, as most GISs have the ability to program applications, the selection of the locations of sampling points can be automated within the GIS software.

3.2.5. Sampling selection

From the sampling frame constructed, a random sample of segments is selected and, from this, a random sample of farmers. Usually, statistical work based on area frames is multistage. The segments are often used to collect surface information on land use and yields; subsequently, a sample of farmers or households included within the segment is selected, from which to collect the sample information on socioeconomic characteristics, or on characteristics that cannot be observed directly in the field.

A. Sampling selection in frames defined using permanent boundaries

The difference between the values of a variable at two points in space, i.e. the spatial variability, generally increases with the distance between these two points. To control this variability, two sampling methods can be applied to select the sample of segments: zone sampling, and systematic sampling.

For zone selection, each stratum is divided into areas or zones having similar size (a kind of substratification). The sample is selected within each zone with equal or unequal probabilities and with or without replacement. Tools to calculate the area of the various units delineated are necessary, to design sampling with PPS probability. As may be clear, this type of selection requires the creation of a new territory partition in the relevant zone.

To select a systematic sample, all segments are numbered, one segment is chosen at random and other segments are chosen at regular intervals until the sample is completed. The sample size being known, the selection range can be determined by dividing the total number of units by the size of the sample. The starting segment is then picked by choosing a random number within the range of selection. From the starting point, the remaining segments are obtained by adding the value of the selection range, until the sample is complete.

B. Sampling selection in frames defined using geometric limits or points

For frames based on geometric limits or points, as in those using squares, transect rectangles or points, generation may occur automatically; the entire construction process can be independent of the sample selection.

This type of frame requires dividing the area into grids or segments; their position in space is identified by the row and column to which the segment belongs, or by their coordinates within a reference system, such as UTM. The information contained in data sources commonly used in agriculture, such as remote sensing, also follows this structure.

Various methods for sampling selection can be used: simple random sampling, systematic sampling, zone sampling, with equal or unequal probabilities, with or without replacement, with probability proportional to size, etc. To optimize the selection, all information relating to the frame's sampling units is required. GIS database management tools enable efficient acquisition and management of the information that is necessary for the selection.

Moreover, it is possible to take into account GISs' ability to import and export frame elements, both geometric and thematic (alphanumeric); thus implying the possibility of using specific sample design software for the data managed with GISs, e.g. the free "R" software (R Project). The CRAN project contains a number of packages that can be particularly useful in sampling design and estimation. These include a *sampling package*, for drawing samples and calibrating the survey design weights, a *survey package*, to detail a complex survey design, and *package stratification*, that allows for the univariate stratification of survey populations. There are also packages for manipulating and reading geographical data (the *maptools package*) and for processing multispectral satellite imagery (the *landsat package*).

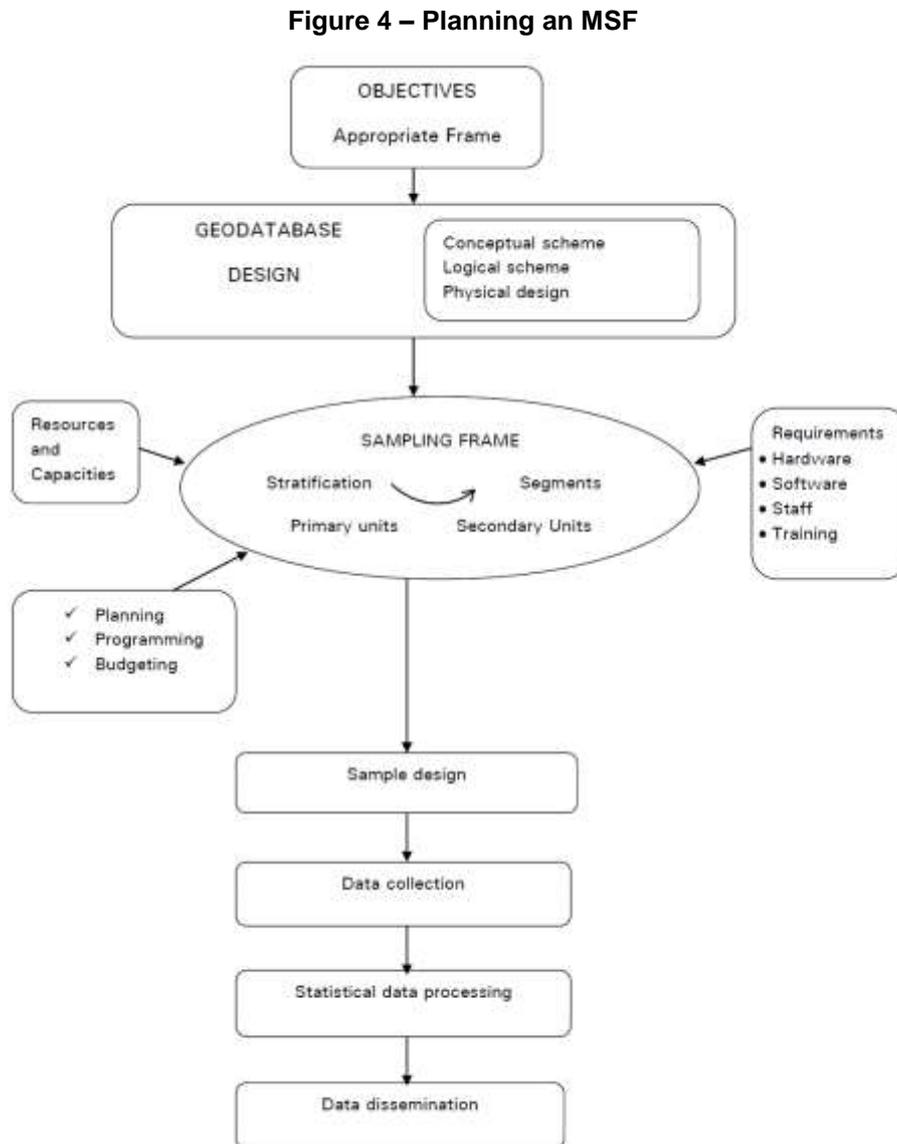
Another aspect to consider is the possibility of using auxiliary information for sample design optimization by considering the spatial variability. Remote sensing images can be an important source of auxiliary information, being capable of providing an overview of the relevant territory; they are usually highly correlated with variables relating to land use.

Table 3 – Remote Sensing and GIS in the construction of MSFs

		GIS	RS
		<p>A common reference system must be used.</p> <p>Not only graphical information should be considered. Qualitative and alphanumeric data should be taken into account.</p>	
1. Collection of materials		Information that is not already digitized should be digitized for the GIS	Satellite imagery as a base map should be considered
2. Delimitation of the area		Delimited in the GIS	Satellite imagery of medium resolution can be used
3. Stratification		Can be done with GIS tools	Stratification should be based on remote sensing techniques
4. Definition of sampling units			Remote sensing can be useful for design optimization
	Permanent boundaries frames	Primary units and secondary units can be delimited in GISs. The probability of selection can be calculated using surface GIS tools.	Satellite imagery of medium and high resolution can be used for surface delimitation
	Geometric limits frames	GIS enables the process of building segments to be automated	
	Point frames	GIS enables point frame construction to be automated	
5. Sampling selection		GIS assists sampling selection	Remote sensing can be useful as auxiliary data, to improve the selection of samples

3.3. Planning MSF construction using geospatial technology (Remote Sensing, GIS and GNSS)

The establishment of sampling frames necessitates proper planning. Figure 4 below shows the stages required in planning the construction and application of a sampling frame.



Among the geospatial technologies developed and applicable to sampling frame construction are digital cartography and orthophotography, remote sensing techniques, GISs, position determination systems (GPS/GNSS) and portable equipment for data collection.

Definition of objectives

As with every information system, the construction of statistical information systems based on MSFs requires the desired objectives to be clearly defined.

Those responsible for developing the economic growth policies of different countries, i.e. essentially government leaders, require tools enabling the retrieval of information on the various relevant economic aspects. In developing countries, agricultural statistical information is a fundamental part of such information. As indicated by Keita, agriculture has a first-order role in the production of food, clothing, fuel, and households, but also has significant impact on poverty reduction (Keita 2010). Agriculture also influences important environmental aspects, such as water consumption, pollution sources, soil degradation, and contribution to climate change.

It is essential to have an information system with statistical aims that enables all users to obtain the information required. The demands of an agricultural system are:

- Agricultural information
 - Production, harvested area, yields
 - Agricultural practices and calendars (planting and harvesting schedules)
 - Agricultural services
 - Consumption of products (seeds, fertilizers, pesticides, water, etc.)
- Livestock information
 - Number of live animals
 - Production
 - Livestock practices
 - Livestock services
 - Consumption of products (feed, animal health, etc.)
- Forestry information
 - Production, harvested area, yields
- Aquaculture and fishery information

- Environmental information
 - Land cover/land use
 - Soil degradation
 - Water management
 - Pollution (soil, water, air)
- Social information
 - Number of households
 - Household incomes
 - Agricultural employment
 - Family dependence on agriculture
 - Sociodemographic characteristics of agricultural farms and their owners
- Economic information
- Agricultural production
 - Prices charged (producer prices, consumer prices)
 - Prices paid
 - Agricultural wages
- Other information on rural development, territorial planning, food security, etc.

When setting up an MSF, the objectives pursued should be defined on the basis of the Global Strategy's purpose of providing a framework, for national and international statistical systems, that can enable production and application of the basic data and information necessary to guide decision making in the twenty-first century, particularly regarding its three pillars: (i) the establishment of a minimum set of core data (ii) the integration of agriculture into national statistical systems, and (iii) ensuring the sustainability of the agricultural statistics system (World Bank 2010).

When establishing objectives, it is necessary to be aware of the minimum data required by the relevant public bodies or private users. On the other hand, it must be recalled that such data should be integrated into the national statistical system; this entails the need to request information concerning national statistical operations, as well as that of

avoiding the need to harmonize data with the other national statistical systems. Finally, it must be considered that in statistical work, data and results must be kept for use by future generations, but the survey respondents' confidentiality must remain protected (EUROSTAT 2012).

When designing a system to be integrated into the frame, an important aspect is the definition of the area frame's typology (physical boundaries, square segments, transects, points). This is based upon the country's characteristics, such as the type of agriculture, the national statistical system, the landscape, the size of farms and fields, the types of physical boundaries, etc.

Geodatabase design

A **database** is a collection of data relating to a particular subject that is systematically stored and is usually in digital format. If the database stores geographical information, it may be called a **geodatabase**.

Database design is a complex process, which requires many decisions, essentially to define the database's data model. Traditionally, the design process features three stages:

- A. *Conceptual design*. During this stage, the information to be used in the database is determined, and the dependence between the different components is defined. This stage is divided in two steps. In the first, the real-world elements of interest for the database are identified and described, whether they present a geographic component or not. In the second step, the relations and dependences between the previously identified elements are established. This design yields a conceptual model that is independent from the software to be used in managing the database.
- B. *Logical design*. Based on the relations and dependences of the elements identified in the conceptual design, and considering process and environment requirements, the schemes established are transformed to a series of structures proper to the data model selected. The product is a logical model that allows developing the database within a database management system (DBMS). Several different model types exist: hierarchical, net, relational, entity-relation, etc.
- C. *Physical design*. The database configuration is specified in the physical storage medium (memory), on the basis of the logical design. The product of this stage is the physical model. The stage includes a detailed description of the data storage structures and the procedures used for its management, as well as the specifications of the hardware and software components that constitute the system.

Resources and Capacities

The use of geospatial technologies for the construction of a sparse sample requires a preliminary analysis of the resources and capabilities of individual organizations. The resources are the means of any kind – physical, technological, organizational or human – with which the organization achieves its objectives. The capabilities are the qualities, skills and competences available to the organization in achieving these objectives, and are usually linked to the organization's available human capital.

To set up the management and updating of an MSF, it is necessary to consider:

The resources available

- A. Tangible resources, i.e. those having a material support and that can be easily identified and quantified. These may be:
 - a. Financial resources, required to develop and achieve objectives, and
 - b. Physical resources, i.e. all the physical infrastructure relating to the construction, maintenance and management of the sampling frame. These include facilities, computers, GPS devices, PDAs, and communication technologies.
- B. Intangible resources, which are difficult to identify and quantify because they refer to information and knowledge. These include:
 - a. Technological resources, such as software, and
 - b. Organizational resources necessary for the development and successful implementation of the activities planned.
- C. Human resources.

Capabilities

- A. *Technical capabilities*. In the context of geospatial technologies, these are the technical skills possessed by the organization that are relevant to the development of objectives (technical knowledge, experience, skills for developing the infrastructure of information systems or learning skills relating to new technologies).

- B. *Management capabilities*. These are the organization's leadership skills in designing, developing and applying geographical information technologies relevant to the performance of the activities and operations of the organization responsible for developing the frame. These include the ability to identify, plan, coordinate and manage the resources needed, as well as to anticipate future needs.
- C. *Organizational capabilities*. These are the organization's skills that are relevant to the development of the organizational aspects of frame construction and maintenance, such as the creation of a culture that is conducive to understanding the frame, or ensuring communication, coordination and cooperation between the parties involved in developing the frame.

Requirements

It is necessary to establish which resources are required to set up the MSF, particularly those relating to geospatial technology. All resources (computational – hardware and software), materials (especially cartographic), staff, communication and project management and supervision must be defined.

As for geospatial technology, the different possible uses of GIS software and satellite and airborne imagery processing software (remote sensing software), both free and commercial, must be taken into consideration. The use of portable GPS devices must also be examined, and a variety of alternatives studied, from specific high-performance equipment – including that for the visualization and capture of GIS data, which entails high costs – to the use of GPS equipment integrated into smartphones, which has low costs.

Planning, programming and budgeting

After collecting the information on the resources and capabilities available to the organization, the construction of the sampling frame must be planned. This involves organizing the activities that are necessary to achieve the objectives defined at a previous stage, to identify the resources required for each activity and to organize the various steps; these are the programmed actions and tasks. Finally, the budget activities must be addressed, i.e. the monetary quantification of the human, material and financial resources needed to complete the established programs.

The use of geospatial information technologies could require major efforts and a huge amount of financial resources. This is why, for developing countries, the possibility of using centralized resources for multiple countries should be considered.

Using Remote Sensing to set up a Master Sampling Frame

Remote sensing plays a major part in building the MSF, as it can be applied in important processes such as the stratification of the territory or the delimitation of frame surface units by photointerpretation or feature extraction. It is a first-order source of auxiliary information that can be used throughout frame construction and implementation (to improve sampling designs and estimates).

The purpose of this Section is to provide recommendations on the use of remote sensing for setting up an MSF and on the classification that can be used to stratify the territory.

The use of remote sensing to set up an MSF is certainly a challenge, as the characteristics of the sampling system, the spatiotemporal scope of application, the accuracy, the costs/benefits relationship, and the operability of the proposed solution all must be taken into account.

Remote sensing is an interesting tool that can improve MSFs, contributing graphic-raster information and georeferenced elements. Therefore, the main characteristics of satellites or sensors must be described, so that the most adequate system can be selected.

4.1. Recommendations on the use of remote-sensing data in setting up Multiple Sampling Frames

Considering the characteristics and observations concerning remote sensing systems displayed in the Annex below, some recommendations on the use of remote sensing to build MSFs are advanced:

1. Generally, the use of optical sensors is recommended, due to their multispectral characteristics. These facilitate the ascertainment of land use and land cover. The greater quantity of information contained within the imagery, and the amplitude of the digital processing techniques of optical sensors, make them more suitable for application in MSFs.

2. In particular, it is recommended to use Synthetic Aperture Radar (SAR) data, preferably fused with optical data, at latitudes where cloud coverage prevents gathering optical data for predominant vegetation cover studies over adequate periods of time.
3. It is assumed that most systems available currently present sufficient radiometric resolution (between 8 and 16 bits) and that higher values do not necessarily lead to a significant improvement in the expected results; thus, the use of sensors with an 8-bit quantification level is sufficient.
4. Since most broad categories used in this type of projects do not require an excessively detailed legend level, the use of hyperspectral sensors is discarded, because it complicates the thematic study of the classes of interest; the use of sensors with a low spectral resolution is preferable. Bands corresponding to red and near-infrared are considered essential, and the visible zone of the electromagnetic spectrum is recommended.
5. It is recommended to use systems consisting of satellite constellations of the same series, as these reduce any problems that may arise due to cloud coverage and crops' phenological cycles. Compared to individual programs, these satellite systems also improve data continuity and expedite image acquisition. Moreover, the experience gained with previous satellites of the same constellation facilitates the treatment and interpretation of the data gathered at a subsequent stage, as consolidated methodologies and known calibrations can be used.
6. Taking into account the fact that the cost of high spatial resolution images is one of the main limiting factors for studies having a global scope, the use of free imagery (Landsat8-OLI or future Sentinel2) should be preferred over that of other low-cost (Terra/ASTER) or commercially distributed imagery, not only for cost reasons but also for the ease with which they can be accessed globally.
7. The use of national space programs should be boosted, in terms of their scope of application, and also within third countries that can be observed in those programs, to facilitate access to spatial information at lower costs.
8. As for the ideal spatial and temporal resolution, there are three levels:
 - a. For first-level territorial stratification, it is recommended to use medium spatial resolution systems (100-500 m) and high temporal resolutions (1-3 days), which facilitate data acquisition in areas with persistent cloud coverage; an example is MODIS.

- b. On a second level, to estimate land use surfaces as well as to validate medium-resolution data results, it is recommended to use high spatial resolution optical sensors (20-30 m) and medium temporal resolutions (15-30 days), such as LANDSAT, SENTINEL2, TERRA or SPOT, or those from national space programs; in case of persistent cloud coverage, these could be complemented with SAR data from e.g. RADARSAT or TERRA-SAR.
 - c. On a third level, for field material preparation, the use of very high spatial resolution systems (1-5 m), which facilitate the location of field sampling zones, should be considered.
9. Regarding the treatment of information obtained from remote sensing, its homogenization, processing, storage, access, and distribution must be integrated into a Global Information Network (GIN). This task is facilitated if free standard products are used. The GIN will serve international agencies and organizations in their efforts relating to the monitoring of land use/cover and the terrestrial environment, and will greatly reduce the resources required to implement such monitoring programs.
10. International organizations such as FAO or JRC-EU must play a key role in defining the objectives of a study, providing staff training and allowing the use of IT applications through the GIS. They should also supervise and ensure the accuracy of results and the stability of actions, establishing appropriate mechanisms to achieve an adequate balance in the cost/benefit relationship.

Table 4 on the next page summarizes the characteristics of each work level and the recommendations for the appropriate systems for their execution.

Table 4 – Characteristics of satellite/sensor systems according to application level

Characteristics of the remote sensing system	Application level					
	<i>I. Stratification</i>	<i>II. Surface estimation. Land Cover/Land Use. Validation.</i>				<i>III. Field material. Field data sampling.</i>
Radiometric R.	≥ 8 bits	≥ 8 bits				≥ 8 bits
Spectral R.	R+NIR	VIS+NIR				VIS
Temporal R. (revisit period)	1-3 days	15-30 days				-
Spatial coverage	> 250,000km ²	2,500-40,000km ²				100-300km ²
Spatial R. (GSD)	100-500m	20-30m				1-5m
Cost (*)	Free	Free	Earth National Observation Program	Low (<0.1\$/km ²)	Medium (<1\$/km ²)	High (5 - 45\$/km ²)
SYSTEM	MODIS	Landsat 8-OLI, SENTINEL2	Depending on country	ASTER, ALOS	SPOT 6-7, IRS	SPOT 6-7, IKONOS, GeoEye, QuickBird, WorldView

Note: Mean prices are estimated for minimum orders of newly acquired basic products (e-GEOS. ASI/Telespazio, 2013).

Most developed countries have national or supranational systems to elaborate statistics and land use/cover maps integrating remote sensing data; however, in the context of global studies – and especially in the case of developing countries – the allocation of training and technological resources to engage in this type of studies should be evaluated, in light of the economic resources available.

The integration of official agricultural statistical systems into National Statistical Systems (NSSs) constitutes a fundamental objective of the Action Plan of the Global Strategy to Improve Agricultural and Rural Statistics for Food Security, Sustainable Agriculture and Rural Development (Alexandridis, Gitas & Silleos 2008). The use of land use and land cover data obtained by means of remote sensing techniques is

currently a fundamental tool in building MSFs that contribute to the abovementioned integration, in studies of both national and global scopes.

The combination of remote sensing, GNSSs, and their integration by means of GISs is a clear example of the synergy that can be achieved between the different spatial technologies, to improve NSSs. The results obtained as a consequence of this union depend mainly upon the knowledge possessed of each technology; for their correct application, the advantages and limitations of each must be known.

4.2. Land cover/land use as stratification of the sample

When variables of agricultural and other social statistics are to be estimated, the use of stratified sampling is very common. In stratified sampling, the population is divided into non-overlapping subsets called strata, which together comprise the entire population; then, an independent sample is drawn from each stratum.

Several reasons may justify stratified sampling (Cochran 1977):

1. Stratification can be used to increase the precision of population estimates
2. Stratification may contribute to avoiding estimation bias, depending upon the estimator selected, when it is not possible to sample some strata, or each stratum contains very different numbers of samples

In addition,

1. Stratification facilitates the application of various data collection techniques
2. Stratification enables different costs in different strata to be taken into account
3. Stratification can be used to obtain estimates for the various levels considered, e.g. strata

Stratification can be useful in accommodating several sampling protocols or estimation procedures for different subpopulations. For example, if a substantial portion of sampling costs derive from travel between plot locations, and data from remote sensors can be used to determine that, for example, certain plots are located on non-forest land, then travel costs could be significantly reduced.

Several factors influence the estimation of agricultural, environmental and socio-economic variables: land cover, land use, soils, climate division and ecological province. Sampling data to estimate those variables often depends on the land cover. Therefore, the sampling would be conducted better if data samples are stratified, using the land cover or land use classes as strata.

Land cover classification is the ordering or arrangement of the bio-physical cover elements observed on the Earth's surface, into groups or sets on the basis of their relationships. Land use classification is the ordering or arrangement into groups of the activities and inputs that people perform on a certain land cover type, to produce, change or maintain it. Each group is called a "class" and has defined, clear, precise and quantitative boundaries based on objective criteria. Classification should be scale- and source-independent. It can be hierarchical or non-hierarchical, and can be performed in two ways: *a priori* and *a posteriori* (Di Gregorio & Jansen 2005). There are several systems of land cover/land use classifications: the CORINE land cover, the USGS National Land Cover Database, the FAO LCCS, etc.

Of these, we recommend the FAO LCCS, because it is independent of the use made of the classification. In FAO LCCS, each class is defined using a set of independent diagnostic attributes (classifiers). Limits between classes depend on the amount and identity of the classifiers. Detailed classes which introduce further classifiers can also be added (Di Gregorio & Jansen 2005).

FAO LCCS

FAO LCCS has two main phases: a Dichotomous Phase and a Modular-Hierarchical Phase. In the first phase, eight classes can be obtained:

- Cultivated and Managed Terrestrial Areas
- Natural and Semi-Natural Terrestrial Vegetation
- Cultivated Aquatic or Regularly Flooded Areas
- Natural and Semi-Natural Aquatic or Regularly Flooded Vegetation
- Artificial Surfaces and Associated Areas
- Bare Areas
- Artificial Water bodies, Snow and Ice
- Natural Water bodies, Snow and Ice

These eight classes were obtained using three classifiers:

1. Presence of Vegetation: yes or no
2. Edaphic Condition: terrestrial or aquatic
3. Artificiality of Cover: artificial or natural

In the Modular-Hierarchical Phase, each of the eight classes mentioned above can be subdivided into more detailed classes, using different classifiers. To design stratified sampling, the first phase (eight classes-eight strata) is generally sufficient.

Remote sensing is a very useful tool to obtain information on land cover and land use. It has been used as a main tool since the very first LCCSs (Anderson *et al.* 1976). It can be used to identify first-phase eight-classes and reclassify them into a new subdivision.

From the early 1970s, remote sensing satellite images have been used to obtain information on land cover and land use (Anderson *et al.* 1976):

National Land Cover Data 1992, 2001 and 2006 (Vogelmann *et al.* 1998; Vogelmann *et al.* 2001).

1. Data used

- Landsat TM images acquired in 1991, 1992 and 1993
- Aerial photographs
- Ancillary data sources:
 - Digital Elevation Models (DTED) and derivatives such as slope, aspect and shaded relief
 - Population density data
 - Wetlands inventory
 - Available water capacity and organic carbon in soils
 - Previous land use and land cover data

2. Defining a Classification System of 21 classes

3. Method:

- Generating mosaics of leaf-on leaf-off TM scenes
- Clustering each mosaic using unsupervised classification algorithms
 - 100 spectrally distinct classes
 - Combination of TM bands: TM3, TM4, TM5, TM7
- Interpreting and labelling clusters using aerial photographs

- Resolving confused clustering using ancillary data sources
- Incorporating information from on-screen digitizing

CORINE Program (Coordination of Information on the Environment) Land Cover

1. Data used

- Landsat TM and SPOT HRV images acquired in 1991, 1992 and 1993
- Aerial photographs
- Ancillary data sources:
 - Topographic maps at scales 1:100,000, 1:50,000, 1:25,000
 - Thematic maps: vegetation, land cover, pedology
 - Statistical information on land use and land cover

2. Defining a hierarchical Classification System of three levels:

- First level – 5 classes
- Second level – 15 classes
- Third level – 46 classes

3. Method:

- Generation of mosaics of TM and SPOT scenes
- Combination of TM MSS and HRV bands to create false-colour images
 - MSS 754, TM 453, TM 432 and HRV 321
- Delineation of land cover units, photo-interpreting false-colour images
- Second delineation of complex land cover units using aerial photography

Advantages, disadvantages, costs and benefits of using geospatial technology for setting up and using sampling frames

The establishment of a sampling frame based on the use of geospatial technologies (GISs, remote sensing, GPS/GNSSs) entails the need for resources and funding, and yields important benefits. This Section discusses costs, benefits, and pros and cons of using these technologies.

5.1. Advantages and Disadvantages

Remote Sensing

Remote Sensing is first of all a tool for setting up and using sampling frames. It can be applied in the following stages of construction and use of sampling frames:

- A. Stratification of the territory
- B. Delimitation of frame surface units by photo-interpretation of satellite images
- C. As auxiliary information for improving sampling designs and estimates
- D. Preparation of the material field

Advantages

1. Satellites currently used for Earth observation are able to capture images of any point of the Earth's surface; therefore, global coverage is available
2. Updates of satellite images of medium and high spatial resolution can be purchased at a relatively low cost, and in some cases at no cost at all
3. The images having medium spatial resolution can be useful for territory stratification
4. Images having high spatial resolution can present sufficient detail to be used in the delineation of surface units, and for field material preparation

5. Satellite images can be accessed online (e.g. on Google Earth), which is especially useful for localizing and identifying segments and plots in the field using portable computers
6. Remote sensing allows information on land use in inaccessible areas to be obtained
7. Satellite imagery can be used as a cartographic mapping source in areas without maps or with only outdated ones; also, existing maps can be updated using satellite imagery
8. Remote sensing techniques can be used in quality control procedures performed upon the data collected in the field

Disadvantages

1. Remote sensing work requires the personnel involved to be highly specialized. This can give rise to high costs. Specific training programs are required.
2. Satellite imaging optical sensors are hindered by the presence of clouds. This can be an obstacle to complete coverage of a large area such as a country.
3. Satellite imagery at high and very high resolutions is usually costly, which often prevents its use in the construction of sampling frames.
4. In some developing countries, if the potential of remote sensing is to be fully achieved, centralized resources for multiple countries may have to be established.

Global Information Systems

As highlighted in previous Sections, the use of GISs for setting up and using sampling frames is particularly important, as they can be employed in each stage of the process.

Advantages

1. GISs offer a wide range of tools for the construction of the various elements making up the frame (polygons, squares, rectangles, lines, dots), for decision making (design) and for the production of outputs (field and diffusion field).
2. GISs provide broad support for representing graphical information, in both physical and digital formats.

3. GISs enable the integration of cartographic and thematic data from different sources (paper maps, digital mapping, remote sensing, lists, databases, GPS coordinates, etc.).
4. GISs facilitate the display of spatial data in a user-friendly manner, enabling them to capture, edit and handle data intuitively. GIS products, which are usually maps, facilitate the transmission of complex information to users.
5. GISs enhance the productivity of storage and information management processes with both spatial and non-spatial data, thereby increasing the speed and productivity of workers.
6. The use of GISs increases efficiency and reduces costs.
7. Data storage systems in GISs are efficient, enabling the analysis of information that is usually separated (graphic elements on one hand and subject data on the other).
8. GISs are a very useful tool for the query, analysis and representation of information, for the purposes of decision making.
9. GISs are designed to optimize operations on geographic information, enabling the efficiency of their management and handling.
10. GISs enable queries, analysis operations, and data display through Internet services, thus facilitating the dissemination of statistical information.

Disadvantages

1. Software costs are high, although free software can be used.
2. The necessary digital data are expensive to purchase, and the process of acquiring non-digitized data is generally more expensive and time-consuming. This is the case with the digitization of the information in databases or in paper maps. In the absence of cartographic data, it is possible to request a photogrammetric flight for mapping products, but this entails a high cost. The variety of information sources may make it impossible to control certain errors, which can thus be unquantifiable.
3. The use of these systems requires adequately trained operators. Staff training plans must be designed and implemented.
4. The systems also require organizational change within the departments involved in the construction, management and maintenance of the sampling frames.

5. GISs are subject to continuous changes due to development and research; its components thus require continuous updating, also by means of staff training.
6. In certain developing countries, the exploitation of GISs' full potential may require the establishment of centralized resources for multiple countries.

Using Global Positioning Systems/Global Navigation Satellite Systems

GPS/GNSS devices can be useful in the construction and use of sampling frames.

- A. GPS/GNSS can be used to delimit the different surface units constituting the sampling frame (PSUs, SSUs, segments and plots). These techniques should not be used often, due to the high financial and time costs of field operations; it is recommended to use them only in specific situations, e.g. for change detection or frame update.
- B. Administrative boundaries can be delimited with GPS/GNSS in areas where they were last defined a long time before, or where only an obsolete digital version exists.
- C. The location of the frame's various elements can be acquired by means of GPS/GNSS, including elements of list frames such as homes, farms, businesses, etc. The georeferencing or geolocation of these elements is essential for the integration of list frames into MSFs based on GIS technology, and for linking list elements to surface elements within the frame.
- D. New elements such as roads or paths can be mapped with GPS/GNSS; maps can also be updated.
- E. GPS/GNSS enable navigation to and identification of various elements of interest within a frame, e.g. the location and recognition of segments during the data collection process. GPS equipment incorporating map or image displays are especially useful for identifying segments and plots; it can also be useful to navigate to or trace other items linked to the segments, such as household and farm headquarters concerning a plot.
- F. GPS equipment can be used to measure distances and surfaces, e.g. the surface of fragmented plots (change detection).

Advantages

1. GPS/GNSS can be used on any point of the Earth's surface; it thus has global coverage.
2. The precision of GPS/GNSS is adequate for the requirements of frame construction. If greater precision is necessary to obtain the coordinates of points or to measure distances and surfaces, Differential GPS (DGPS) systems can be used.
3. Currently, manual equipment is cheap; the use of DGPS systems can be more expensive.
4. GPS/GNSS equipment is user-friendly, requiring only basic training. If DGPS is needed, then a higher training level is required.
5. GPS/GNSS can be integrated into mobile GIS equipment, enabling the direct collection of georeferenced data. This allows for the direct incorporation of the data into the GIS without manipulation, which reduces the risk of transmission errors.
6. Maps and images can be uploaded onto GPS/GNSS equipment, which facilitates the location and identification of frame components (segments, households, plots, etc.).
7. In the retrieval of coordinates, human errors are minimized; this cuts costs, as less time and staff are required.
8. These technologies also enable measurements to be gathered under adverse meteorological conditions.

Disadvantages

1. The use of GPS/GNSS systems can be hindered by physical obstacles. In urban areas with tall buildings and narrow streets, or wooded areas or forests, it may not be possible to use the satellite signal.
2. GPS/GNSS operations can be costly in terms of time and personnel, because the information must be captured on the field.
3. The use of DGPS systems to improve precision requires more costly equipment and more time for data collection and further processing.
4. Staff training programs must be expanded if equipment superior to basic services, such as DGPS, is required.

5.2. Costs and benefits of geospatial technologies

The creation of sampling frames based on the use of geospatial technologies (GIS, remote sensing, GPS/GNSS) implies the need for resources and funding, and may entail high costs. On the other hand, the benefits deriving from the good construction of the system are such as to make these technologies essential to frame construction. Proper planning and budgeting for the various elements to be used are crucial; this is all the more true in developing countries, where resources are scarce. To establish the cost of implementing the system, its specific components must be ascertained.

5.2.1. Costs

The components of a proper costs definition for the use of geospatial technologies in constructing MSFs are the following:

System design. In this phase, the system's architecture is defined. This structure consists mainly of hardware and software components. Software design includes designing the databases and defining the applications and procedures developed within the system. This process should take into account not only the initial needs; indeed, it is also essential to forecast future needs. If an MSF is being constructed, this stage must also include frame design and sample selection, because these influence the later stages of material preparation and information collection and analysis, as well as storage needs.

Considerations on system design

The design of a GIS in which information is captured using geospatial technologies should be considered, as well as the design of geographical databases.

The overall frame construction, sample selection and planning of the process of capturing information must also be arranged.

Hardware. This consists of the various components of the physical part of the computer equipment, including computers, storage systems, security systems, printing devices (printers, plotters, etc.), and equipment for the capture of information. If geospatial technologies are used, the equipment for capturing information constitutes an essential and specific element of the system, consisting of GPS/GNSS equipment, and tablets and laptops with capture devices on their screens. Smartphones and other electronic devices to capture information can also be used.

Considerations on the hardware

Hardware requirements vary substantially, depending upon the system's design and the resources available. These can vary greatly, from complex multi-user systems with redundant servers located in several geographic locations, to computers with a single-user system.

The equipment must be selected taking into consideration the system's possible future growth and needs, both in terms of expanding existing equipment and of purchasing new equipment.

To determine the physical equipment's configuration, it is necessary to take into account future processing and data storage needs.

Storage needs (and therefore the size of storage devices) must be examined carefully, taking into account not only the information requirements that are necessary to and generated during construction of the frame, but also the fact that the latter should be updated on a regular basis. It must also be recalled that statistical frame-based information will be acquired over time. This should be borne in mind for the storage of backup copies.

In the acquisition of equipment, it is necessary to consider whether the supplying company will provide technical support; this is essential for the proper maintenance of the equipment and for the efficient purchase of additional parts or elements.

Software. This is a set of programs and procedures having the purpose of carrying out the tasks assigned to the system. The software programs required for setting up an MSF based on geospatial technology are:

- A. an operating system, which controls the computer's tasks
- B. GIS software, developed to execute the functions of a GIS. This software also assists the treatment of remote sensing images
- C. a DBMS
- D. GPS/GNSS software, developed to plan and process information collected by the GPS/GNSS equipment

The software is essential for the system's development and should be selected with care.

Considerations concerning the software

Criteria for the selection of the software, based on the project's needs and financial resources, should be established. Relevant criteria are the level of international

recognition and the reputation of the software, the availability of technical support, and the existence of training services and technical documentation.

Software requirements vary substantially, depending upon the design of the system and the resources available. The possibility of using open source software instead of proprietary software should be evaluated. Steiniger *et al.* propose a guide that may be particularly useful for the selection of free GIS software (Steiniger & Hunter 2013).

In software acquisition, georeferenced DBMSs and software for Computer-Assisted Personal Interviewing (CAPI) must also be considered.

The software selected must be documented, and must have been validated to ensure that it is suitable for use within the system.

Data. This is all the information required by the system. In this case, it consists of graphical information (cartography) and thematic information from different sources. The information introduced or generated within the system can be:

1. Information required to construct the frame. This information essentially comprises: (i) previously built frames (ii) cartography constructed on different scales (iii) orthophotography and/or aerial photography (iv) satellite imagery (v) thematic maps and (vi) DTMs or Solid Terrain Models (STMs).
2. Material for capturing statistical information in the field.
3. Statistical information collected during fieldwork.
4. The results of information processing and analysis.

The information needed to set up the frame may derive from different sources:

- A. from the organization itself (e.g. the cartography from previous frameworks, population censuses, etc.)
- B. national or international agencies related to the body in charge of building the frame (a national cartography agency, national or international statistical sources, etc.)
- C. third parties (satellite images, GIS layers produced by firms and other agencies, etc.)

Data from sources A and B above tend to be easily accessible and without costs, whereas sources of type C may incur high costs.

Considerations concerning the data

In the case of satellite imagery, it is advisable to evaluate the possibility of using free sources, although if high-resolution images are required, high costs may have to be sustained. The selection of satellite images to be used in stratifying the territory and in preparing any necessary field material usually depends upon budget availability, and should be limited, if possible, to low-cost or free-of-charge images.

The acquisition of materials that are not free or low-cost should be limited to those that are strictly necessary.

All costs for the acquisition of field data – and not only those relating to staff, software and hardware (e.g. transport costs) – should be considered. It is also important to include the costs inherent in transitioning from paper to digital systems, such as for scanning, digitizing, georeferencing, projection, geolocation, etc.; thus, the specific technical and human resources necessary to execute these operations should be taken into account.

Staff. To achieve the objectives identified during system design, it is important to define the organizational structure. This involves establishing the project's different jobs and the relationships between them. For each job, it is important to establish the set of tasks to be performed, as well as the skills required of the persons occupying these positions. The process for planning the human resources comprises:

1. design of the organizational model and of the jobs required;
2. recruitment and selection of personnel; and
3. training of staff, particularly in the use of geospatial technologies.

Human resources considerations

It is essential to plan the human resources that will operate the system, both initially and in the future.

Staff should be recruited on the basis of both the capacities and the motivation of candidates. The use of highly technical resources (computers, GPS/GNSS equipment, satellite images) requires highly qualified personnel. The selection process must ensure that the staff selected possesses the technical and practical knowledge and skills to execute the tasks required of them.

It is necessary to establish training programs, both initial and ongoing, for the personnel working with the system. It is especially important to provide proper training for the staff assigned to capturing information in the field.

Facilities. These are the areas in which the work on constructing and managing the MSF will take place. Among the various elements to be considered, it is important to provide for the possibility that physical space will be needed for computers and equipment to capture information, communication networks equipment between computers (wiring), maps and documents in paper format, etc.

Considerations concerning the facilities

The requirements of the necessary facilities, such as volumes, power supply, network communications, air-conditioning, etc., must be exhaustively analysed.

Quality control. The system designed should feature tools and activities that enable the quality of its components to be assessed, i.e. whether the system's elements meet the requirements for achieving the project's objectives. An example of a characteristic to be subjected to quality control is the accuracy of cartographic elements. Quality control protocols should be established for each stage of MSF construction, sample design, preparation of field material and data collection. All procedures and data transfer should be subject to appropriate and systematic checks.

Considerations concerning quality control

A quality control plan for all system processes must be established.

Procedures that ensure information integrity and confidentiality should be designed. These procedures must be applied to the stages of information collection, storage, transmission and processing.

All quality control processes must be documented.

Maintenance and updating. The system should work properly at all times. For this reason, maintenance and updating mechanisms for its different components are essential. As mentioned in previous Sections, the data used to construct the MSF requires updating on a permanent basis. In the case of list frames, for example, their constituent elements may become obsolete due to the disappearance of existing elements, the emergence of new elements or the failure to include all elements in the initial phase. With area frames, the need to update is less urgent, but should still be taken into account. Similarly, physical equipment such as computers, GPS/GNSS and software also require updating and maintenance.

Therefore, it is necessary to provide for the maintenance and updating of:

- A. *The hardware.* Mechanisms for maintaining the equipment must be put in place, and periodic investments to upgrade equipment and purchase new equipment should be considered.

- B. *The software.* This may have to be changed over time, if the requirements for achieving the project's objectives evolve. Maintenance program software must be installed. A suitable software update policy should be established, including for the acquisition of new versions. If commercial software is used, maintenance contracts could be stipulated with suppliers, and include upgrades to new versions.
- C. *The data.* The sampling frame must be maintained and updated continuously, reflecting the changes that may occur over time; this will enable it to be updated thoroughly and on a timely basis.

Considerations concerning maintenance and upgrading

A plan for maintaining and updating equipment and software must be defined. Trained personnel are required to perform these tasks, or contracts for the purpose must be established with reputable companies.

The maintenance of the equipment used, such as computers or GPS/GNSS equipment, should include their verification in the applicable environmental and operating conditions.

A work plan and staff for the maintenance of sampling frame data should be designated.

The system's entire maintenance and updating process must be fully documented.

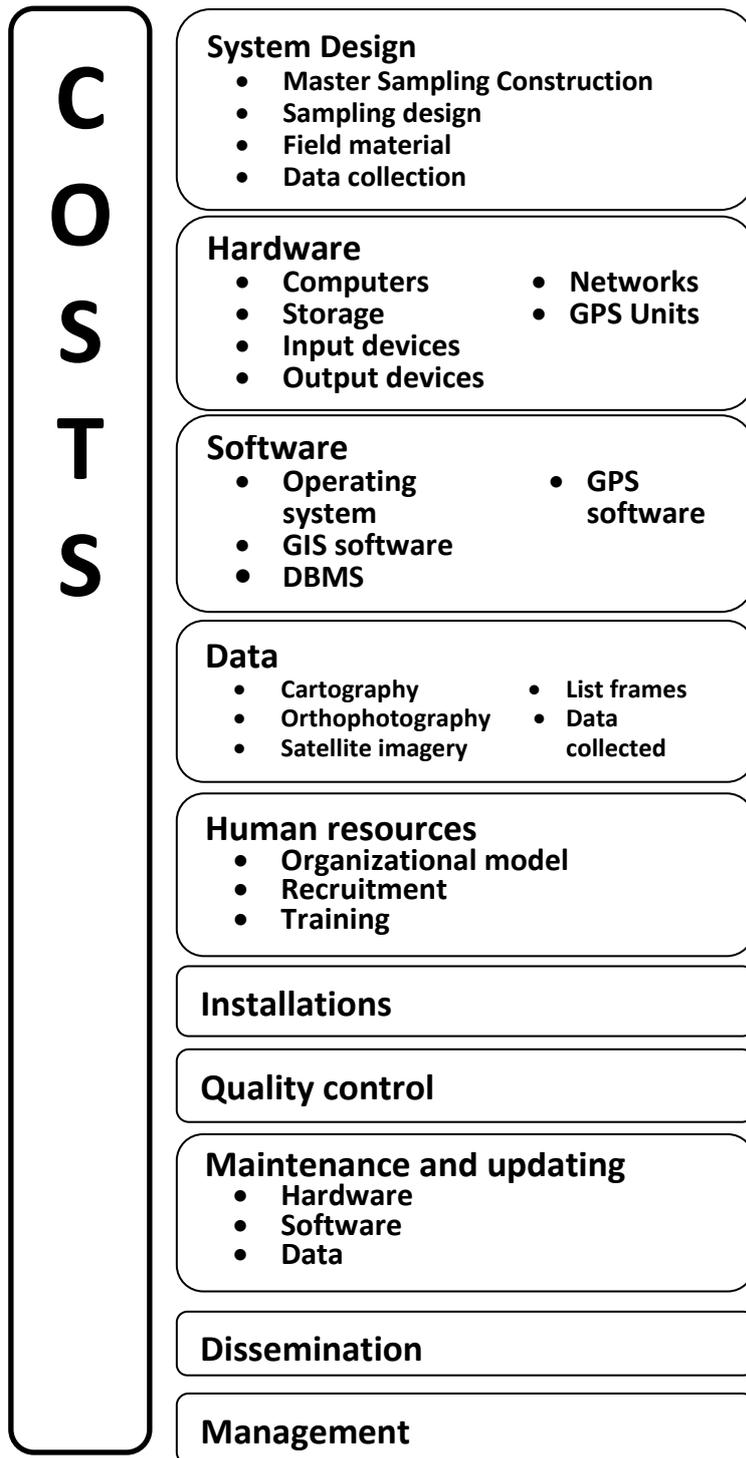
Dissemination of results. Finally, a process for the dissemination and publication of the results of the statistical process and of the information captured at different levels should be established. The demand for this type of information is rising on a daily basis, and requires the institution of a clear policy for accessing sources of information. The use of new information technologies, particularly web and digital storage systems such as DVDs or CDs, facilitates access to all the information generated during the statistical process, including field data, results, reports, mapping or any other type of information generated from the system.

Considerations concerning the dissemination of results

In setting up an MSF and during the statistical process, a plan for the dissemination and access to data must be established.

Data confidentiality and protection of the respondent must be ensured. In some cases, the dissemination of results entails costs, but may also be a source of revenue if the data or products are sold. Finally, when calculating costs, those arising from the **management** of the system, including those relating to the contracting processes of outsourced system services, should be taken into consideration.

Figure 5 – Costs of the use of geospatial technologies



Ambrosio provides a comprehensive description of the cost structure for frame building, and a detailed overview of the current prices of satellite imagery: see Chapter 6 of the Technical Report on Identifying the Most Appropriate Sampling Frame for Specific Landscape Types (FAO 2014).

Several free and open source GISs are available. Steiniger *et al.* outline the main projects of open source GIS software and study the issues to be taken into account when choosing such software for use in business and research (Steiniger & Hunter 2013). They examine the software projects with respect to the various functional categories of GIS software (desktop GISs, spatial database management systems – SDBMS –, web map servers, GIS servers, Web GIS clients, mobile GISs, and libraries and extensions), and propose a brief guide to the selection of free software.

5.2.2. Benefits

The use of geospatial technologies for the construction, management, maintenance and use of sampling frames presents a great competitive advantage over traditional procedures, thus leading to significant benefits. These benefits can be considered in terms of increased productivity (efficiency), i.e. the relationship between the quantity of output produced and the media used, or in terms of their effect on the objectives envisaged (effectiveness).

Among the benefits relating to improved productivity (efficiency) are:

- **Increased production.** Filing information within a computerized system and georeferenced data highly facilitates statistical work, thus increasing the production of statistics.
- **Less resources needed.** Systems based on geospatial techniques require fewer, but more qualified, staff to construct and manage the system. This decrease is particularly evident in relation to the number of individuals involved in capturing information. An increase in productivity can thus be achieved.
- **Reduction in the time required to execute work.** The management of information within a computerized system enables a more efficient access to information, so that processes are faster and the time required to fulfil objectives decreases. This is particularly relevant in the computerized automation of routine processes that are traditionally performed through manual means, such as with data that is captured on paper and digitized at a later stage. The use of new technologies for data capture in the field and the possibility of electronic transmission of data can lead to a significant reduction in the time used to capture and store the data. With the use of these technologies, the waiting times for the results of the statistical processes are cut by a significant measure.

- ***Improving data quality and control.*** The use of computerized systems for building, managing and updating sampling frames, for preparing field material or for data collection involves the replacement of certain manual operations. This leads to an improvement in data quality, as human errors in data capture and manipulation, and systematic errors in particular, can be avoided. The use of geospatial techniques involves not only the use of specific equipment and software, but also of procedures and systems to control and monitor the entire process; this leads to an improvement in data quality and data control.
- ***Information coherence.*** The use of computerized systems for setting up and using sampling frames requires consistency in the storage and processing of data. Coordinated, consistent and systematic processing of information ensures that the statistical process is properly and effectively implemented, and guarantees the sound quality of the data and of results.
- ***Improved data maintenance and updating.*** Up-to-date mapping is required for system maintenance. Traditional paper maps or aerial photographs are usually not up-to-date, often due to the fact that the cartography was produced on paper. The use of integrated GPS/GNSS technology and portable systems for mapping enable the quick update of cartographic databases, thus allowing sampling frames to be updated and maintained in a flexible and efficient manner.
- ***Improved products.*** The use of geospatial technologies in an integrated information system can improve not only data capture, but also the outcome and the ability to offer new products to statistics users, such as the production of thematic maps or the provision of disaggregated data.
- ***Improved statistical efficiency.*** The use of geospatial technologies improves statistical efficiency, due to its ability to provide auxiliary information. The auxiliary information obtained from remote sensing, or obtained from different sources and managed with the GIS, can be particularly useful in optimizing sample unit size, proposing the type of sampling to be performed or determining the number of stages. The auxiliary data can also be used to improve the estimates.

The benefits relating to the objectives envisaged (effectiveness) include:

- ***Possibility of detailed analysis on different scales.*** The information captured and stored on systems that use geospatial technologies enables information to be processed at different levels of disaggregation. The demand for information at the regional or local level is increasing, which means that the use of tools capable of responding to these demands becomes a priority. Construction of the sampling frame should take into account not only the use of geospatial

technologies, but also the need for the system to be designed in such a way as to be capable of meeting evolving demands.

- ***Provision of reliable information.*** Decision-making requires reliable information. The construction of frameworks based on geospatial technologies is a first-order tool for providing reliable information for use in any decision-making process, such as the formulation of agricultural, social and rural development policies. Geospatial technology applied to the construction of sampling frames can be especially useful in planning policies, enabling enhancement of general welfare and saving lives.
- ***Improved data sharing among different agencies.*** There is an increasing demand to share information between public and private organizations. The integration of the entire statistical process within a single information system greatly enhances the ability to share both data and the results of their analysis.
- ***Improved dissemination of results.*** As mentioned above, the demand for information is rising substantially. The existence of new communication technologies, such as social networking or portable data storage devices, facilitates the dissemination of information. The integration of the entire statistical process within a computerized system with geospatial capabilities can improve the dissemination of results, as well as the access to the databases generated during the construction and operation of the sampling frame.
- ***Promotion of the participation of stakeholders.*** Reliable and fast access to information by stakeholders, whether public or private, fosters the participation of these parties in the process of defining objectives, thereby promoting the system's overall development.

Although the use of these technologies requires a high amount of initial funding, and the technologies are greatly dependent upon maintenance and repairs, they provide long-term benefits that are essential to the development of modern statistical systems and the construction of MSFs. Both costs and benefits can be difficult to quantify; this is especially true in the latter case, because the implementation of an integrated system to manage a sampling frame based on geospatial technology can have benefits in agencies or entities other than that responsible for the construction and financing of the system. Furthermore, the relevant costs tend to be incurred during the initial stages of project implementation, while the benefits may not be seen until long after the project has been fully implemented; it is impossible to obtain immediate results. Therefore, significant work is required to raise awareness, with the agencies financing the project, of the future benefits that the initial expenditure can achieve.

Among the potential benefits of implementing geospatial technology devices is cost reduction. Compared to traditional non-ICT management systems, the introduction of such technology must entail a reduction in the costs relating to the material, personnel, processing and handling of the information acquired in the field, to compensate for the increased costs arising from the acquisition and maintenance of the necessary equipment and the relevant staff training. Geospatial technologies are cost-effective for large-scale operations, large-scale surveys and statistical operations that are to continue over time.

Factors to considered when using remote sensing to set up a Multiple Sampling Frame

The main goal of any survey in which data relating to natural resources is obtained from satellites is subject to – among other factors – selection of the appropriate satellite and sensor. The optimal characteristics include the data capture system's resolution, provided through a variety of parameters, as well as other determining factors relevant to the achievement of the proposed objectives. The field methods used in remote sensing projects are often poorly planned, and the final products often contain hidden weaknesses that could be avoided with careful planning (McCoy 2005).

Since 1972, when NASA launched Landsat1 – the first satellite for studying natural resources – the possibilities and uses for Earth observation satellites have proliferated. Over the last 20 years, numerous satellites have been launched into orbit, with considerable improvements. Understanding the parameters of a sensor from a user's perspective is not easy; therefore, to enable their comprehension and selection, it is important that their characteristics be standardized, depending upon the importance and dependence of fusion and data comparison (Joseph 2000).

A. Data acquisition systems

There are basically two types of systems relating to the energy flux captured by a sensor: the first system is passive, and the second is active. Passive sensors acquire the energy flux emitted by the Sun and reflected by the Earth's surface, and that is related to the land covers' chemical properties. The scope of their action is mostly within the visible and infrared regions of the electromagnetic spectrum, which is why they are called optical sensors. Active sensors are equipped with their own energy source and acquire the returned echo of signals produced by objects, and relate to their physical properties. The domain of these sensors is in the microwave region of the electromagnetic spectrum, and they are known as radar sensors (Mather 2003). The origin of the energy flux determines a range of capabilities for each system; for this reason, this must be the first choice to perform.

Most satellites used in the remote sensing of natural resources follow low sun-synchronous orbits (Low Earth Orbit – LEO, 400-900 km), and are therefore satellites equipped with passive sensors that capture relevant information in their descendent trajectories (N-S, diurnal), and limited or null information in their ascendant trajectories (S-N, nocturnal). Active sensors are not affected by this restriction, and capture relevant information in both trajectories of their orbits.

Given the above observations, and the characteristics ensuing from the electromagnetic radiation properties of both domains, optical sensors are affected by a serious limitation in terms of cloud cover. Radar sensors can penetrate the cloud cover since they are capable of operating regardless of meteorological conditions and solar illumination (Mather 2003).

Given the characteristics of both of the above systems, and at a first glance, radar sensors may be considered preferable to optical sensors; however, optical sensors are generally better able to identify land use and land cover; thus, they provide more possibilities than radar sensors.

However, in areas with persistent cloud cover, the use of radar sensors may be the only source of information from remote sensing.

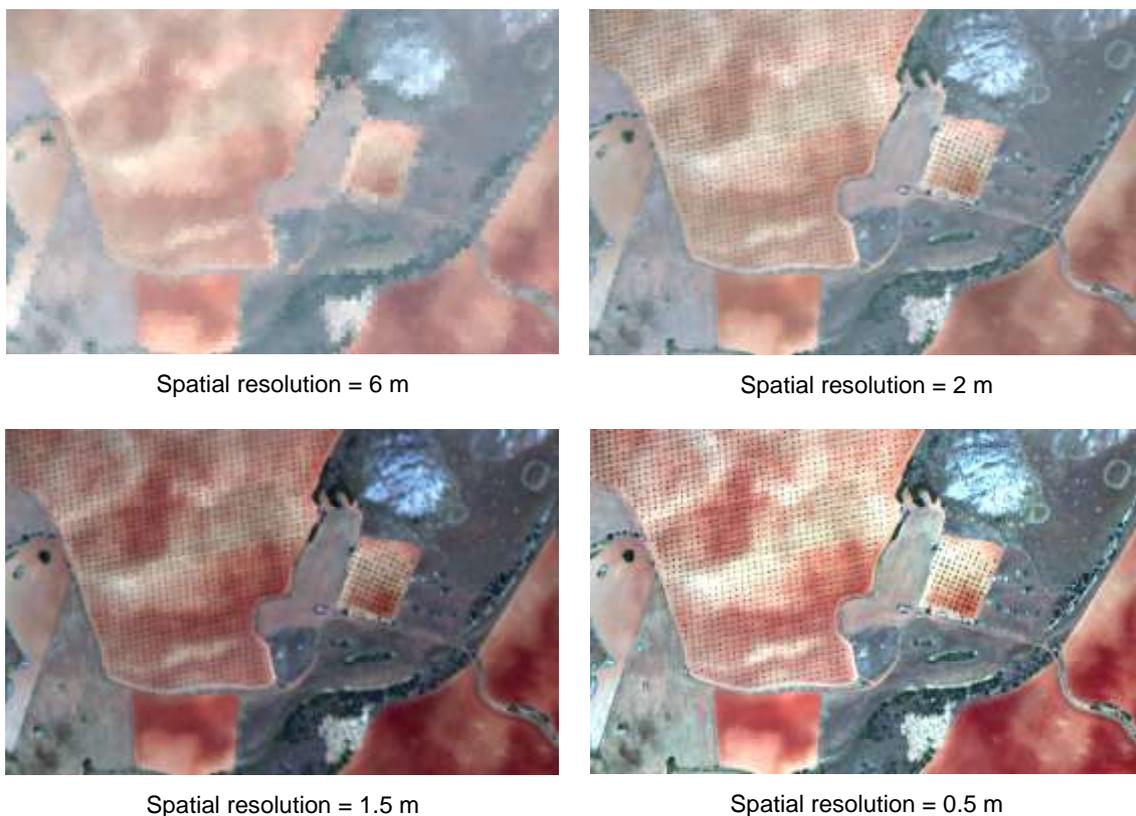
B. Spatial resolution

As seen in Figure A.1 on the following page, spatial resolution is normally defined on the basis of the dimensions of the smallest identifiable object in an image, or the capacity of a sensor to perceive details. Although spatial resolution is associated with pixel size, the concept is more complex (Mather 2003; Townshend 1980) and there is no single satisfactory measurement. It is related to the Instantaneous Geometric Field of View (IGFOV), which is the image size of the detector projected onto the ground by the optical system, and to the Ground Sampling Distance (GSD), which quantifies the distance to the ground in which two consecutive pixels are recorded. When spatial resolution is expressed as the sensor's sampling angle, it is denominated Instantaneous Field of View (IFOV) (Calle & Salvador 2012; Joseph 2000).

On the other hand, although IGFOV and the GSD are different terms, the ratio between them has a direct impact on the radiance value attributed to a pixel. Besides, the IGFOV suffers degradations, which may generate a reduction in contrast. Due to the above, the most important function in defining spatial resolution is the Modulation Transfer Function (MTF), which establishes image contrast. This quantifies the sensor's sensitivity to contrast based on the radiometric variations of a scene. The MTF measurements in high resolution sensors follow standard protocols (Helder, Choi & Anderson 2006). To establish a spatial resolution concept that can enable sensors to be compared, NASA's report (NASA SP 335 1973) introduces the Effective Instantaneous Geometric Field of View (EIFOV), which is the resolution corresponding to a spatial

frequency (ground resolution) for which the system MTF is 0.5. The MTF is also an indicator of the precision of a pixel's radiance measurement, since a low MTF value indicates a contribution of other pixels to the selected pixel and vice versa; thus, Joseph 2000, introduces the concept of "IFOV radiometric precision", which defines the resolution when the MTF is greater than 0.95; and recommends that instrument designers indicate the following three parameters related to spatial resolution: (1) Instantaneous Geometric Field of View (IGFOV) (2) Radiometrically accurate IFOV (RAIFOV) and (3) MTF at IGFOV.

Figure A.1. Comparison of different remote sensing data, in terms of spatial resolution



To avoid neglecting the terms described above, but also the need to formulate complex definitions concerning the general applications of remote sensing, the simplified term "pixel size" or GSD is still used as the most commonly accepted term to describe spatial resolution. Most image suppliers provide this data, and, in some cases, the IFOV value, to facilitate interpretation of the spatial resolution concept by non-expert users of remote sensing.

Today, due to the rapid advancement of remote sensing technologies, it is possible to acquire images having spatial resolutions that range from several centimetres to kilometres. A higher spatial resolution naturally leads to a greater capacity to detect details, but an excessively high resolution may cause negative effects, such as greater

costs, a decrease of spectral resolution, a reduction of spatial coverage, and a lower temporal resolution (Ma *et al.* 2012).

The spatial resolution is fundamental for structure location and for the positioning of point elements in the MSF (Carfagna 2013). In general, using on-site measurements for model calibrations and their validation requires a robust method, to add spatial field measurements having the same scale as the remote sensing data (Baccini *et al.* 2007).

The spatial resolution should be selected carefully in relation to the purpose pursued, to optimize the balance between effectiveness and cost. The concept of “adequate spatial resolution” (Atkinson & Curran 1997), can be described as the spatial scale containing the least volume of data and the greatest quantity of information, even when this scale is not the most accurate available. The characterization of spatial heterogeneity constitutes the foundation of the image’s spatial structures at a given spatial resolution, and is also the basis of an adequately selected spatial resolution (Ma *et al.* 2012).

Moreover, an image’s spatial resolution is related to the classification level employed for land use and land cover, and to the results and precision reached in the thematic classification. While images having higher spatial resolution contain more detailed information on the terrain, they do not necessarily offer greater precision in classification (Hoffman, Smith & Lehmann 2000; Hsieh & Lee 2000).

In terms of spatial resolution, sensor choice should be determined by the knowledge of the spatial frequency at which the instrument is to sample the scene, and that can provide the necessary information on the parcels under study (Duveiller & Defourny 2010). Both authors propose a system that is based not only on pixel size but also on their purity, which can be used to: i) guide users in choosing the most adequate images for their specific purposes ii) evaluate the suitability of existing remote sensing systems for agricultural monitoring in different parts of the world and iii) provide reference to space agencies in designing future sensors for agricultural monitoring.

Cultivation parcels may differ not only in size or shape, but also in their spatial distribution. Therefore, depending upon the part of the world in which the work is being performed, and the study’s specific conditioning factors, the spatial resolution requirements will differ, and will be closely related to the spectral properties of the adjacent objects – crops (Duveiller & Defourny 2010). These authors propose pixel sizes between 30-140 m depending upon the geographic location and type of crop; this could be extended to 120-300 m in large parcels, and be lower for other types of landscape.

Sensors having greater spatial resolution are useful for cartography and for detailed control of smaller areas, but not in the context of regional and global studies; this is due to their limitations relating to spatial coverage and acquisition frequency (Pax-Lenney & Woodcock 1997).

The research conducted by Teillet *et al.* (1997) upon the effects of spectral, spatial and radiometric characteristics of vegetation indices in forest areas, compared the behaviour of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) with those of SPOT-HRV, Landsat-TM, NOAA-AVHRR, EOS-MODIS, and Envisat-MERIS; the nominal spatial resolution of AVIRIS was degraded from 20 m to 60 m, 100 m, 260 m, 500 m, and 1,100 m. The study concludes that the changes observed in the Normalized Difference Vegetation Indices (NDVIs) depend upon the nature of the land cover, especially in wooded and cut areas; in the study area, NDVI changes occurred in scales of approximately 260-500 m, irrespective of the spectral band characteristics; this circumstance is also seen in other vegetation indices such as the Soil Adjustment Vegetation Index (SAVI), the Modified Soil-Adjusted Vegetation Index (MSAVI), the Ratio of Vegetation Index (RVI), and the Data Vegetation Index (DVI), the behaviour of which is similar to NDVI.

In any case, the selection of the most adequate sensor is connected with the other characteristics of the satellite or sensor, especially in the multispectral and multi-temporal dimensions. Research on land use in the Mediterranean wetlands suggested the use of medium-resolution images such as those deriving from a Moderate Resolution Imaging Spectroradiometer (MODIS), as such images offer similar precision to that obtained with other spatial resolutions such as Landsat (Meléndez-Pastor *et al.* 2010). Moreover, this entails a substantial cost reduction in the management and monitoring of wetlands using free or low-cost imagery having medium or low spatial resolution, which is especially attractive when using remote sensing imagery for MSFs, given that the study is conducted on a global scale.

In projects including studies of land use and land cover for large surfaces, such as the CORINE Land Cover (Coordination of Information on the Environment, CLC) (CORINE Land Cover 2013), the Global Land Cover Facility (GLCF) (Global Land Cover Facility 2013), and the Global Earth Observation System of Systems (GEOSS) (Global Earth Observatory System of System 2013), satellite data are used for cartographic scales in the order of 1:100,000. The SPOT and Landsat series are the most frequently used, primarily due to their duration and stability, and because they satisfy the characteristics required by the goals of these projects.

FAO, in Project TCP/BUL/8922 entitled “Pilot study in Bulgaria: preparation of land cover maps and associated database” (FAO Environment and Natural Resources Service 2002), Landsat5-TM scenes are used to create thematic maps at a scale of 1:50,000, and IKONOS panchromatic 1 m resolution scenes to develop cartography at a scale of 1:5,000.

The elaboration and quality assurance of cartographic documents are governed by national and international regulations. By way of example, the Federal Geographic Data Committee (FGDC) (USA 1998) establishes a methodology to estimate location accuracy on digital maps and geospatial data. Quality assurance is performed in relation

to other high-precision georeferenced points from the Root Mean Square Error (RMSE) at a 95% confidence interval, and upon at least 20 well-distributed points within the study area. The horizontal and vertical exactitude value is set from the RMSE. In the same document, the values proposed by the National Standard for Spatial Data Accuracy (NSSDA) and the American Society for Photogrammetry and Remote Sensing (ASPRS) are compared. In practice, to obtain a quick estimate of the recommended pixel size and, indirectly, the spatial resolution of the sensor to apply on a given scale, the lineal-visual perception limit (lvpl) can be used. This is established as: $lvpl = 0.2mm \cdot E$, with E being the scale denominator that can be associated with the GSD. For example, for a scale of 1:50,000 scale, the lvpl value would be of 10 m; thus, to work with remote sensing data on the basis of that scale, it would be necessary to use sensors having a pixel size of ≤ 10 m.

In any case, the operability and acquisition costs of remote sensing images for use in MSFs must be borne in mind; the existence of free products of medium and high spatial resolution aside, it is therefore necessary to recall that several countries possess, through their respective space agencies, natural resource observation satellites having characteristics (resolutions) that satisfactorily meet the requirements for this type of global project. According to the latest data available (1 September 2013) from the Union of Concerned Scientists (Union of Concerned Scientists 2013), there are 90 LEO sun-synchronous satellites, which belong to 36 countries or are shared with third parties.

C. Spectral resolution

The opportunity to observe the occupation and use of land surface is limited by the atmospheric characteristics and the radiation used. Thus, sensors should possess spectral capacity in the atmospheric windows where remote sensing is possible, but for wavelengths at which land covers display reflectance and/or temperature discontinuities. Therefore, well-defined spectral intervals through localized and width-determined spectral bands must be identified (Calle & Salvador 2012). An increase in spectral width enables the receipt of more radiance from smaller pixels (this improves spatial discrimination), but also leads to the mixing of spectral characteristics and to a loss of information. This is the essential focus of the debate on spatial vs. spectral resolution; however, there has yet to be a clear definition of the effective spectral width to be used for quantification purposes or, more importantly, as a representative wavelength.

In general, electro-optic sensors are multiband or multispectral, meaning that individual images of the same area observed are registered separately in discrete spectral bands, defined in spectral regions that best capture the more descriptive spectral attributes of an object. A simplified definition of the term “spectral resolution” refers to the width of each spectral band. There are two important aspects to consider in relation to spectral resolution (Mather 2003): (i) the location of the band in the spectrum, its width and the number of spectral bands determines the degree of discrimination of individual objects

in a multispectral image; (ii) the use of multispectral images may offer a greater capacity for discrimination than a single band alone.

The simplified concept of location in the electromagnetic spectrum, the width and number of bands, is not well defined, and is variable in every sensor. Therefore, for a more rigorous definition, other terms such as SNR (Signal-to-Noise Ratio) must be considered, where “signal” is defined as the information contained in the data received by a sensor, and “noise” is the unwanted variation added to the signal – which can be either random or systematic, and could be due to the fact that the instrument’s electromechanic elements reduce the operation’s perfection (Mather 2003). As an example, to estimate the level of noise in the ETM+ sensor, Platt and Goetz (2004) used the following model, proposed by John Baker (NASA/Goddard Space Flight Center):

$$\text{SNR} = \text{DN}/(a+b*\text{DN})^{0.5},$$

in which DN is the pixel’s digital level, and a and b are the calibrated coefficients of each band in the ETM+ on 6 September 2002. Therefore, Joseph (Joseph 2000) recommends that the following parameters for spectral bands be specified: (i) central wavelength (ii) bandwidth and (iii) response percentage outside the band.

The Spectral Responsivity Function (SRF) is the function that specifies the sensitivity with which a sensor detects radiance for each wavelength λ , having null values below and above the two given wavelength limits. A common method for expressing spectral bandwidth is FWHM (Full-Width at Half-Maximum), in which $D\lambda$ is set as the difference between the values of λ where the SRF is 50% (Calle & Salvador 2012). In any event, this procedure can be inaccurate for certain functions, and proposals to use other techniques, such as Radiometric Bandwidth Normalization, have been advanced (Palmer 1984).

The spectral responses of many similar objects of the same kind, such as the types of vegetation, water, rocks or bare soil, can be subtle, and will be separated only if the registering device is capable of detecting the spectral reflectance of an object within a narrow band. The sensor’s spectral resolution must match as closely as possible the reflectance curve of the object under study, to ensure that the identification of the above is as real as possible. This is achieved with hyperspectral sensors such as AVIRIS with 244 bands, and to a lesser extent with CASI (Compact Airborne Spectrographic Imager) with 144 bands, MODIS (Moderate Resolution Imaging Spectroradiometer) with 36 bands, or even with ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), with 14 spectral bands. Unfortunately, the increase in spectral resolution entails a significant output SNR reduction of the sensor.

According to Platt and Goetz, the factors that may affect the accuracy of the classification include the distance from the ground at which two consecutive pixels are recorded (GSD), the number of spectral bands, and the sensor’s SNR (Platt & Goetz

2004). The latter varies from sensor to sensor, from band to band, and from pixel to pixel, and can therefore influence the accuracy of the classification. However, generally, it can be said that at a higher SNR, more useful information is available in the data used.

Several studies have been conducted over the years to determine the best band combination in multispectral sensors in relation to the studied object, and also to discriminate between objects of the same type. Kondratyev and Pokrovsky (1979) proposed the use of an algorithm based on factorial analysis to determine the optimal observation parameters by means of remote sensing, considering the general requirements of complex studies on the environment and natural resources; the proposed method could be used to select spectral intervals for the solution of complex problems in oceanography, hydrology, geology, forestry and agriculture.

In the research performed by Platt and Goetz (2004) on land use classification in bordering urban areas, the use of AVIRIS (224 bands) hyperspectral imagery against Landsat TM/ETM+ (6 bands) and SPOT XS (3 bands) improved the urban and agricultural classification, because vegetated areas are easily discriminated in the near-infrared; in cases where land uses are similar but present separable spectral signatures, a rise in the number of bands improves the accuracy of the classification; the opposite occurs when land uses are spectrally inseparable or clearly distinct. In these cases, a greater number of bands may add additional noise and spectral heterogeneity, reducing the classification's accuracy. In this research, it was proven that a lesser GDR, a greater SNR and a higher number of spectral bands may improve the accuracy of land use cartography, but the net gain usually depends on the scene and the classification method.

Given the above considerations, sensors are designed to obtain useful information on the objects studied in atmospheric windows that allow reflectance to be registered; from their spectral signatures, the sensors can identify and discriminate land cover, using more or less sophisticated and complex algorithms for multispectral imagery thematic classification.

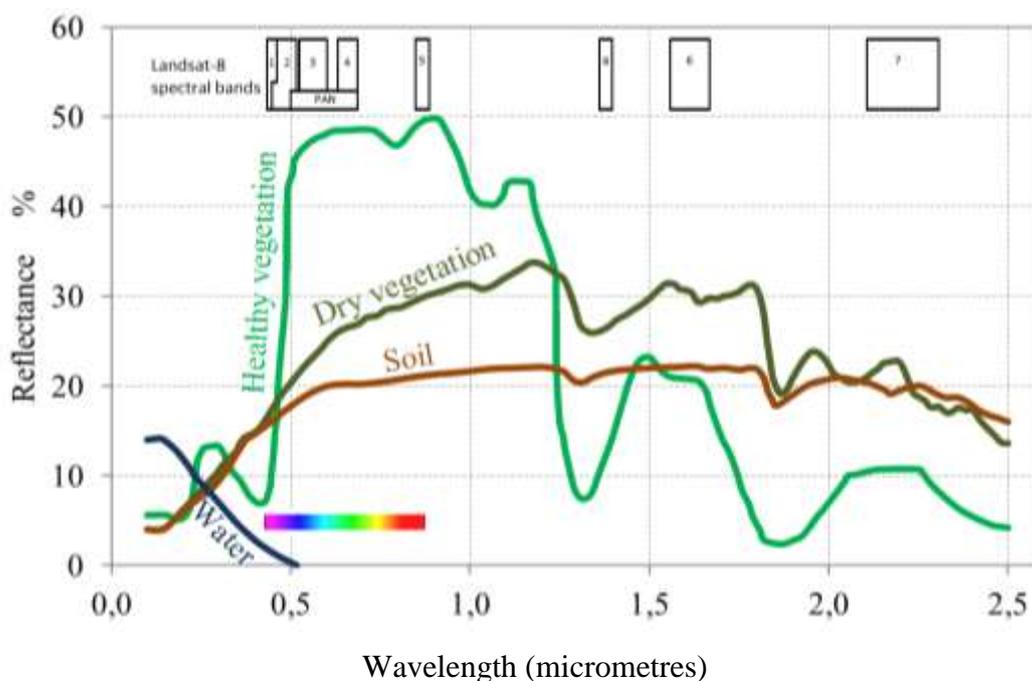
By way of example, Table A.1 on the following page shows the spectral bands and technical specifications of the Operational Land Imager (OLI) instrument installed in the Landsat8 satellite (ESA 2013); and Figure A.2 displays the spectral signatures of soil, vegetation, and water, over the spectral bands of the Landsat8 satellite.

Table A.1 – NASA/USGS requirements for Landsat8-OLI spectral bands

Band Nr	Band Name	Spectral range (nm)	Use of data	GSD	Radiance (W/m ² sr μm), typical	SNR (typical)
1	New Deep Blue	433-453	Aerosol/coastal zone	30 m	40	130
2	Blue	450-515	Pigments/scatter/coastal	30 m (TM heritage bands)	40	130
3	Green	525-600	Pigments/coastal		30	100
4	Red	630-680	Pigments/coastal		22	90
5	NIR	845-885	Foliage/coastal		14	90
6	SWIR 2	1560-1660	Foliage		4.0	100
7	SWIR 3	2100-2300	Minerals/litter/no scatter		1.7	100
8	PAN	500-680	Image sharpening		15 m	23
9	SWIR	1360-1390	Cirrus cloud detection	30 m	6.0	130

Source: ESA, Earth Observation Portal 2013.

Figure A.2 – Spectral signatures of soil, vegetation and water, and Landsat8 spectral bands.



Taking into account the above, and only considering spectral resolution, it can be said that at greater spectral resolutions, there is a greater ability to discriminate and a higher complexity of process; this fact is related to the level of detail of the legend in thematic categories. Considering the contribution of remote sensing to MSFs, in a first-level facing territory stratification where it is not necessary to descend to concrete categories, as in the case of the legend of the LCCS proposed by FAO (FAO 2000), and using many practical applications where a first level of covers in 6 levels is established (FAO *et al.* 2009), in the present case, the use of multispectral sensors with 2 or 3 bands in the visible zone, one in the near-infrared zone, and a complementary medium-infrared zone of the electromagnetic spectrum, could be sufficient for this type of study. These bands are most popular if they have medium or high spatial resolution optical sensors, such as MODIS, Landsat, SPOT or TERRA. In this context, Alexandridis, Gitas and Silleos (2008) used the MODIS/TERRA MOD09GQK product having only 1 and 2 bands – which correspond to red and infrared bands – to further develop the NDVI, in researching the optimal temporal resolution for vegetation monitoring in Greece.

In any case, it is important to consider that any Remote Sensing Survey (RSS) regarding vegetation, or in which vegetation is an important element for territory stratification (FAO 2000), the red and infrared bands must be available, since the discrimination between healthy/vigorous and sick/senescent vegetation, and other current land occupations, present considerable differences in these spectral bands; this is due to the differences in chlorophyll absorption and reflection of the wavelengths at the corresponding radiances for red, and leaf mesophyll for near-infrared. These differences are well-known in most vegetation indices calculated from the aforementioned bands. These bands, having variable width and location depending upon the sensor, are crucial to vegetation monitoring studies based on vegetation indices, especially the NDVI (Alexandridis, Gitas & Silleos 2008).

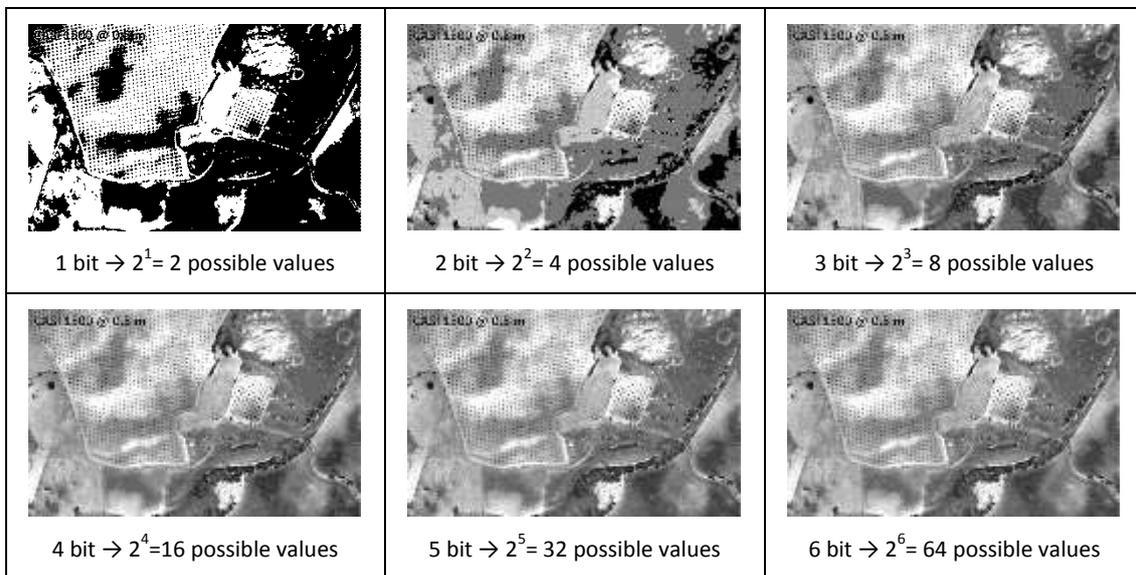
Finally, the spatial and spectral resolutions of remote sensing systems are closely related and, in general, because of technical limitations, it can be stated that a high spatial resolution is associated with a low spectral resolution, and vice versa.

D. Radiometric resolution

In a general form, radiometric resolution is referred to as the number of bits used by a sensor to quantify the physical measurement of radiance ($W/m^2/\mu m/sr$) (Calle & Salvador 2012), and more precisely, as the Noise Equivalent differential Reflectance or Temperature (NE Δ T), in the solar or thermal spectrum. The NE Δ ρ or NE Δ T is defined as the minimum change in reflectance or temperature that can be detected by a sensor (Joseph 2000), and depends on various parameters such as the SNR, the saturation value of the signal, and the number of bits in which the signal is quantified.

A bit is a digit in the binary numeration code capable of representing 2^n possible values. In a 1 bit/pixel image, each pixel can have only two possible values ($2^1=2$), [0, 1], equivalent to a black (0) and a white (1) image; a two-bit image could have 4 possible values ($2^2=4$), [0, 1, 2, 3], resulting in one black (0), one white (3), and two intermediate grey (1 and 2) values. When the number of DN increases to 16 (4 bits/pixel), the amount of visible details increases, compared to the same 1 bit/pixel image, but with 256 (8 bits/pixel) grey levels, generally, considerable differences with the previous image (Figure A.3 below) cannot be observed; however, the human eye is not as sensitive to intensity variations as it is to tone variations (Mather 2003). Although human vision is not capable of appreciating those differences visually, it is possible to quantify them analytically.

Figure A.3 – The effect of the number of quantization levels on a digital image



On the other hand, the number of bits/pixel cannot be increased unlimitedly, since the sensor's SNR must be considered. The leap size from one radiance level to another cannot be lesser than the noise level, because it would be impossible to determine whether a level change is due to a real variation in the radiance of an object or in the noise magnitude.

SPOT-HRV and IRS-LISS quantify the signal in 8 and 7 bits respectively, but they could have the same $NE\Delta\rho$ for a determined reflectance or radiance if the SNR and saturation value are selected correctly. Today, systems are designed with 11 or more bits (e.g. 12 bits in LANDSAT8's OLI), but unless these systems have the corresponding SNR, they do not necessarily possess a better radiometric resolution. In terms of quantification, an instrument's resolution capacity does not necessarily indicate the accuracy with which it can provide measurements; however, a greater number of bits raises the dynamic range, thus increasing the analytical possibilities of discriminating similar objects. Therefore, Joseph (Joseph 2000) suggests indicating in radiance units the quantification level of the signal in bits, as well as the differential radiance equivalent in noise.

The relation between radiometric resolution and the capacity to distinguish different vegetation types was investigated by Tucker (Tucker 1979), who reported an improvement of only 2-3% in 256 DN and 64 DN images. Various methodologies have been proposed to analyse the degree of redundancy, with the measurement of entropy (H) proposed by Bernstein *et al.* (1984) being one of the most commonly used to compare the quantity of information (in bits/pixel) in two images on the same area with different radiometric resolutions.

On a practical level, Rama Rao, Garg and Ghosh (2007) compared a 12-bit simulation image of the LISS-III sensor with the original 7 bits of the same sensor to classify land use and land cover, and obtained an improvement of 3% on the overall classification, which rose to between 4-6% for the 12-bit sensor, in cases where categories in the same class are more heterogeneous. The research suggests that for exact and accurate cartography of land uses and land cover, spectral bandwidth and location and the classification methods used are more relevant than an elevated radiometric resolution of the images. On the other hand, Platt and Goetz (2004), comparing the behaviour of real AVIRIS (12-bit) data and synthetic Landsat-ETM+ (8-bit) in land use classification in urban outskirts, concluded that although AVIRIS shows a moderate advantage over Landsat in classifying vegetated heterogeneous areas, this is mostly due to the higher number of bands, rather than to a greater SNR. As also indicated in this research, a lower GDR, a higher SNR, and a higher number of spectral bands can improve the accuracy of land use cartography, but the net benefit frequently depends on the scene and the classification method used.

Regarding the information contained in spatial images, and as for information extraction related to land occupations, Mather (2003) indicates that “all that is relevant”; this implies that part of the inherent information from Earth observation data is redundant for the purposes of obtaining thematic cartography, especially those describing inter covers. Indeed, in an 8-bit image with few spectral bands, there are more spectral band combinations than types of cover that can be set, since most legends have only a few dozen classes at best. Hence, reduction of the spectral data’s radiometric resolution (histogram quantification) can be a very effective step in digital classification, as it can reduce the possible number of further classes identified.

In general, sensors are designed to register lower or higher reflectance responses (water, bare soils, snow) without saturating the signal, and occupying the lowest and highest values of the histograms. However, in most scenes, the whole DN range is not covered because one or many categories of extreme reflectivity are absent, such that individual band histograms usually show a Gaussian shape with few extreme values, and with relative maximums and minimums from predominant occupations and uses of land in the scene. In these cases (Chilar *et al.* 2001), the image can be quantified with a more reduced DN number, without any apparent information loss concerning existing land covers. In the algorithm proposed by these authors, called FHQ – Flexible Histogram Quantization – it is assumed that histograms have at least two peaks (as soil and water)

and that most of the information of interest is located within one of these. The algorithm calculates the number of levels to be quantified and identifies the digital values of each level. In the research of random samples of 8-bit Landsat TM and 10-bit Advanced Very High Resolution Radiometer (AVHRR) images, from a Canadian cover, the mean quantification error of the FHQ was 1.68 DN for the entire scene, and 1.41 for ground pixels. Based on the test of 34 mono-band images included in the comparison, the mean radiometric resolution decreased from 255 to 23.3 DN, which is equal to a reduction factor of 10.94 n for an image of n multispectral bands. The FHQ method was compared with other quantification methods, and this proved that FHQ holds considerably more radiometric discrimination than histogram normalization, lineal quantification or scaling methods.

Regarding the use of remote sensing in MSFs, due to excessive or redundant information within remote sensing data, the appropriate radiometric resolution for this type of studies must be determined, considering that it is a work of first-level territorial stratification in broad thematic classes; using 7/8-bit radiometric resolution may be sufficient to attain this objective, as sensors with a higher signal quantification degree would not, *a priori*, improve territorial stratification, but instead add more information and spectral noise.

E. Temporal resolution

The term “temporal resolution”, the simplest of those discussed, at least in terms of definition, has evolved as satellites following different types of orbits were launched, with sensor designs capable of varying the pointing angle (off-nadir) or lateral vision, especially perpendicularly to the satellite’s movement (across-track). Considering the platform alone, temporal resolution can be defined as the time interval elapsing between the acquisition of two consecutive images of the same place on the surface (Mather 2003); this is also known as the period or repetition cycle.

This interval of time may vary from minutes to days, depending on the characteristics of the satellite’s orbit. Satellites maintaining a stationary position relative to the Earth, usually located in the Equatorial plane, are called geostationary; these have the highest temporal resolution because they are constantly focused upon the same location on the surface. The fixed position with respect to the Earth is achieved matching the orbital periods of the Earth and the satellite, from which derives Kepler’s Third Law; for a mean radius of the Earth of 6,370 km, the altitude of the orbit is 35,785 km. This is the case with most meteorological satellites located in the equatorial belt at a distance of 36,000 km from the surface and occupying different positions depending on the observation zone involved, with temporal resolutions in the order of 15 min, which are currently insuperable due to technical limitations.

Most natural resource observation satellites move around the Earth following circular and polar orbits (from N to S), maintaining a specific duration of the repetition cycle.

The temporal resolution of polar orbit satellites is determined by the following parameters, which define the orbit: altitude, shape and orbital inclination.

The relationship between the orbital period and the orbit's radius is given by the following equation:

$$T = 2\pi r \sqrt{\frac{r}{g_s R^2}},$$

where g_s is the acceleration due to gravity ($0.00981 \text{ km}\cdot\text{s}^{-2}$), R is the Earth's radius (approximately 6,370 km), and h is the altitude of the orbit (being $r=R+h$). Therefore, varying the altitude of a circular orbit satellite, the time required to complete one orbit also changes; and for higher altitudes, there are higher orbital periods.

Circular orbits are usually not polar, but rather quasi-polar. The angle formed by the orbital plane and the Earth's equatorial plane is the orbital inclination, and is usually expressed by i . Changes in orbit are fundamentally due to precession, mostly caused by the non-spherical shape of the Earth originating a movement of the Earth's rotation axis that is similar to a spinning top. When the orbital precession is the same as the Earth's rotation around the Sun, the relationship between the node line and the Sun remains constant, and the satellite will pass a given point of the land surface at the same time as the local solar hour (Local Mean Sun Time – LMST) (NASA 2013).

This type of orbit is called Sun-synchronous and is followed by most satellites used in remote sensing of natural resources. In other words, the position of the Sun and the satellite will be approximately the same for each season of the year at a given latitude, which implies that light conditions for the purposes of image acquisition will be similar throughout a certain season over the years, or throughout a given area over several days. This fact is particularly important in multi-temporal studies, for change detection and image mosaicking.

Therefore, the type of orbit of a satellite determines the nature of the relationship between the satellite and the direction of solar illumination, and not only the time necessary to complete an orbit (one of the incidental factors in temporal resolution). Temporal resolution also depends upon the width of the swath, i.e. the longitude on the surface corresponding to a scanned line, which can vary (from tens to hundreds of kilometres). A satellite having a swath width greater than another will offer images of the same location on the surface with a higher frequency, although at the expense of spatial resolution. Besides, swath width determines the capacity of the sensor to capture, in one scene, the study area's entire extension without resorting to the acquisition of contiguous images and further mosaicking. Generally, it can be affirmed that at greater swath widths, there are higher temporal resolutions and lower spatial resolutions.

To date, it has been assumed that the instrument located in the satellite observes the surface in nadir form; however, in 1986 the launching of the French satellite SPOT

(*Système Probatoire d’Observation de la Terre*) incorporated the possibility of changing the lateral inclination of the HRV (*Haute Resolution Visible*) sensors by $\pm 27^\circ$ in a direction perpendicular to the satellite’s along-track. This offered two new characteristics: i) a reduction in the time necessary for image acquisition relating to the same area and ii) stereoscopic capacity, by enabling observation of the same zone from different positions, thus creating a parallax that allows stereo pairs to be obtained. The first characteristic – called the aiming capacity of the sensor, lateral and oblique vision capacity or incidence angle variation capacity – offers a temporal coverage with a higher frequency (less than 3 days in 45° latitudes) than nominal (26 days), offering the orbital pattern of the SPOT satellite and the swath width of the HRV sensor (Mather 2003; SPOT Image 2002). This characteristic may also be found in more modern sensors such as IKONOS (1999), with a $\pm 30^\circ$ aiming capacity, KOMPSAT (Korea Multi-Purpose Satellite) (1999) with a $\pm 45^\circ$ aiming capacity, or Quickbird-2 (2001) with a $\pm 30^\circ$ aiming capacity (ESA 2013).

With this new characteristic, the term “period or revisit cycle” is introduced; this is not to be confused with temporal resolution (period or repetition cycle) (Joseph 2000).

Images obtained with a natural repetition cycle retain the same acquisition geometry. The radiometric variations caused by the Bidirectional Reflectance Distribution Function (BRDF) are minimal and do not affect the data. This does not occur in images obtained by sensor orientation (off-nadir), and it can have greater significance if the spatial resolution is higher, or in applications related to the study of temporal series, such as the products derived from vegetation indices (Calle & Salvador 2012).

Another important factor improving temporal resolution for the same repetition cycle is due to the overlapping of adjacent trajectories (sidelap). This would be minimal at the Equator and maximum at the poles, which can lead to a coverage of the same zone in a lesser time than that nominally specified for a specific satellite/sensor system (Bindschadler 2003).

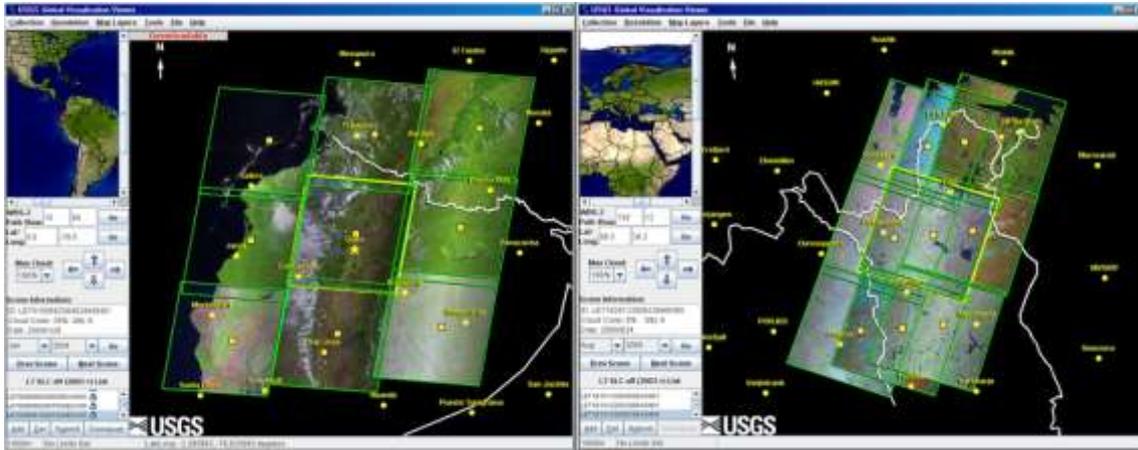
According to the Landsat 7 Science Data Users Handbook (NASA 2011), in the case of the ETM+ sensor on the Landsat7, in the standard Worldwide Reference System (WRS) used to define the orbital trajectories and scene centres, the standard scene WRS overlaps with adjacent scenes by 5% in the Equator and has a swath width of 185 km. The same document indicates the adjacent trajectory sidelap at different latitudes, from 0° to 80° in leaps of 10° , with extreme values going from 7.3% to 83.9%. Hence, Bindschadler (2003) proposes the following equation to calculate the distance between adjacent trajectories (C) in Landsat7:

$$C = (2\pi R_e \cos\theta)/233 ,$$

R_e being the Earth’s mean radius (6,370 km) and θ the latitude of the centre of the scene, enabling a percentage calculation of the overlap with the adjacent scenes. In

Figure A.4 below, there is an example of lateral overlap in Landsat 7 scenes at different latitudes, obtained from the USGS' GLOVIS visor.

Figure A.4 – Lateral overlap of Landsat7 scenes at 0° latitude (Equator) and 68° (Finland) (GLOVIS-USGS)



Because of lateral overlap, Joseph (Joseph 2000) proposes the indication, in addition to the repetition period, of the revisit period in 0° and 40° latitudes, as standard values to facilitate and compare this magnitude across different sensors.

Another characteristic related to temporal resolution is the possibility of gathering data from the same point on the surface from different satellites of the same constellation, which operate simultaneously in tandem missions; and obviously not from different satellites or sensors involving more elaborate image processing. Since the launch of Landsat1, the Earth's first natural resources observation satellite (which was in orbit from 23 July 1972 to 06 January 1978) and its successor Landsat2 (in orbit from 22 January 1975 to 27 July 1983), and thanks to the continuity of Earth observation missions, it is possible to speak of remote sensing systems constituted by satellites of the same constellation series (Landsat, Spot+Pleiades, ERS, TerraSAR-X, etc.) which function simultaneously and are equipped with very similar or identical sensors. This is due to the fact that the expected lifetime for most satellites is usually exceeded, in some cases greatly so, by technical design expectations. This is the case with Landsat5, which had a lifetime design of 3 years, but actually functioned for 28 years and 10 months (from 1 May 1984 to 21 December 2012), thus gaining the Guinness World Record for Longest Operating Earth Observation Satellite (NASA 2013). Revisit capacity due to the simultaneous operation of more than one satellite could occur on a daily basis, as is the case with SPOT6 and 7 (ESA 2013); this could take place without losing spatial resolution, unlike in the case of the MODIS sensor, which offers a maximum spatial resolution of 250 m with the same repetition period (one day).

Considering the characteristics mentioned above, temporal resolution can be defined more precisely and completely as the time elapsing between the acquisition of two images of the same area of the surface, by the same satellite/sensor, and with the same observation geometry that establishes swath width; taking into account the “revisit period” or “tandem missions” improves the overall concept.

As mentioned above, there is a close relationship between temporal resolution and spatial resolution, which is apparent in cases where vegetation monitoring and change detection take place. Borak, Lambin and Strahler’s research (2000) on change detection at low spatial resolutions indicates that low spatial resolution satellite sensors offer the advantage of obtaining frequent coverage of land surfaces, which facilitates the surface monitoring process; on the other hand, high spatial resolution satellite sensors provide reliable information of land covers at a local scale. They thus conclude that regional scale processes cannot be detectable at the local scale, and vice versa. At a more advanced level, Inglada, Hagolle and Dedieu (2011) propose using several image fusion techniques combining high spatial and low temporal resolution satellite data, from e.g. SPOT-HRV or Landsat-TM, with low spatial and high temporal resolution satellite data from e.g. SPOT-Végétation or ENVISAT/MERIS, to generate soil cover maps and temporal reflectance profiles on the surface, with a spatial resolution of 10-30 m and a temporal resolution of approximately 10 days.

In the context of vegetation monitoring, the great number of natural resources satellites in orbit offers an enormous variety of temporal and spatial resolutions, and, considering their relationships, a risk of low accuracy in describing the phenomena studied arises, due to the low temporal frequency; and sampling having high temporal frequency could increase project costs without adding additional benefits. Therefore, the selection of an adequate temporal resolution is important to ensure optimal monitoring of the phenomenon and cost-effectiveness (Cao & Lam 1997; Goodchild & Quattrochi 1997). On the other hand, vegetation monitoring models to elaborate fire prevention, agricultural compensation for yield losses, and national policy development plans based on field surveys are extremely expensive, or excessively biased, if based upon secondary data sources (Biggs *et al.* 2006; Droogers 2002).

In most vegetation monitoring studies, the temporal resolution selected depends upon the balance between cloud detection and vegetation dynamic change monitoring, considered on a global scale (Huele, Jusetice & Leuwen 1999). However, the local variability, the observation period, and the parameters monitored can influence this selection (Alexandridis, Gitas & Silleos 2008).

In conclusion, the research performed by Alexandridis *et al.* to evaluate the appropriate temporal resolution for monitoring vegetation from NDVI on a national scale in Greece – which is overall applicable to the Mediterranean basin, in the dry season and with the index used – proposed a 10-day period for the entire study area, for natural and cultivated vegetation, two of the major categories used in FAO LCCS (FAO 2000).

The optimal temporal resolution depends upon the type of vegetation; for cultivated vegetation, this is of 7 days, while for natural vegetation of 11 days. This variation is attributed to the slow phenological cycle of natural vegetation, crops' reliance upon agricultural practices, and the country's weather conditions (Alexandridis, Gitas & Silleos 2008).

An important aspect related to temporal resolution in the case of static studies, especially in remote sensing applied to vegetation, is the adequate selection of the image acquisition date or dates, or the time interval in which they should be acquired, normally known as the "window time". The impermeability of the cloud cover is an inherent characteristic of passive sensors, especially at certain latitudes, which often restricts image availability (De Barros Ferraz, Silva Almeida & Vettorazzi 2006). In studies involving vegetation cover estimation, this is even more significant, because of the limitations imposed by the phenological plant cycle and the agricultural techniques used. Therefore, the temporal resolution of optical sensors plays a key role in selecting the adequate sensor on the basis of the availability of optic images of the study area, which is more important in studies having national, continental or global scale.

Depending upon the dimensions of the study zone, vegetation monitoring on a national scale can be performed on the basis of satellite images having great coverage (swath width), such as NOAA-AVHRR, Terra/Aqua-MODIS o SPOT-VEGETATION; among these, the MODIS sensor will be emphasized, as it offers greater spatial and spectral resolution and is more sensitive to vegetation conditions, at the same temporal resolution as other systems (Huete, Didan *et al.* 2002; van Leeuwen, Huete & Laing 1999).

At certain latitudes, the date of image acquisition is critical since the maximum growth season of crops coincides with rainy seasons in several cases (Duvellier & Defourny 2010). The method proposed by Duvellier and Defourny, focused upon agricultural monitoring requirements regarding spatial resolution of the sensors, can be used to evaluate costs, in terms of the loss of accuracy in estimating cultivated areas or signal variability in sensors, when the images available are outside the optimal time window for agricultural studies.

In the research of Alexandridis *et al.* (2008), to evaluate the adequate spatial resolution for national-scale vegetation studies in Greece, temporal series are elaborated from MODIS products; the authors mention the frequent and irregular presence of clouds in passive sensor images as the major problem creating these series, where big clouds may mask vegetated zones while smaller ones distort the registered reflectance of vegetation.

Therefore, regarding temporal resolution, because of the different climatic conditions of the Earth, the selection of the most adequate satellite/sensor systems for remote sensing in MSFs will inevitably be linked to the climatic conditions of the area study that condition image availability. In general, a minimum temporal resolution of 15 days can

be sufficient to serve the requirements imposed by the most adequate phenological cycles of crops, in the case of temperate climates; the most suitable date is also very much related to the phenological cycle of the most important crop in the study area, due to its economic importance or superficial extension. In areas with persistent cloud coverage, it will be necessary to consider using radar sensors or fusion with optical data (FAO *et al.* 2009).

F. Other considerations

Remote sensing is a valuable tool to monitor agricultural resources. However, the spatial patterns of the Earth's agricultural landscapes vary significantly; thus, depending upon which area of the globe is studied, different image requirements will apply (Duveiller & Defourny 2010).

The most adequate satellite/system selection to investigate MSFs depends upon the many factors that have described in this Section, in which it was sought to relate them with the characteristics or resolutions defining the type of image that they can offer.

General studies (Calle & Salvador 2012) indicate that the main factors in comparing quality and justifying image acquisition costs are those relating to spatial, radiometric, and spectral characteristics, and that the temporal resolution is established by the orbital terms and conditioned by the user's availability. However, in our case, since most sensors offer sufficient radiometric and spectral resolutions for global studies, such as those mentioned in this Report, we consider the spatial and temporal resolution to be the priority.

Regarding spatial resolution, Larson and Wertz (1999) propose the Relative Quality Index (RQI) to compare high spatial resolution optical sensors having similar performance. The RQI is based upon the following three characteristics: i) SNR at a spatial frequency of zero (high SNR values correspond to elevated quantities of information); ii) MTF of the instrument to the Nyquist frequency (high MTF values correspond to elevated quantities of information for sampling frequencies between zero and the Nyquist frequency); and iii) GSD (low GSD values correspond to high quantities of information), according to the expression

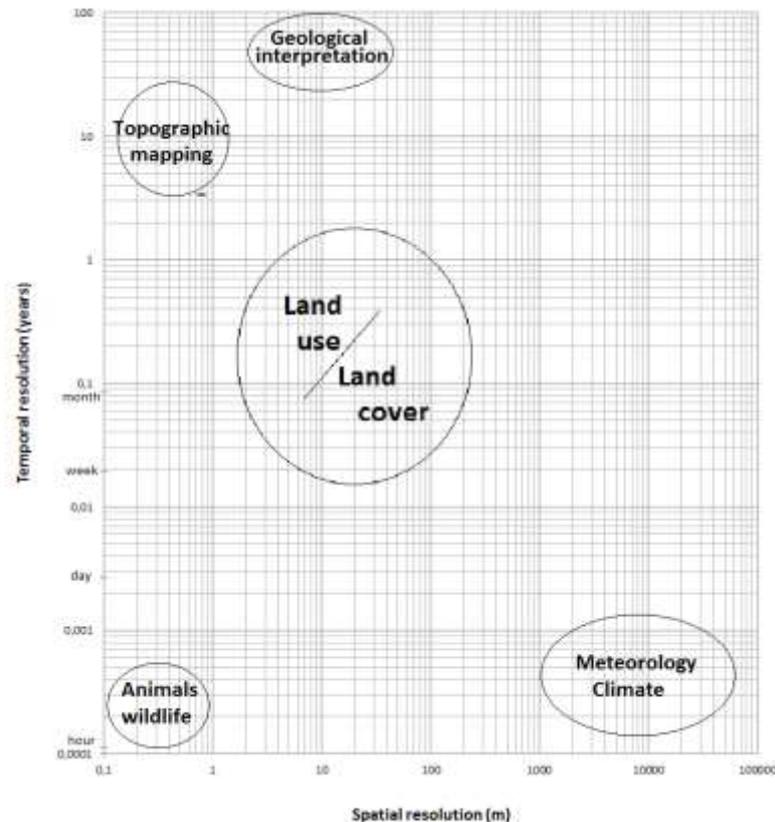
$$RQI = \frac{SNR}{SNR_{ref}} \cdot \frac{MTF}{MTF_{ref}} \cdot \frac{GSD}{GSD_{ref}}$$

where the subscript *ref* refers to the reference instrument.

On the other hand, Allan (1984) provides an interesting review of the relation between spatial and temporal resolution considering user requirements, presenting a graph that relates both concepts depending upon the type of application. The diagram in Figure A.5 on the following page shows that the different applications are very far apart in terms of needs. The requirements of spatial resolution for land use and crop monitoring

may be satisfied with sensors from 10 m to 50 m; for Level 1 land use, i.e. to identify the seven or eight most important categories of land use (Anderson *et al.* 1976), sensors in the order of 100 m spatial resolution should be used. Regarding vegetation monitoring, which is normally present in nature in a continuous form, low spatial resolution (1 km) and low-cost remote sensing systems can be used.

Figure A.5 – Remote sensing applications, in relation to spatial and temporal resolution



To elaborate a crop information system in Romania (FAO 1999), Landsat and SPOT scenes were employed for the territorial stratification of the entire Romanian territory. This was done to obtain homogenous areas from the point of view of land use, and NOAA satellite images acquired daily during the growing season were used in two ways: i) as a general plan for agrometeorological forecasts, to consolidate data on a national scale; and ii) as a monitoring and warning system that assists the detection and analysis of areas displaying an atypical behaviour pattern.

Furthermore, Project TCP/BUL/8922 “Pilot study in Bulgaria: preparation of land cover maps and associated database” (FAO 2002) used Landsat scenes to build thematic maps at a scale of 1:50,000 for cover classification according to the LCCS (FAO 2000); it uses IKONOS *pansharp* of 1 m spatial resolution (allowing cartography elaboration at a scale of 1:5,000), in specific interest areas, to: i) update existing large-scale soil and topographic maps (drainage system, road networks, etc.); ii) update large-scale land cover/land use inventories and monitoring of permanent crops such as vineyards and orchards.

The cases mentioned above have used three different satellites to address the research upon crops and land covers, revealing there is no one single system that is capable of fulfilling all user needs, but also that one system is capable of solving several problems. Nonetheless, the RSS will contribute to enhancing national capacity in mapping, monitoring, reporting and inventory techniques. In certain countries, this may form the basis for the preparation of a national monitoring system and testing of additional variables (FAO 2007); the only apparent disadvantage of the improved RSS may be an increased cost.

As for the costs of images and their characteristics relevant to studies using remote sensing data, it is necessary to establish the level of application, which usually depends upon spatial resolution (FAO 1998). Comparing the field sampling system, Tomppo and Czaplewski's research (2002) on estimating the potential of remote sensing for elaborating a worldwide forest inventory considering only high-resolution spatial data, such as Landsat satellite images – the most widely used high-resolution images – about 400 to 450 images are needed to perform a 10 percent sampling of the entire globe. The estimated cost would amount to approximately USD 255,000, while a survey based purely on field measurements, instead, could cost from USD 10 million to approximately USD100 million. Therefore, it is very important to take into account the availability of free images from the Landsat program, available since October 2008 (NASA 2008), or from the future satellite SENTINEL2 of the COPERNICUS program (ESA 2013).

The selection of a satellite/sensor system is not a simple task; no quantitative limits can – or must – be established, nor does it have a single solution, and it is necessary to consider at least the following factors that are related to the remote sensing system mentioned in this Section:

- Climate – As related to the remote sensing system used and the availability of optical images and the development of the vegetation.
- Work scale – Extension of the territory analysed, relating to the image coverage and spatial resolution.
- Acquisition costs – As related to the work scale and the availability of free images, provided for low or no cost by national Earth observation programs, or acquired commercially.
- Processing costs – As related to the technological and formative elements available for the study.
- Cost/benefit relationship – This depends upon the objectives and resources used.

- Scope of application – As related to the level of detail of the proposed thematic legend, land use and/or land cover.
- Comparison of results – This is related to data homogeneity and the methodologies employed.
- Accuracy of results – This concerns the scale of work and the scope of application.
- Action stability – Duration of the activity over time, diffusion and integration of results.

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