Geographic information systems and remote sensing for plant germplasm collectors

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Introduction to GIS

A geographic information system (GIS) is a 'computerized information storage, processing and retrieval system that has hardware and software specifically designed to cope with geographically referenced spatial data and the corresponding attribute information' (FAO, 1988). In other words, a GIS is a database management system dedicated to the simultaneous handling of spatial data in graphics form and of related, logically attached, non-spatial data. For example, if the spatial data are the location of cities or districts in a country, the associated attributes could be the name, current population, past population and population growth rate of each. If any modification is made in one kind of data, an appropriate modification is automatically made in the other.

GIS technology has obvious applications in such fields as urban planning and natural resources management, but until fairly recently relatively expensive mainframes or minicomputers were necessary to run the software. Since the 1980s and the advent of the 80386 microchip, however, both hardware and software have become more cost-effective and easily available, increasing the potential of GIS as a problem-solving tool. Many national and regional institutions in developing countries have set up GIS facilities and are building up spatial databases relevant to their mandates. Such multilateral agencies as the Food and Agriculture Organization (FAO), the United Nations Environment Programme (UNEP)'s Global Resources Information Database (GRID), the United Nations Training and Research Institute (UNITAR) and the United Nations Sudano-Sahelian Office (UNSO), as well as bilateral donors, have supported these efforts through the provision of hardware, software, data and training. The planned national database of China is an instructive example, as it has been conceived specifically as a tool to aid biodiversity conservation. As proposed by the World Wide Fund for Nature (WWF), there will be seven regional databases, one in each of the biogeographic divisions of the country, plus a central repository in Beijing, at the Commission for Integrated Survey. Information on species richness, endemism, habitat threat, protected areas, watersheds, human pressure and the physical environment will be mapped and combined to derive maps of 'gene-pool sensitivity' and 'environmental sensitivity' for each of the provinces and autonomous regions of the country (McNeely *et al.*, 1990).

Some examples of GIS software packages are listed in Box 16.1. GRID (1992) gives the results of a survey of the characteristics and capabilities of a wide range of GIS software and hardware packages, and also lists other sources of such technical information. The main components of GIS software are (Burrough, 1986):

- data input, verification and editing;
- data storage and database management;
- data manipulation and analysis;
- data output;
- user interface.

These fit together as shown in Fig. 16.1.

Data input and data sources

'Data input is the procedure of encoding data into a computer-readable form and writing the data to the GIS database' (Aronoff, 1989). It includes the linking of the spatial and attribute data and the verification of data quality standards. Data entry is the major constraint on GIS implementation, as it is usually labour-intensive, time-consuming and

Box 16.1
Commonly available GIS software

Name	*Publisher*
Atlas*GIS	Strategic Mapping
GisPlus	Caliper
MapInfo for Windows	MapInfo Corps
PC ARC/INFO	Environmental Systems Research Institute
SPANS	Tac Systems
MARS	Montage Information Systems
IDRISI	Clark University
GRASS	Public domain
ERDAS	ERDAS Inc.
Hyperdyne's Mapix	Montage Information Systems

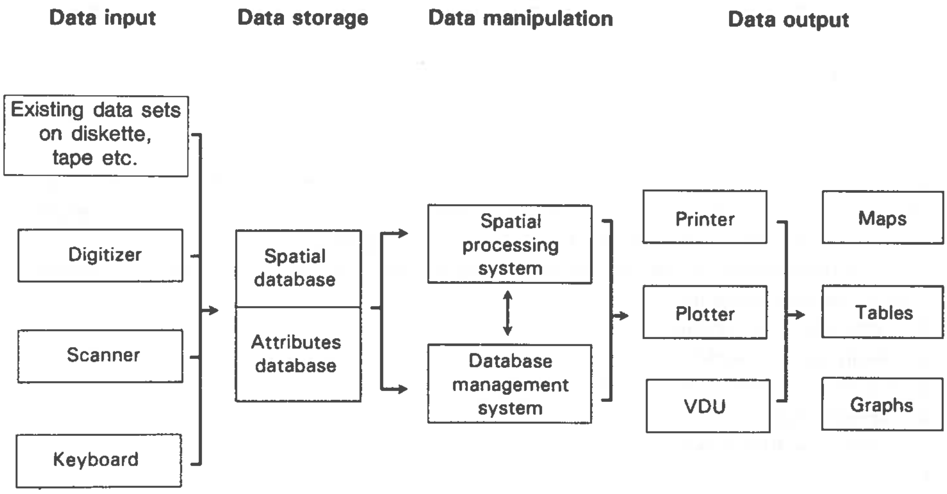

Fig. 16.1. The components of a GIS and their relationship to each other.

thus expensive. There are four ways of entering data into a GIS (e.g. Burrough, 1986):

- Attribute data are usually entered from a computer *keyboard*. This can be done as part of the same operation during which the geographic data are entered (e.g. during digitizing of maps) or as a separate operation. Thus, collectors could enter passport and other data into a separate database and import this into a GIS at a later date.
- In *digitizing*, the most common method of entering geographic data, a map is mounted on a digitizing table or tablet and the features to be entered are traced using a cursor or pointer. The coordinate data produced are either fed directly into the GIS or stored in a computer file for later use.
- *Scanning*, a kind of automated digitizing, involves generating a digital image of the map by moving an electronic sensor over its surface.
- *Remotely sensed* data (i.e. data recorded at a distance from the object of interest) can come from aerial photographs, electro-optical scanners or microwave receptors (see Table 16.1 for a summary of the more widely used systems).

For any given application, the logical first step is to ascertain whether suitable digital data sets already exist. Various data sets are held by organizations such as FAO, UNEP/GRID, the International Soil Reference and Information Centre (ISRIC), the World Conservation Monitoring Centre (WCMC) and the international agricultural research centres (IARCs), though these are mostly (though not

Box 16.2
Some FAO digital databases

Africa

1. Integrated terrain units (FAO soils, US Department of Agriculture (USDA) soils, United Nations Educational, Scientific and Cultural Organization (Unesco) geology, physiography, geomorphology, landform, surface forms, potential vegetation, land use).
2. Desertification study (soil hazard, wind hazard, water hazard, salinity hazard, population pressure, animal pressure).
3. Template (boundaries, etc.).
4. Mean annual rainfall.
5. Number of wet days per year.
6. Agroecological zones.
7. Countries and provinces.
8. Rivers.
9. Watersheds.
10. Roads.
11. Cities.
12. Ecofloristic zones.
13. Vegetation (actual).
14. Irrigation and water potential study (potential irrigable soils, aquifer rank, water availability).

Other developing countries

1. Desertification study (soil texture, slope, pedogenic factors).
2. FAO soil map.
3. Agroecological zones.
4. Countries.
5. Template.
6. Vegetation (S and SE Asia).
7. Ecofloristic zones (S and SE Asia).

exclusively) at a regional or global scale (scales 1:1 million down to 1:100 million). As an example, some of the digitized data sets held at FAO and at GRID that could be of interest to collectors are listed in Boxes 16.2 and 16.3. The WCMC databases are introduced in Chapter 10. There are also relevant regional sources of data sets, such as the Regional Centre for Services in Surveying, Mapping and Remote Sensing in Nairobi, the Regional Remote Sensing Programme in Bangkok and the Regional Remote Sensing Centre in Burkina Faso. Local-level data sets (up to scales of about 1:20,000) may be available from such centres and from national agriculture, environment, planning and cartography services, as well as from private companies. Conditions of availability will vary.

GRID's Meta-Database is an interactive electronic catalogue of spatial environmental data sets archived at GRID centres throughout

Box 16.3
Some GRID digital data sets

Global

1. Political and natural boundaries.
2. Elevation.
3. Soils and soil degradation.
4. Vegetation.
5. Human population.
6. Cultivation intensity.
7. Ecosystems.
8. Life zones.
9. Wetlands.
10. Temperature and moisture availability surfaces.

Africa

1. Political and natural boundaries.
2. Elevation.
3. Slope and aspect.
4. Soils.
5. Soil degradation and desertification.
6. Human population.
7. Roads and railways.
8. Hydrology and watersheds.
9. Protected areas.
10. Cattle and buffalo distribution.
11. Ecoclimatic suitability indices.
12. Vegetation and land cover.
13. Cultivation intensity.
14. Ecosystems.
15. Temperature.
16. Rainfall.
17. Evaporation.

National data sets are also available for a number of countries in Africa, Latin America and Asia. However, prior approval from the respective country is needed, prior to distribution.

the world. It is planned that it will in future also hold details of data (both electronic and otherwise) held in other institutions. The National Aeronautics and Space Administration (NASA) Master Directory provides a similar service, and GRID also has access to this. The GRID Meta-Database may be consulted at GRID centres and via the Internet, but there is also a personal computer (PC) version. Dangermond (1988) provides a review of the practical problems involved in entering existing data sets into a GIS.

The most common data requirement will be for base-layer data sets, showing country boundaries, internal administrative boundaries, rivers and lakes, altitude (contour and spot heights) and so on. The most commonly used medium-resolution data set of this type has been *World Data Bank II*, but the *Digital Chart of the World* (DCW), based on the 1 : 1 million Operational Navigational Charts and recently released on four CD-ROMs, is of potentially greater use. However, the extraction of data subsets can be difficult and data quality is variable (Anon., 1992). The EROS Data Center is using the DCW to develop a global digital terrain model (a quantitative model of landform in digital form) on a 1 km grid basis. The Centre for Resource and Environmental Studies (CRES) at the Australian National University has or is developing high-resolution digital terrain models and climate surfaces for Africa, Australia, New Guinea, China and southeast Asia (H.A. Nix, pers. comm.). On soils, FAO's revised 1 : 5 million *Soil Map of the World* is the best available strategic-level digital data set. ISRIC is developing a worldwide digital database for soils and terrain on a scale of 1 : 1 million, but the time frame for this work is 10–20 years. 'Skeleton' continental coverages are being prepared.

As for satellite data, GRID can give advice on how to obtain data sets from commercial and other sources, though it cannot procure these for users. FAO's Remote Sensing Centre has a comprehensive database of reference maps and imagery which is available to member nations and FAO programmes. Resolution varies from kilometres to tens of metres, depending on the system (Table 16.1). The cost of obtaining these data sets can be very high. Also, analysis (which will involve image restoration or correction, image enhancement and information extraction) is complex, requiring specialized software, hardware and skills. Careful ground truthing is necessary for many applications. However, for inaccessible areas for which there are no detailed maps, for example, remote sensing may be the only source of some data. It is also often the only source of data on changes in vegetation and land use, whether from year to year or from week to week in a given growing season. If the raw remote sensing data itself are beyond the reach of the collector, for either financial or logistical reasons, publications may be available analysing such data and presenting the results in maps and other potentially useful hard-copy forms. Hilwig (1987) lists numerous published examples of the application of remote sensing to agroecological characterization, classification and mapping (refer to the list of specialized journals at the end of this chapter).

Data storage

There are two main types of GIS software, which differ in how they store data. Vector-based systems store geographic data as points. Series of connected points make up lines, and lines enclosing an area make up polygons. In contrast, raster-based systems store data as grid cells, each

Table 16.1. Summary of characteristics of five satellite-based remote sensing systems, compared with aerial photography (adapted from Hilwig, 1987). Note that the smallest mappable area on a map (3 × 3 mm) corresponds to 900 ha at a scale of 1 : 1 million and 2.25 ha at a scale of 1 : 50,000.

System	Scale range	Spatial resolution	Temporal resolution	Property detected
Aerial photography	1 : 70,000–1 : 120,000	1–7 m	10–20 years	Reflectance of visible and infrared solar radiation
Landsat TM (Thematic Mapper)	1 : 100,000–1 : 1 million	30 m	16 days	Reflectance of visible, photographic infrared and thermal radiation
Landsat MSS (Multi-Spectral Scanner)	1 : 250,000–1 : 1 million	80 m	18 days	Reflectance of visible, photographic infrared
SPOT HRV (High Resolution Visible) panchromatic and MSS	1 : 50,000–1 : 1 million	10–20 m	26 days	Reflectance of visible, photographic infrared
NOAA AVHRR (Advanced Very High Resolution Radiometer)	1 : 3.5 million–1 : 10 million	1 or 4 km	12 hours	Reflectance of visible, photographic infrared and thermal radiation
Meteosat	Not applicable	2.4–5.0 km	30 min	Reflectance of visible, photographic infrared and thermal radiation

representing a memory location in the computer. Lines are rows of grid cells and polygons are groups of adjacent grid cells. Remote-sensing data are in raster form, each picture element (pixel) being a grid cell. Vector systems require more computing power but less storage memory than raster systems. They represent map data better, because lines on the map remain lines, rather than becoming rows of grid cells.

It is possible to convert vector files to raster files, but incorporating raster data into a vector system is not usually as efficient. Vector systems will be best for some applications, raster systems for others. Burrough (1986) recommends the use of vector data structures for archiving phenomenologically structured data (e.g. topographic units, soil types) and for the highest-quality output, and raster methods for the rapid overlay and combination of maps and for spatial analysis.

Data manipulation

The spatial processing system and database management system of a GIS allow one to bring together diverse data sets, make them compatible among themselves, analyse and combine them in different ways and display the results as a map or statistics on a computer screen or hard copy. Some standard GIS capabilities include (Burrough, 1991):

- *Geometric correction.* The scale, projection, etc. of different maps may be changed to make them comparable.
- *Digital terrain model analysis.* The altitude contours on a topographical map may be used to produce maps of slope, aspect, intervisibility, shaded relief, etc.
- *Interpolation.* Point data may be used to create isopleth (equal-value contour) maps.
- *Overlay analysis* (Fig. 16.2). Different maps of the same area may be combined to produce a new map, e.g. maps of slope, soil, wind speed and vegetation cover may be overlaid to synthesize a map of potential soil erosion.
- *Proximity analysis.* Buffers may be generated around features.
- *Computation of statistics.* Means, counts, lengths and areas may be calculated for different features.
- *Location.* Entities having defined sets of attributes may be located.

How can such features be of use to the germplasm collector? There are clearly applications beyond simplifying the production of high-quality maps of sample distributions and the like. All of the analyses

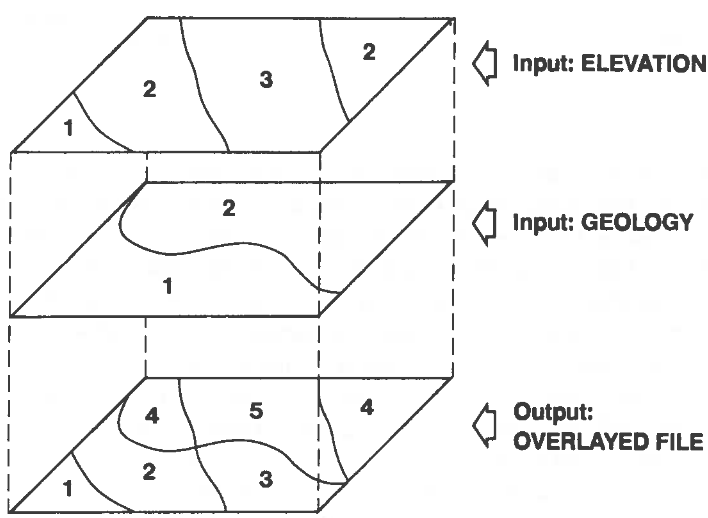

Fig. 16.2. Schematic representation of the GIS overlay facility.

described in Chapter 15, in fact, will be facilitated by the use of GIS. Some particular applications are summarized below under the separate headings of mission planning and the documentation of collections.

Planning

A GIS can delimit areas where particular conditions or combinations of conditions are found

This will be important when material with particular characteristics is being targeted for collecting. Thus, for example, areas can be identified where the occurrence of a particular soil type is combined with that of a particular rainfall regime. The raw rainfall data from meteorological stations would be transformed by the GIS itself into isohyets as part of this analysis. Data on the distribution of different states of a characterization descriptor could be superimposed on the initial output to investigate possible associations.

A GIS can combine data sets to generate derived data sets of predictive or enhanced descriptive value

This is not simply identifying the co-occurrence of conditions, but actually combining different kinds of data in some sort of mathematical model. Thus, data on human population, accessibility (road networks, etc.), economic development, potential for irrigation and agroclimatic suitability for cash crops or modern varieties could be used to develop a model for the risk of genetic erosion among landraces. Potential for irrigation and agroclimatic suitability are themselves predictive models that will be of interest to the collector. In particular, agroclimatic or agroecological classification of the target region into areas which are environmentally homogeneous and different from each other can be an efficient way of organizing a stratified collecting strategy. Data for different characterization descriptors can also be combined using a multivariate statistical procedure, for example to derive maps of principal component scores or systematic function scores.

A GIS can calculate climatic 'envelopes' for species, landraces or genotypes

In conjunction with digital terrain models and the climatic surfaces that can be derived from these, species distribution data can be used to calculate ranges for different climatic parameters, defining the adaptation of the taxa under consideration. Though still at the research stage, the BIOCLIM program of Nix, Busby and Hutchinson (Busby, 1986), for example, uses climatic interpolation surfaces to estimate conditions at each of a set of sites given latitude, longitude and altitude; it then derives a climatic envelope for the set of localities. Once the ranges of up to six important rainfall and temperature variables represented by the input sites have been calculated, programs such as AFRMAP (Booth *et al.*, 1989) and WORLD (Booth, 1990) can be used to display all the regions (if interpolation surfaces are available) or localities (if only point data are available) where such conditions obtain. This is not only useful in species introduction (i.e. the identification of homoclimes), the application for which the programs were initially developed, but also, for example, in identifying areas where the taxon has perhaps not been collected but where it might still be expected to be found on the basis of climate.

Remote sensing can be used to locate areas of interest

Different vegetation types can often be recognized in aerial photographs and satellite imagery. Isolated areas of cultivation can also be identified, and in some cases the types of crops grown recognized.

Satellite imagery can provide data on vegetation development with very short lag times

Use of such data would allow collectors to be very precise in timing their visit to areas showing vegetation flushes. This is particularly important in the arid and semiarid tropics, where rainfall is unpredictable in both space and time. For example, Meteosat and NOAA Advanced Very High Resolution Radiometer (AVHRR) data on rainfall and the state of vegetation (as measured by the Normalized Difference Vegetation Index, or NDVI) are analysed by FAO's Agricultural Real Time Environmental Monitoring Information System (ARTEMIS) to allow up-to-the-minute surveillance of the state of crops and vegetation in Africa and Asia. The information is available not only at FAO headquarters in Rome but, via Intelsat and the Data and Information Available Now in Africa (DIANA) system developed in collaboration with the European Space Agency (ESA), also in three regional centres in Africa (the Regional Centre for Services in Surveying, Mapping and Remote Sensing in Nairobi, the National Meteorological Service in Harare and Centre AGRYHMET in Niamey). See, for example, Justice *et al.* (1987) for descriptions of the annual course of NDVI in a variety of East African vegetation types, and how this measure relates to the phenology of rainfall and plant growth (see also Justice *et al.*, 1985; Davenport and Nicholson, 1993). One could conceivably read off latitudes and longitudes for a set of potential target collecting sites from satellite imagery and use a Global Positioning System (GPS) receiver to locate them in the field a matter of days later.

Satellite imagery and other remote-sensing systems can provide information on long-term vegetation change in an area

Actual trends and developments in deforestation and desertification can be monitored using remote-sensing data stretching back over many years. Examples include the work described by Skole and Tucker (1993) for the Amazon and Gastellu-Etchegorry *et al.* (1993) for Sumatra. This will help identify areas threatened with, or actually experiencing, habitat modification, and therefore perhaps genetic erosion.

Documentation

Fuller and more accurate passport data can be obtained

Using GIS, the collector would be able to record latitude, longitude, altitude, soil type, vegetation and other attributes for collecting sites automatically by overlaying their locations on different digitized base maps. The capability to generate isopleth maps, and in particular digital terrain models, allows the values of particular attributes (e.g. climatic factors) at collecting sites to be accurately estimated on the basis of data collected at other points, in this case nearby meteorological stations.

A GIS can assist in data verification

For example, a GIS can spot outliers due to miskeying of latitude, longitude or other attribute data.

A GIS can produce listings of samples satisfying different criteria

All collecting sites with particular attributes (of the environment and/or germplasm) or combinations of attributes can be picked out. For example, a map of collecting site distribution may be overlaid on soil and rainfall maps to identify those collecting sites where the material collected might be expected to be adapted to particular combinations of edaphic and climatic conditions.

Data output

The ability to produce high-quality hard copies of the results of analyses is an important feature of GIS software and hardware. The software usually allows such manipulations as selecting particular areas or layers of a map for output, scale change, colour change, etc. (Burrough, 1986). As for the hardware, there are various possible options. A 35-mm camera attachment allows photographs to be taken of the visual display unit (VDU) screen, for example. Black-and-white maps can be prepared by dot matrix printers, which are cheap but relatively low-quality. Colour plots can be generated by ink-jet printers and pen plotters. Laser printers produce the highest-quality output, but are expensive. The results of numerical analyses can usually be output as histograms and tables and can also be exported to other software for further analysis.

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Productivity in Africa Through the Use of Intelligent Geographic Information Systems' (Nairobi, Kenya, 14–18 January 1991). Tom Hazekamp and Mark Perry (IPGRI) made valuable comments on an early draft.

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Further reading

Articles on GIS and remote sensing commonly appear in the following publications (FAO, 1988):

Cartographica
GIS World
IEEE Transactions of Geoscience and Remote Sensing
International Journal of Remote Sensing
International Journal of Geographical Information Systems
Photogrammetric Engineering and Remote Sensing
Proceedings of the IGU International Symposium on Spatial Data Handling
Proceedings of AUTO-CARTO
Remote Sensing of Environment

There are GIS news groups on Usenet (e.g. comp.infosystems.gis) and also various relevant list server mailing lists (e.g. acdgis-1@awiimc12.imc.univie.ac.at). For a full list, see 'A Biologists's Guide to Internet Resources' by Dr Una Smith, Department of Biology, Yale University, New Haven, CT, USA (smith-una@yale.edu).

Useful addresses

FAO
Remote Sensing Centre
FAO
Via delle Terme di Caracalla
00100 Rome
Italy
Tel: +39 6 57975583
Fax: +39 6 57973152, 57975155 or 5782610
Telex: 625852 FAO I

GRID
There are a number of GRID centres spread throughout the world. Though each has particular regional responsibilities, data and information can be obtained from any centre. No charges apply, but users are requested to supply media. In addition to the centres listed below, there are plans for further centres in Russia (boreal forests), Fiji (South Pacific environmental data), Brazil (Amazonian data sets) and Canada (freshwater data). In the list below, both Dialcom and Internet electronic mail addresses are provided, in that order.

Africa, South-West Asia, Latin America and the Caribbean
GRID-Nairobi
UNEP
Box 30552
Nairobi
Kenya
Tel: +254 2 230800 ext. 4187
Fax: +254 2 226491
E-mail: 141:UNE008; hcroze@nasamail.nasa.gov

Asia and the Pacific
GRID-Bangkok
GPO Box 2754
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Tel: +66 2 5162124
Fax: +66 2 5162125
E-mail: 141:UNE096

Global and Europe
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Poland
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Fax: +48 22 270328