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# Local, national, and global applications of GIS in agriculture

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GIS has a significant role to play in agriculture at several scales from local to global. The development of several new digital databases at regional and larger scales, the advent of new continuous data collection and remote sensing techniques at the farm scale, and the continued migration of GIS to more and more powerful desktop computers have caused an explosive growth in the number and variety of agricultural applications during the past few years. The most important applications are probably those connected with precision or site-specific farming, which aims to direct the application of seed, fertiliser, pesticide, and water within fields in ways that optimise farm returns and minimise chemical inputs and environmental hazards.

## 1 INTRODUCTION

Agriculture is an inherently geographical practice and it is not surprising that this, together with the extremely large sums of money involved make it a natural application for GIS. Many site-specific farming systems utilise GIS and several related technologies (global positioning system, receivers, continuous yield sensors, remote sensing instruments) to collect spatially referenced data, perform spatial analysis and decision-making, and apply variable rate treatment (Usery et al 1995). Barnsley (Chapter 32) and Lange and Gilbert (Chapter 33) provide reviews of global positioning systems (GPS) and remote sensing technologies. These advanced technologies offer numerous advantages at scales ranging from the farm field to the entire globe because they can be used to: generate and synthesise new information cheaply and quickly; document data sources and methods of integration; provide diagnostics for error detection and accuracy assessments; provide input data for a variety of crop yield and non-point source pollution models; and prepare maps and tables that meet specific needs. However, these advantages are currently limited by: our lack of knowledge of statistical methods for summarising spatial patterns; the difficulty of moving geographical data and model results between different scales and resolutions; and the cost and difficulty of field validation. Finding ways to advance our knowledge in these areas is vital because the continued development of new GIS and related technologies will only improve food and fibre production systems to the extent that we can utilise this information to build sustainable agricultural production systems which match land use with land capability.

## 2 GLOBAL AND CONTINENTAL ASSESSMENTS

Several projects have been initiated during the past decade to build spatially distributed databases that cover continents and even, in some instances, the entire globe. Few, if any, attempts have been made to implement them as part of global- or continental-scale agricultural assessments, although the potential applications of these data include their deployment in GIS and spatial decision support systems to improve food production systems, manage pests and diseases, minimise soil erosion, preserve biodiversity, and simulate the effects of climate change. The following account describes: two recent GIS-based climate and land cover database projects; the current status of global-scale topographic, climatic, soil, and land cover databases; and how this information might be combined with a series of models in continental- and global-scale assessments of erosion potential.

Hutchinson and Gallant (Chapter 9) and Hutchinson et al (1996) describe the development and distribution of a gridded topographic and mean monthly climatic database for the African continent. The digital elevation model (DEM) was constructed by applying the ANUDEM (Hutchinson 1989) elevation gridding procedure to spot heights, selected points on elevation contours, selected streamlines, and the coastlines of the continent and significant offshore islands obtained from 39 1:1 million scale air navigation maps. The ANUDEM program uses an efficient iterative finite difference procedure to interpolate a regular grid of elevations from point and contour elevation data and streamlines. A drainage enforcement algorithm was applied to the fitted DEM, and the natural discretisation error associated with the incorporation of elevation data onto a regular grid was smoothed based on the slope of the DEM and the grid spacing (Hutchinson 1996). The final Africa DEM shown in Plates 58 and 59 has a spatial resolution of 0.05° of longitude and latitude (approximately 5 km), and was validated by deriving the major streamlines from the DEM and checking them against the known streamline network for Africa. This new African DEM is a modest improvement over the ETOPO5 DEM (see *http://edcwww.cr.usgs.gov/glis/hyper/guide/etopo5* for further information) that has been prepared at a spatial resolution of 0.083° of latitude and longitude for the globe.

Hutchinson et al (1996) have also prepared monthly mean precipitation and temperature grids by applying fitted thin plate spline surfaces to the Africa DEM. The procedures in ANUSPLIN (Hutchinson 1991, 1995a) were used to fit trivariate thin plate spline functions based on longitude and latitude in degrees and elevation in kilometres to climate station data. Mean monthly values of rainfall, daily minimum temperature, and daily maximum temperature were collected from a variety of sources for about 6050 precipitation and 1500 temperature stations for the period 1920–80. The continent was divided into a series of tiles before applying the surface fitting programs which determine the optimal trade-off between goodness of fit and surface smoothing by minimising the generalised cross validation. The monthly temperature datasets were weighted uniformly and the monthly precipitation datasets were weighted using an approximate local error variance estimate. The output included various summary statistics and diagnostics that facilitated error detection and interpretation of the final products. The final surfaces interpolated monthly mean temperature to within standard errors of about 0.5°C and monthly mean precipitation to within errors of 10–30 per cent (Hutchinson et al 1996). Plots of the July mean daily maximum temperature and mean precipitation for the entire continent are shown in Plates 60 and 61.

Similar products have been prepared for other regions as well. Daly and his co-workers have generated a series of monthly mean precipitation grids for the USA using the PRISM model (Daly et al 1994; Daly and Taylor 1996), and Running and Thornton (1996) prepared daily estimates of precipitation and temperature for the state of Montana, USA in 1990 using the MTCLIM-3D model. Stillman (1996) compared ANUSPLIN, MTCLIM-3D, and PRISM model performance and found that the models produced statistically similar monthly mean precipitation estimates for a 60 000 $km^2$ study area covering parts of the US states of Idaho, Montana, and Wyoming during the period 1961–90. These computer-generated products represent a major advance over their hand-drawn predecessors in that: they cost less and can be produced more quickly; they are repeatable; and they can be used with the visualisation tools commonly found in GIS and remote sensing software to develop customised map and tabular summaries (Custer et al 1996; Daly and Taylor 1996).

The development of new digital soil databases has not progressed as quickly as the development of DEMs, and the two approaches that currently provide global coverage are digital versions of paper maps. The first utilises soil pedon information coded by ecoregion, and the second combines soil pedon information with soil maps using one or more soil classification (taxonomy) systems.

In the first case maps depicting Holdridge life zones (Holdridge 1947) or ecosystem complexes (Olson et al 1985) can be combined with the global soil pedon database of Zinke et al (1984) to illustrate the first approach (Kern 1994; Post et al 1982). This particular soil pedon database designates 3256 Holdridge and 3700 Olson codes for 4118 pedons. Unfortunately, no soil classification information is included in the database and the majority of soil samples are derived from North America and central Eurasia.

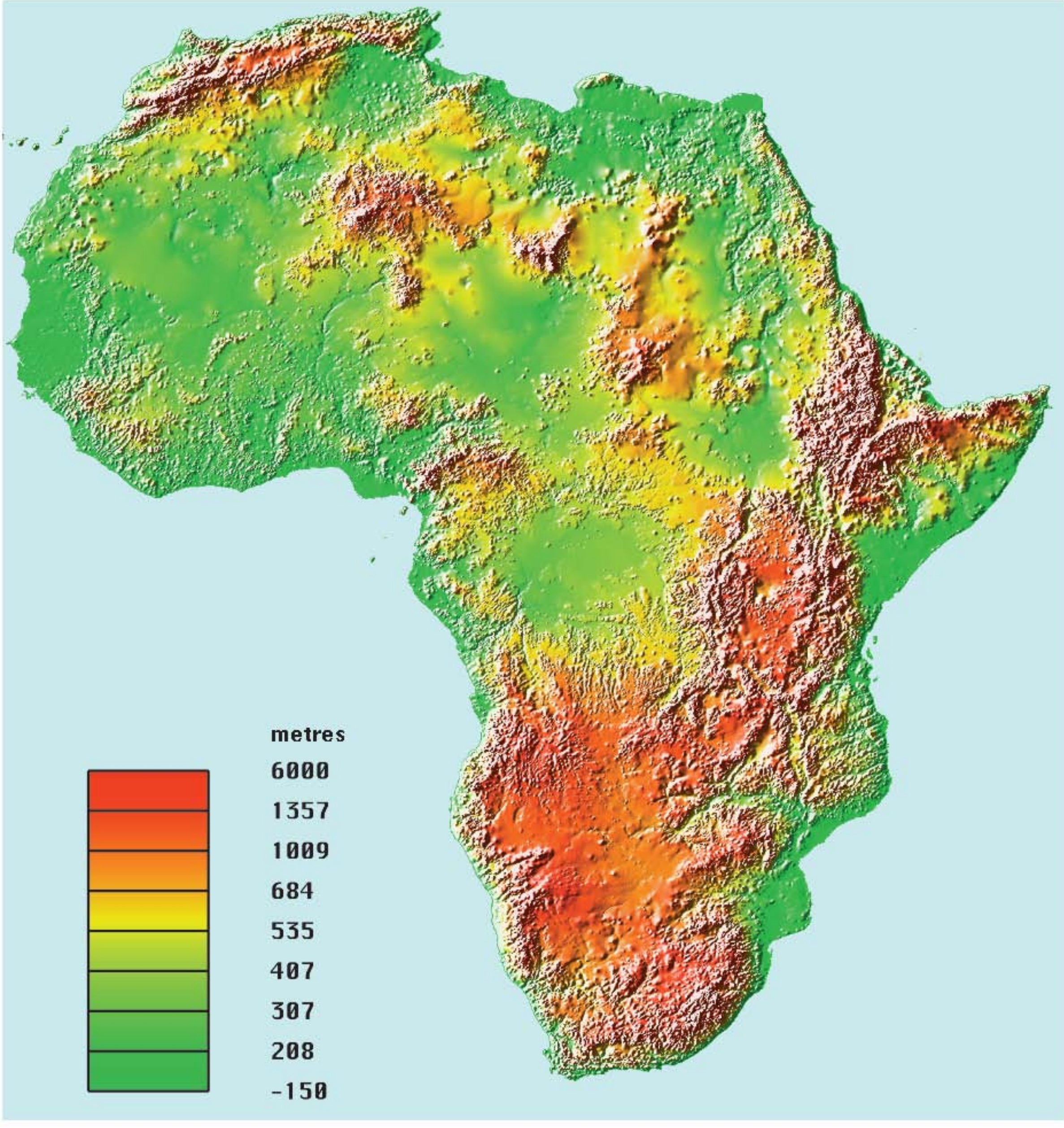


**Plate 58** Three-minute (5-km) resolution DEM for Africa: shaded relief and elevation.

**Plate 59** Three-minute (5-km) resolution DEM for Africa: derived stream network.

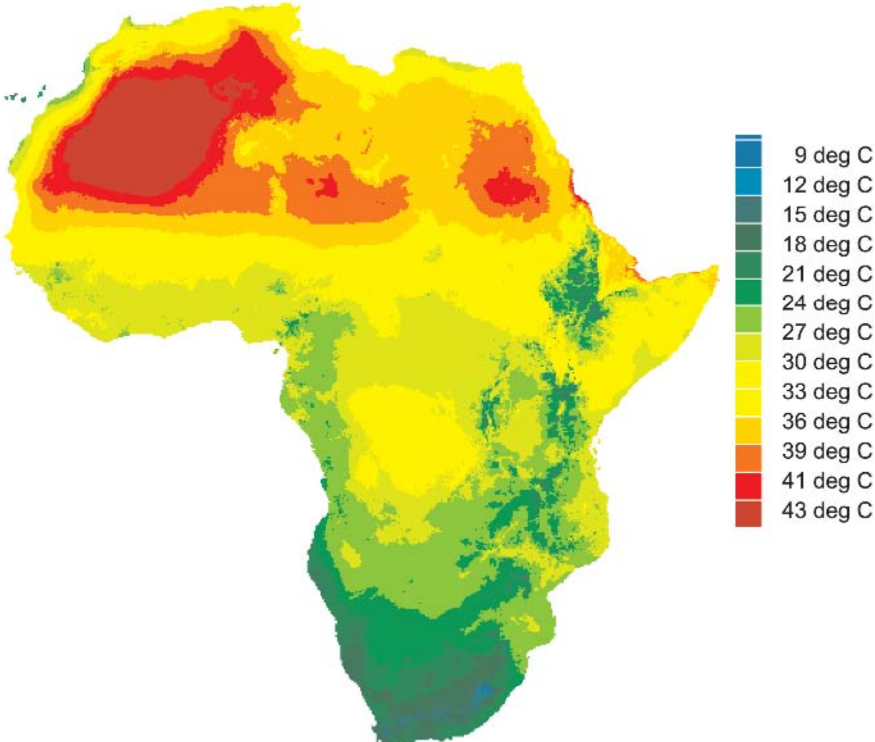


**Plate 60**
Africa: July mean daily maximum temperature.
(*Source*: Hutchinson et al 1996)

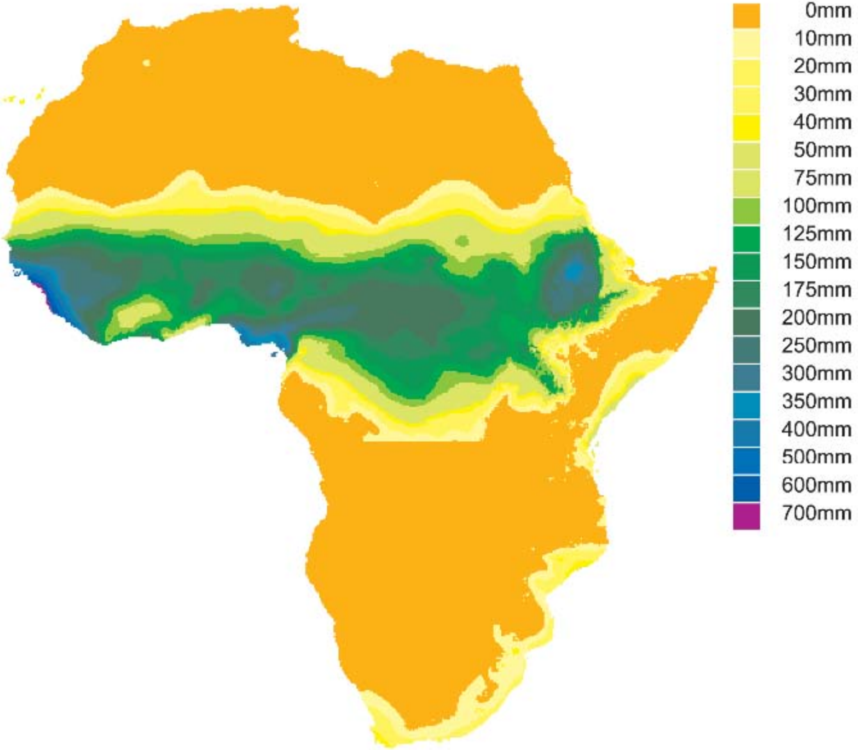


**Plate 61**
Africa: July mean precipitation.
(*Source*: Hutchinson et al 1996)

The second approach uses soil maps based on one or more soil taxonomic system(s) to aggregate soil pedon information. The FAO/UNESCO soil map of the world (Food and Agriculture Organisation 1974–78) was originally published at a scale of 1:5 million. It was compiled from national soil maps available at that time and additional field work by FAO staff. This map is probably the most comprehensive soil map that is currently available (Kern 1994, 1995). The legend contains approximately 5000 map units that specify dominant soil units, associated soils, and inclusions. Associated soils cover at least 20 per cent of the map unit area, and inclusions cover less than 20 per cent. The Food and Agriculture Organisation (1978) estimated the composition of each map unit using the methodology developed in the Agroecological Zones Project. A digital version can be obtained from the Global Resource Information Database Project of the United Nations Environment Program (Kern 1995).

Ecoregion maps (Olson et al 1985; Omernik 1996) are also used to describe land cover at continental and global scales, although reliance on these products for this purpose should diminish in the next few years as a new method of land cover characterisation developed by the United States Geological Survey (USGS) and University of Nebraska-Lincoln is implemented. The new method is based on the statistical analysis of multi-date advanced very high resolution radiometer (AVHRR) satellite data (Barnsley, Chapter 32; Estes and Loveland, Chapter 48) complemented by elevation, climate, ecoregion, and other digital geographical datasets (Brown et al 1993; Loveland et al 1991). Loveland et al (1995) have generated a multi-level digital geographically referenced land cover database for the contiguous USA. This serves as a prototype for a global land cover database that is currently under development. The prototype has a spatial resolution of 1 $km^2$ and divides the contiguous USA into 159 seasonal land cover classes representing alpine tundra (4 classes), western forest (43), shrubland (18), grassland (17), cropland (56), eastern forest (16), coastal wetland (3), barren land (1), and water (1) cover types.

This new land cover database represents a major advance over ecoregion maps because it: provides better spatial resolution; identifies a larger number of land cover types; can provide input data for a number of climatic, hydrologic, and ecological models (Steyaert et al 1994); and can be used with the visualisation tools commonly found in GIS and remote sensing software to develop maps and tabular summaries that meet specific needs. The USA prototype should be used with care since no rigorous accuracy assessment has been completed. Several preliminary studies at the state level (Lathrop and Bognar 1994; Turner et al 1993) and affirmation of the internal consistency of the database (Merchant et al 1994) indicate that it offers a reasonable depiction of national land cover. However, a more rigorous assessment is required to justify its use for local (county-scale and larger) GIS applications. This might involve the 1992 National Resources Inventory data that were collected at 800 000 randomly selected sample plots throughout the USA by Soil Conservation Service field personnel and resource inventory specialists (see Kellogg et al 1994).

The development of these digital climate and land cover products is likely to promote several important new agricultural applications in the next few years. The Africa climate surfaces, for example, might be combined with the cumulative seasonal erosion potential (CSEP) concept proposed by Kirkby and Cox (1995) to provide a simple climatic index of erosion potential. The CSEP model provides a powerful and physically-based methodology for estimating the climatic element in soil erosion (De Ploey et al 1991). Kirkby and Cox (1995) generated a series of global climatic erosion potential maps at a spatial resolution of 0.5° of latitude and longitude. The Africa climate database produced by Hutchinson et al (1996) means that the CSEP could be applied at a spatial resolution of 0.05° of latitude and longitude, and used as a soil erosion reconnaissance tool throughout Africa. The CSEP concept can be used for uncultivated vegetation, or modified for other land uses, such as field crops or grazing. The new land cover database products described would be useful here, and the concept could be extended further with the addition of topography and measures of susceptibility to soil erosion (as digital versions of these data become available) to estimate sediment yield over periods ranging from decades to geological timespans.

## 3 NATIONAL AND REGIONAL ASSESSMENTS

GIS techniques have been used for farm-related assessments at national and regional scales for many years (Usery et al 1995). These techniques have been combined with GIS and remotely-sensed data to support assessments of land capability (Corbett and Carter 1996), crop condition and yield (Carbone et al 1996; Korporal and Hillary 1993; Wade et al 1994), range condition (Ringrose et al 1996), flood and drought (Korporal and Hillary 1993; Wade et al 1994), soil erosion (Desmet and Govers 1995; Wilson and Gallant 1996), soil compaction (Bober et al 1996), surface and ground water contamination (Geleta et al 1994; Halliday and Wolfe 1991; Tim 1996; Wilson et al 1993; Wylie et al 1994), pest infestations (Everitt et al 1994; Kemp et al 1989; Liebhold et al 1993), weed eradication (Lass and Callihan 1993; Prather and Callihan 1993), and climate change impacts (Kern 1994, 1995). Most of these projects have addressed proof of concept, and there are few documented examples of routine GIS-based surveillance and assessment activities. To illustrate how the use of GIS techniques in farm-related assessments has evolved in the past few years, these projects can be grouped under three headings: new GIS data layers and analytical techniques (algorithms); new GIS-based modelling applications; and model and/or database validation studies.

### 3.1 New GIS data layers and analytical techniques

Corbett and Carter (1996) showed how GIS technology can be used to: synthesise and integrate many more data than in the pre-computer era; and shift the design of agroecological and agroclimatological studies towards user-specific classifications. Their analysis focused on Zimbabwe, a semi-arid country where a national agroecological classification and map, the Natural Regions scheme, had been widely used in agricultural research and policy-making (Plate 62; Vincent and Thomas 1960). This map used rainfall and temperature data to calculate effective rainfall and vegetation to interpolate this variable between stations. Corbett and Carter (1996) constructed seasonal rainfall surfaces for Zimbabwe using decadal (ten day) rainfall data (82–99 stations; 31 years of data), the Africa DEM (13 400 cells), and the ANUSPLIN procedures described by Hutchinson (1995b). They generated surfaces showing mean rainfall and annual rainfall anomalies to describe the main rainfall period (March–October) for Zimbabwe in terms of rainfall variability. They demonstrated that the natural regions (Plate 62) experienced considerable spatial variability in terms of mean and interseasonal variability of rainfall (Plate 63). Corbett and Carter (1996) then combined these surfaces with those of Deichmann (1994) to show that only 19 per cent of Zimbabwe's population lives in areas that can expect to receive more than 600 mm of rainfall (a rough boundary for maize cultivation in southern Africa) with 75 per cent probability (Plate 63).

At least three approaches utilising GIS and/or GPS have been implemented in an attempt to improve soil attribute predictions at regional scales. One approach has evaluated the use of these tools to improve traditional soil surveys. Long et al (1991), for example, examined the potential of using GPS methods in soil surveys and found that these methods were more efficient than traditional methods of mapping, and sufficiently accurate to support positioning/navigating in fields and field digitising of soil boundaries. A second approach has combined geostatistical modelling with soil survey maps to generate improved soil descriptions. Foussereau et al (1993) used a resampling method called bootstrapping (Hornsby et al 1990; see also Fischer, Chapter 19) to measure the variability of soil taxonomic units and evaluate the sensitivity of the chemical movement through layered soils (CMLS) model outputs to variations in soil input data (Nofziger and Hornsby 1986, 1987). The new soil property values that were generated with this non-parametric sampling method were combined with the original soil pedon sample data, and used to generate a series of pseudo-profiles for a series of Monte Carlo simulations that captured the (statistical) variability of selected soil attributes within soil taxonomic units for a citrus grove in Florida. Rogowski and Wolf (1994) took a slightly different approach and combined spatially interpolated (Kriged) distributions of measured values with soil map unit delineations within a GIS framework. Their method produced a map that preserved the map unit boundaries, and incorporated the spatial variability of the attribute data within the map unit delineations. This approach appears promising for countries and regions with well-developed soil survey programs.

The third approach has abandoned traditional soil survey methods altogether and explored the possibilities of integrating GIS, pedology, and statistical modelling to improve soil resource inventory (Bell et al 1992, 1994; Finke et al 1996; Gessler et al 1995; McKenzie and Austin 1993;

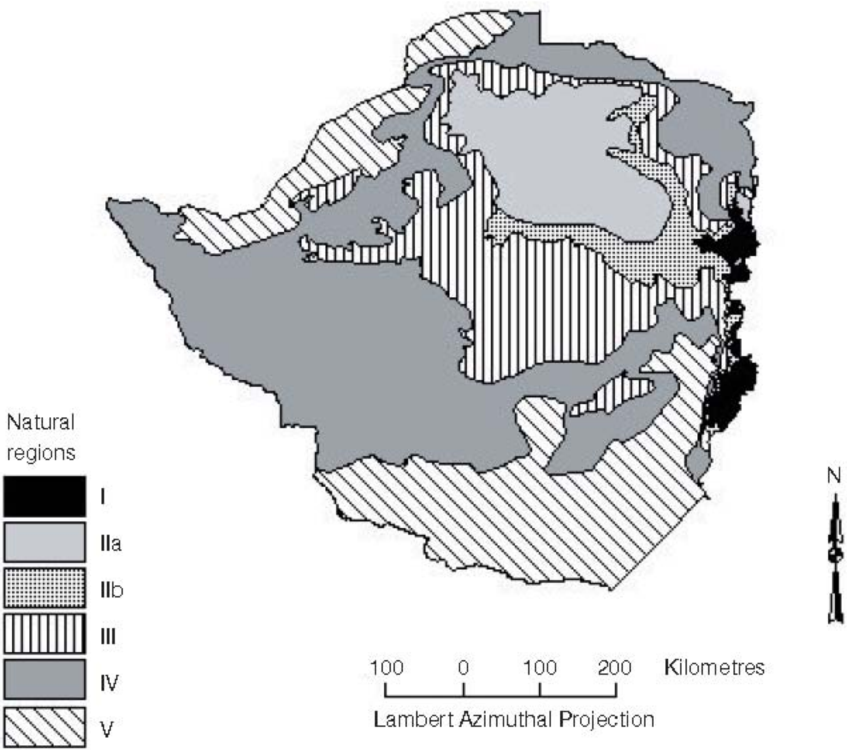


**Plate 62**
Zimbabwe: natural regions map. See Table 1 in Corbett and Carter (1997) for descriptions of the regions and their suitability for agriculture.
(*Source*: Corbett and Carter 1997)

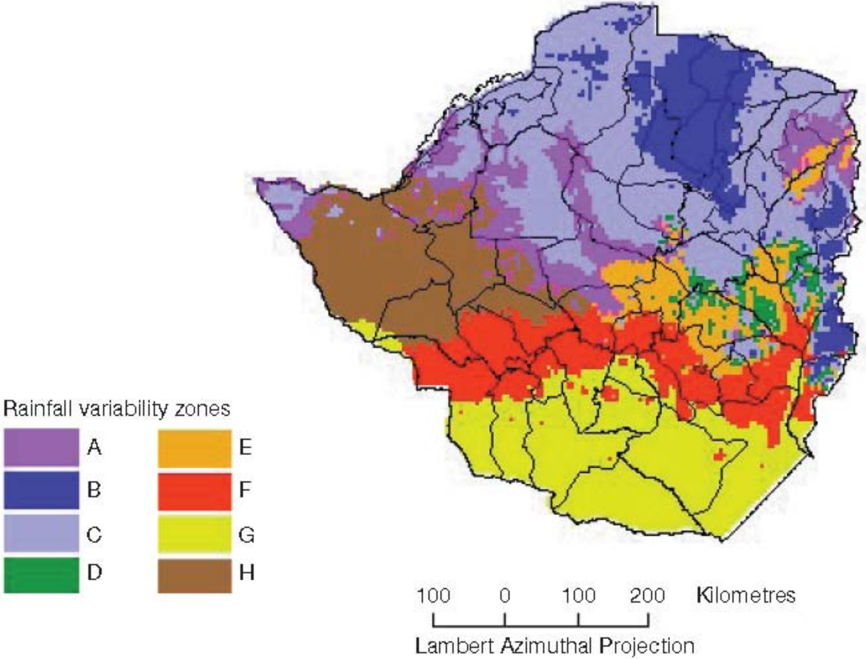


**Plate 63**
Zimbabwe: rainfall variability zones. See Table 4 in Corbett and Carter (1997) for zone descriptions.
(*Source*: Corbett and Carter 1997)

Rogowski 1997; Rogowski and Hoover 1996). In one such study, Bell et al (1994) combined a GIS with an existing soil-landscape model to create soil drainage maps. The soil-landscape model used multivariate discriminant analysis and class frequency information to predict soil drainage class from parent material, terrain, and surface drainage feature variables for the unglaciated ridge and valley physiographic province of Pennsylvania (Bell et al 1992). The terrain and surface drainage model inputs were generated using a series of operations found in many GIS software products, from published DEMs (30 metre spatial resolution) and hydrography (as represented on 1:24 000 topographic maps). Combinations of these three sets of landscape variables were defined by overlaying the digital maps and applying the soil-landscape model to create maps of soil drainage class probability and most likely soil drainage class (Figure 1). The modelled soil drainage class map agreed with the county soil survey (1:20 000 scale) for 67 per cent of the study area and with 69 of 72 (95 per cent) randomly selected field locations. The largest discrepancies between the model and soil survey maps occurred in areas predicted as somewhat poorly drained to moderately well drained by the model and well drained by the soil survey (cf. Figures 2(b) and 2(c). Bell et al (1994) concluded that their techniques: consistently assigned soil drainage class based on landscape attributes; recorded the metadata and decision criteria used for drainage class assignments; estimated the uncertainty associated with the drainage class assignments (Figure 2(a)); and generated a digital database for GIS applications (Figure 2(b)). This type of approach may be especially helpful in regions and countries that lack well-developed soil survey programs (Gessler et al 1995).

However, the two major problems with these types of statistical models are: their finite domain and the difficulty of extrapolating the results to other areas where the soil-landscape relationships are different; and the limited availability of high quality topographic and hydrologic input data. The soil and climate database development projects described above may help to solve the first problem to the extent that model domains can be defined as areas having similar physiography and climate (Bell et al 1994). With regard to the second problem, the development and evaluation of topographic and hydrologic databases that extend over large areas (regions) is an area of active research. Numerous researchers have evaluated the suitability of 30 m USGS DEMs for hydrologic modelling applications. In one such study, Hammer et al (1994) compared these DEMs with field data and found that they correctly predicted slope gradient at only 21 and 30 per cent of the field sampling locations, respectively, in two 16 hectare study areas in Atchison County, Missouri, USA. Similar results have been obtained

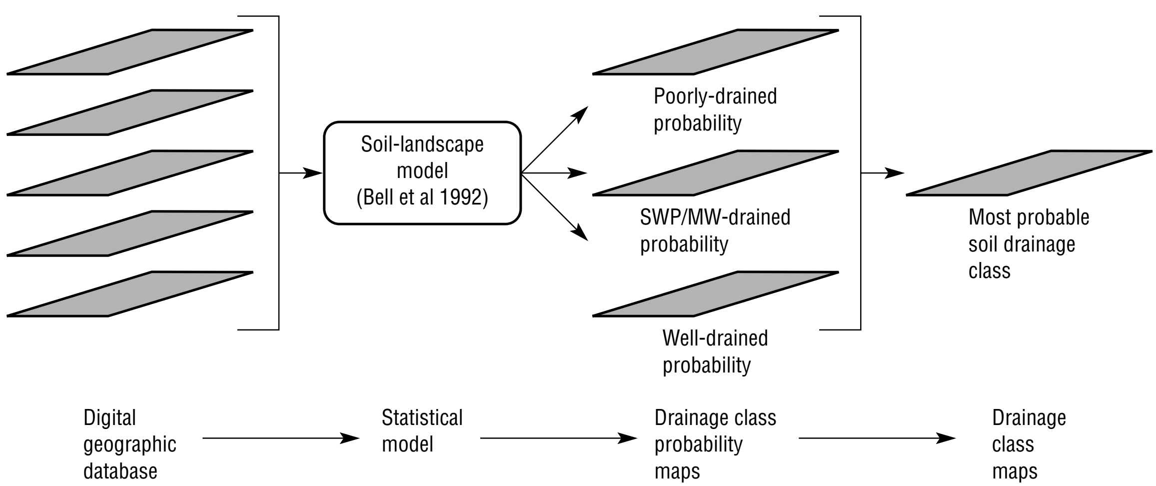


**Fig 1. Procedure used to create drainage class maps using the soil-landscape model (SWP = somewhat poorly, MW = moderately well-drained).**
*Source*: Bell et al 1994

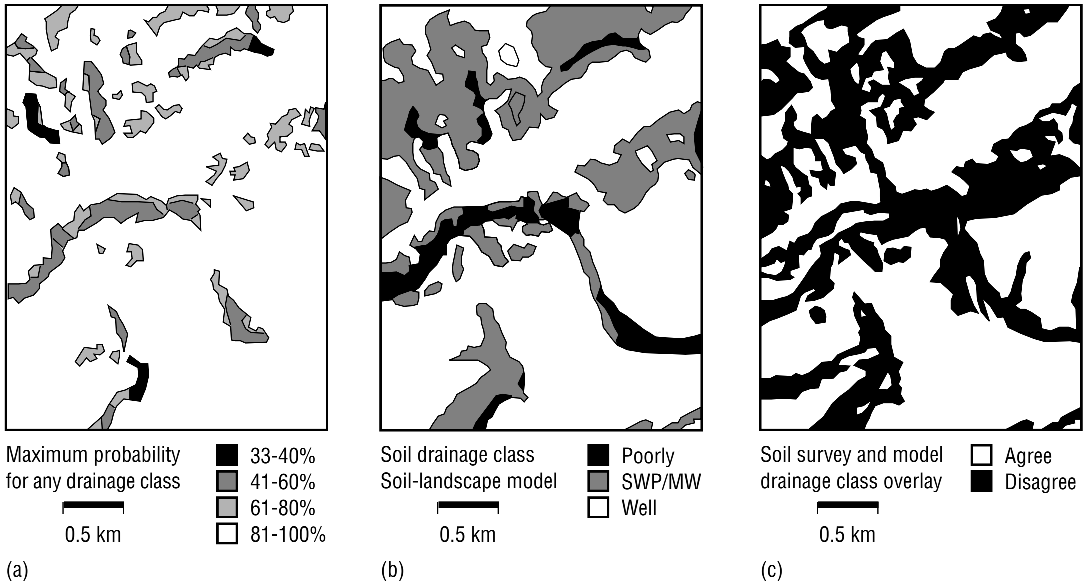


**Fig 2. Maximum probability for any soil drainage class: (a) soil drainage class map generated by the soil-landscape model; (b) soil drainage class map generated by the soil-landscape model; and (c) areas of agreement and disagreement between the soil-landscape model and the soil survey map of soil drainage class at Licking Creek. (SWP = Somewhat pooly drained; MW = moderately well drained.)**
*Source*: Bell et al 1994

by Panuska et al (1991), Zhang and Montgomery (1994), and Mitasova et al (1996; see also Mitas and Mitasova, Chapter 34). Hence, DEMs with spatial resolutions of 2–10 metres may be required to represent important geomorphic processes and patterns in many agricultural landscapes.

The development and testing of new terrain analysis techniques is another active area of research. Numerous algorithms have been proposed for routing flow across the land surface and calculating up-slope contributing areas during the past decade. Four of these methods are incorporated in the grid-based versions of the TAPES (Gallant and Wilson 1996) terrain analysis programs that can be used to calculate a variety of primary topographic attributes. The four methods are: the D8 algorithm (O'Callaghan and Mark 1984) that allows flow from a node to only one of eight nearest neighbours based on the direction of steepest descent; the Rho8 algorithm (Fairfield and Leymarie 1991) that is a stochastic version of the D8 algorithm in which the expected value of the direction is equal to the aspect; the FD8 and FRho8 algorithms (Freeman 1991; Quinn et al 1991) which enable flow dispersion or catchment spreading to be represented in up-slope areas; and the DEMON stream-tube algorithm of Costa-Cabral and Burges (1994). Quinn et al (1995) have recently proposed a modified version of the FRho8 algorithm that starts with the full multiple flow direction option near the catchment boundary and generates progressively straighter flows as it descends towards permanent channels. It is clear that the choice of flow direction algorithm can have a large impact on computed terrain attributes (Desmet and Govers 1996a; Wolock and McCabe 1995), although more work is required to ascertain which of these algorithms works best in specific environments. It is unfortunate that the D8 algorithm, which tends to produce flow in parallel lines along preferred directions (which only agree with aspect when aspect is a multiple of 45°) and cannot model flow dispersion, remains the most widely used method for determining drainage areas in GIS software.

More sophisticated terrain attributes have been proposed for calculating the combined length–slope factor in the revised universal soil loss equation (RUSLE: Renard et al 1993). This model is used to determine eligibility and compliance with farm conservation programs throughout the USA (Glanz 1994). Moore and Wilson (1992, 1994), for example, derived a dimensionless sediment transport index that is a non-linear function of specific catchment area and slope by considering the transport capacity limiting sediment flux in the Hairsine-Rose, WEPP, and catchment evolution erosion theories. This index is equivalent to the combined length–slope factor in RUSLE for a 2-dimensional hillslope, but is simpler to use and conceptually easier to understand. This index can be calculated in either EROS (Wilson and Gallant 1996) using one of the four flow direction algorithms noted above or the Idrisi GIS (Eastman 1996) using the D8 algorithm (Desmet and Govers 1996b).

This type of index can also be extended to 3-dimensional terrain to simulate slope convergence and divergence (Desmet and Govers 1996b; Moore and Wilson 1992). This form of the equation may predict different length–slope values in some landscapes and should be used with caution in GIS-based RUSLE applications since the original model is statistically based and one factor should not be altered independently of the other model inputs. Another form of the sediment transport capacity index that calculates the change in the sediment transport capacity index between pairs of hydrologically connected cells may help to distinguish those farmland areas experiencing net erosion and deposition (Desmet and Govers 1995; Moore and Wilson 1992, 1994). This last attribute could be used in GIS-based applications of RUSLE because the model should only be applied to landscapes experiencing net erosion (Wilson 1996). These terrain indices provide valuable information independently of RUSLE, and both Desmet and Govers (1996b) and Wilson and Gallant (1996) have advocated using them to evaluate erosion hazards in those parts of the world that lack sufficient data to implement formal erosion models, for example.

### 3.2 GIS-based modelling applications

The models described in the previous section were used to develop new GIS data layers. These data layers have also been used with some of the information they are designed to replace in various GIS-based applications of existing crop yield and non-point source pollution models. The climate surfaces generated by Corbett and Carter (1996), for example, could also be used as inputs in genotype-sensitive crop models to assess the risks for specific crop varieties. This possibility is illustrated by Carbone et al (1996) who used GIS and remote sensing technologies with the SOYGRO (Wilkerson et al 1983) physiological soybean growth model to predict the spatial variability of soybean yields in Orangeburg County, South Carolina, USA. This model relates the major processes of soybean growth (photosynthesis, respiration, tissue synthesis, translocation of protein, senescence, etc.) to environmental conditions. SOYGRO has been tested in a variety of environments and has proven reliable in estimating yield in well-managed conditions (Curry et al 1990). It requires meteorological, soil, and crop management inputs.

A state-wide land cover classification derived from five winter SPOT scenes was used to classify land cover and identify agricultural regions within Orangeburg County, USA. Meteorological inputs were compiled in ARC/INFO using Thiessen polygons (see Boots, Chapter 36) centred on five local climate stations, and the soil inputs were obtained from an ARC/INFO soil coverage derived from the 1:24 000 county soil survey. The 46 soil types delineated in the original county soil survey were reduced to the eight dominant soil types that are important to soybean production, and the SOYGRO model was run for 40 combinations of weather and soil conditions over a six year period (1986–91). The results showed that the spatial variability in simulated county yield was large and linked to soil moisture availability. This soil property is a function of available water holding capacity and the timing and amount of precipitation, both of which varied greatly across space. Carbone et al (1996) concluded that the examination of spatial patterns of simulated yield improved county production estimates and highlighted vulnerable areas during droughts.

Many more projects have combined GIS and environmental models to evaluate the impacts of modern agriculture. Wilson et al (1993), for example, modified the CMLS model and combined it with the USDA-NRCS State soil geographic database (STATSGO) (Bliss and Reybold 1989; Reybold and TeSelle 1989) and Montana agricultural potentials system (MAPS) (which divides Montana into 18 000 20 $km^2$ cells and stores more than 200 different land and climate characteristics for each of these cells (Nielsen et al 1990) to assess the likelihood of groundwater contamination from selected herbicides in Teton County, Montana, USA. CMLS is a 1-dimensional solute transport model that uses a piston flow approach to simulate the vertical movement of selected chemicals through the agricultural root zone on a layer by layer basis. The STATSGO and MAPS databases were overlaid to produce polygons with unique soil and climate characteristics, and attribute tables containing only those data required by the CMLS model. The Weather Generator (Richardson and Wright 1984) was modified and used to generate daily precipitation and evapotranspiration values. A new algorithm was developed and used to estimate soil carbon as a function of soil depth. The depth of movement of the applied chemicals at the end of the growing season was estimated with CMLS for each of the soil series in the STATSGO soil mapping units and the results were entered into ARC/INFO to produce the final hazard maps showing 'best', weighted average, and 'worst' case results for every unique combination (polygon) of soil mapping unit and climate. County weed infestation maps for leafy spurge (*Euphorbia esula L.*) and spotted knapweed (*Centaurea maculosa Lam.*) were digitised and overlaid in ARC/INFO with the CMLS model results for picloram (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid) to illustrate how the results can be used to evaluate the threat to ground water posed by current herbicide applications.

Geleta et al (1994) extended this approach and used the EPIC-PST crop growth/chemical movement model (Sabbagh et al 1991) interfaced with the Earthone GIS to evaluate crop yield and nitrate ($NO_3$-N) movement to surface and ground waters for four soils and nine cropping systems in the Panhandle counties of Oklahoma. The EPIC-PST model was developed to simulate the effect of different agricultural management practices on crop yield and on pesticide and nutrient losses by surface runoff, sediment movement, and leaching below the root zone. This model uses the erosion productivity impact calculator (EPIC: Williams et al 1983) as a basic building block and adopts the pesticide-related routines from the groundwater loading effects of agricultural management systems (GLEAMS: Leonard et al 1987) model.

Representative soil profiles for the most important agricultural soils were obtained from a local soil project report and information on cropping systems and rotations, tillage practices, irrigation methods and amounts, and chemical application practices were compiled from interviews with farmers and local resource specialists. Crop yield and $NO_3$-N movement in runoff and percolation was simulated over 20 years for each combination of crop, soil, cropping system, and chemical treatment. No GIS was used in this part of the project; however, Geleta et al (1994) also digitised the county soil maps in the GIS and described how these data could be used with the model results to compare the predicted changes in crop yields and nitrogen losses on different soils under water quality protection policies that targeted specific soils and/or cropping practices.

### 3.3 Model and database validation

The GIS-based modelling applications described above illustrate how three existing models have been modified and combined with GIS to take advantage of the new opportunities for the collection, analysis, and display of spatially distributed biophysical and socioeconomic data afforded by these software systems. The GIS is used to compile and organise the input data and/or to display the model outputs in these applications. The integration is achieved by passing data between the GIS and the model of choice (see, for example, Wilson et al 1993) or by embedding the model in the GIS or in a decision support system organised around the GIS (e.g. Engel et al 1993). The GIS software, digital databases, and computer models were developed by different groups of scientists at different times and places, and the benefits and limitations of this integration warrant closer scrutiny (Wilson 1996).

Numerous studies have examined the sensitivity of model outputs to different input data sources and resolutions (Brown et al 1993; De Roo et al 1989; Kern 1994, 1995; Panuska et al 1991; Wilson et al 1996: see Weibel and Dutton, Chapter 10, for an overview of scale and generalisation issues). In one such study, Wilson et al (1996) combined the WGEN and CMLS computer models used in their earlier work with two sets of soil and climate inputs to evaluate the impact of input data map resolution on model predictions. The basic soil and climate inputs were acquired from either: the STATSGO database; the USDA-NRCS (County) Soil Survey Geographic (SSURGO) database (Bliss and Reybold 1989; Reybold and TeSelle 1989); the MAPS database; or a series of fine-scale monthly climate surfaces developed using ANUSPLIN (Hutchinson 1995a), published climate station records, and USGS DEMs (with a spatial resolution of 0.00083° of longitude and latitude).

Fifteen years of daily precipitation and evapotranspiration values were generated and combined with soil and pesticide inputs in CMLS to estimate the depth of picloram movement at the end of the growing season for every unique combination (polygon) of soil and climate in a 320 $km^2$ area in Teton County, Montana, USA. The results showed that: the mean depths of picloram movement predicted for the study area with the SSURGO (county) soils and MAPS (coarse-scale) climate information, and the two model runs using the fine-scale climate data were significantly different from the values predicted with the STATSGO (state) soils and MAPS climate data (based on a new variable containing the differences between the depths of leaching predicted with the different input data by soil/climate map unit and testing whether the mean difference was significantly different from zero at the 0.01 significance level); and CMLS identified numerous (small) areas where the mean centre of the picloram solute front was likely to leach beyond the root zone when the county soils information was used. This last measure may help to identify areas where potential chemical applications are likely to contaminate groundwater. These results taken as a whole, however, illustrate how different model inputs are likely to generate different model predictions (see Beard and Buttenfield, Chapter 15; Fisher, Chapter 13; Heuvelink, Chapter 14, for overviews of the sources, propagation, and management of errors in GIS).

Similar results have been generated when these types of sensitivity tests have been performed over larger geographical areas as well. Kern (1994), for example, compared three methods for estimating spatial patterns and quantities of soil organic carbon (SOC) in the contiguous USA. This information is required for studies of soil productivity, soil hydraulic properties, and the cycling of carbon-based greenhouse gases. The first method used the ecosystem complex map of Olson et al (1985) (which has a spatial resolution of 0.5° of latitude and longitude) with 2392 soil pedons from a database developed by Zinke et al (1984) to estimate SOC.

The second method used the order, suborder, and great group levels of the USDA soil taxonomic system (Soil Survey Staff 1975) to aggregate the 5272 soil pedons in the USDA-SCS soil pedon database that could be assigned to great soil groups. The National Soil Geographic Database (NATSGO: Bliss 1990; Reybold and TeSelle 1989) was used to delineate major land resource areas (MLRAs: Soil Conservation Service 1981) and determine the areal extent of great soil groups in each MLRA. The NATSGO database combines MLRAs, which represent land resource units with similar patterns of soils, climate, water resources, and land units that were originally compiled at a map scale of 1:7.5 million (Soil Conservation Service 1981), and the 1982 Natural Resources Inventory, which represents the most extensive inventory of soil, water, and related resources ever undertaken on non-federal land in the USA (Kern 1995).

The final method used the FAO/UNESCO soil map of the world and the accompanying legend with 255 soil pedon descriptions to estimate SOC by soil unit in the contiguous USA. The USA part of the world soil map is based on the same 1:7.5 million scale general soil map that was used to delineate MLRAs (Soil Conservation Service 1981). Kern (1994) recommended using one of the two soil taxonomy approaches because these approaches predicted more realistic spatial SOC patterns than the ecosystem approach. The second soil taxonomy method (not surprisingly) produced the most detailed results, although it should be noted that all three methods generated similar overall SOC estimates for the contiguous USA.

In a similar study, Kern (1995) compared the geographical patterns of soil water-holding capacity derived from the NATSGO database and the FAO/UNESCO soil map of the world. This information is required for studying the response of vegetation and water supply to climate change. Kern (1995) concluded that the NATSGO database was superior because the map unit composition was based on a statistical framework with a large sample size and it better characterises rock fragment content and soil depth. These results suggest that the NATSGO database should be used in place of the FAO/UNESCO soil map of the world in climate change projects for the contiguous USA.

A much smaller group of studies have varied model inputs and compared model outputs with field data. In one such study, Inskeep et al (1996) compared several modelling approaches that might be applicable for classifying SSURGO (1:24 000) soil map units according to their leaching potential. This enabled them to model results based on detailed site-specific measurements and compare observed data collected at a field site in southwestern Montana, USA. Data from a two year field study of pentafluoro-benzoic acid, 2,6-difluorobenzoic acid, and dicamba (3,6-dichloro-2-methoxybenzoic acid) transport in fallow and cropped systems under two water application levels were compared to simulations obtained using the CMLS and leaching and chemistry estimation (LEACHM) models. LEACHM is a 1-dimensional finite difference model designed to simulate the movement of water and solutes through layered soils (Wagenet and Hutson 1989). It has been validated and used as a predictive tool at the plot and field scale (Wagenet et al 1989), and several attempts have been made to combine this model with GIS databases for regional scale assessments of leaching behaviour (Hutson and Wagenet 1993; Petach et al 1991).

Inskeep et al (1996) varied the resolution of model input parameters according to different sources of data. Model inputs were obtained primarily from detailed soil profile characterisation and site-specific measurements of precipitation, irrigation, and pan evaporation for one run (Case 1). LEACHM predictions were also generated using estimated conductivity and retention functions from SSURGO textural data (Cases 2 and 3). CMLS predictions were generated using detailed site-specific measurements (Case 1), and volumetric water contents estimated from SSURGO textural data and daily water balance estimated from WGEN and the MAPS climate database (Cases 2 and 3). Comparison of observed and simulated mean solute travel times showed that: LEACHM and CMLS performed adequately with high-resolution model inputs; model performance declined when field conditions were conducive to preferential flow; saturated hydraulic conductivity values estimated from regression equations based on textural data were problematic for generating adequate predictions using LEACHM; and CMLS predictions were less sensitive to data input resolution, in part because the CMLS provides an oversimplified description of transport processes. These results demonstrate the importance of model validation and suggest why model predictions based on GIS-based model input datasets with low spatial resolution may not accurately reflect transport processes occurring in situ.

## 4 LOCAL APPLICATIONS

The number and variety of local agricultural GIS applications have increased dramatically during the past five years. Some applications target individual farms. Ventura (1991), for example, utilised the spatial analysis tools in PC ARC/INFO to perform fully automated conservation program determinations, compliance monitoring, and farm planning in Dane County, Wisconsin, USA. This particular application is noteworthy both for its substance and because it illustrates how rapidly the computing resources, user interfaces, and database functions in desktop GIS have evolved during the past five years. Similarly, Vorhauer and Hamlett (1996) used GIS to determine possible pond sites and estimate rainwater harvesting potential for a 172-hectare farm in Pennsylvania, USA. An even larger number of applications, however, target individual farm fields.

Most of these field- and subfield-scale applications are connected with precision or site-specific farming, which aims to direct the application of seed, fertiliser, pesticide, and water within fields in ways that optimise farm returns and minimise chemical inputs and environmental hazards (Carr et al 1991; Usery et al 1995). Most site-specific farming systems utilise some combination of GPS receivers, continuous yield sensors, remote sensing, geostatistics, and variable rate treatment applicators with GIS (Peterson 1991; Usery et al 1995). The basic goal is to combine these advanced technologies to collect spatially referenced data, perform spatial analysis and decision-making, and apply variable rate treatment (see Figure 3).

Different data collection and analysis strategies incorporate varying levels of technology. Differential GPS is usually used to collect spatially referenced data. The National Environmentally Sound Production Agriculture Laboratory (NESPAL) in Georgia, USA, for example, specifies four or more ground control points in fields, measures their locations to less than 0.1 metre using differential GPS, and reproduces these points in all GIS layers (Usery et al 1995; see Lange and Gilbert, Chapter 33, for a description of the use of ground base stations in GPS-based measurement). The locational information must be collected using differential GPS so that the VRT operator can match field and map locations simultaneously (Schüller and Wang 1994). Field locations can be measured with a GPS attached to a VRT applicator to less than 1 metre precision using a known base station and signal with differential correction (Usery et al 1995).

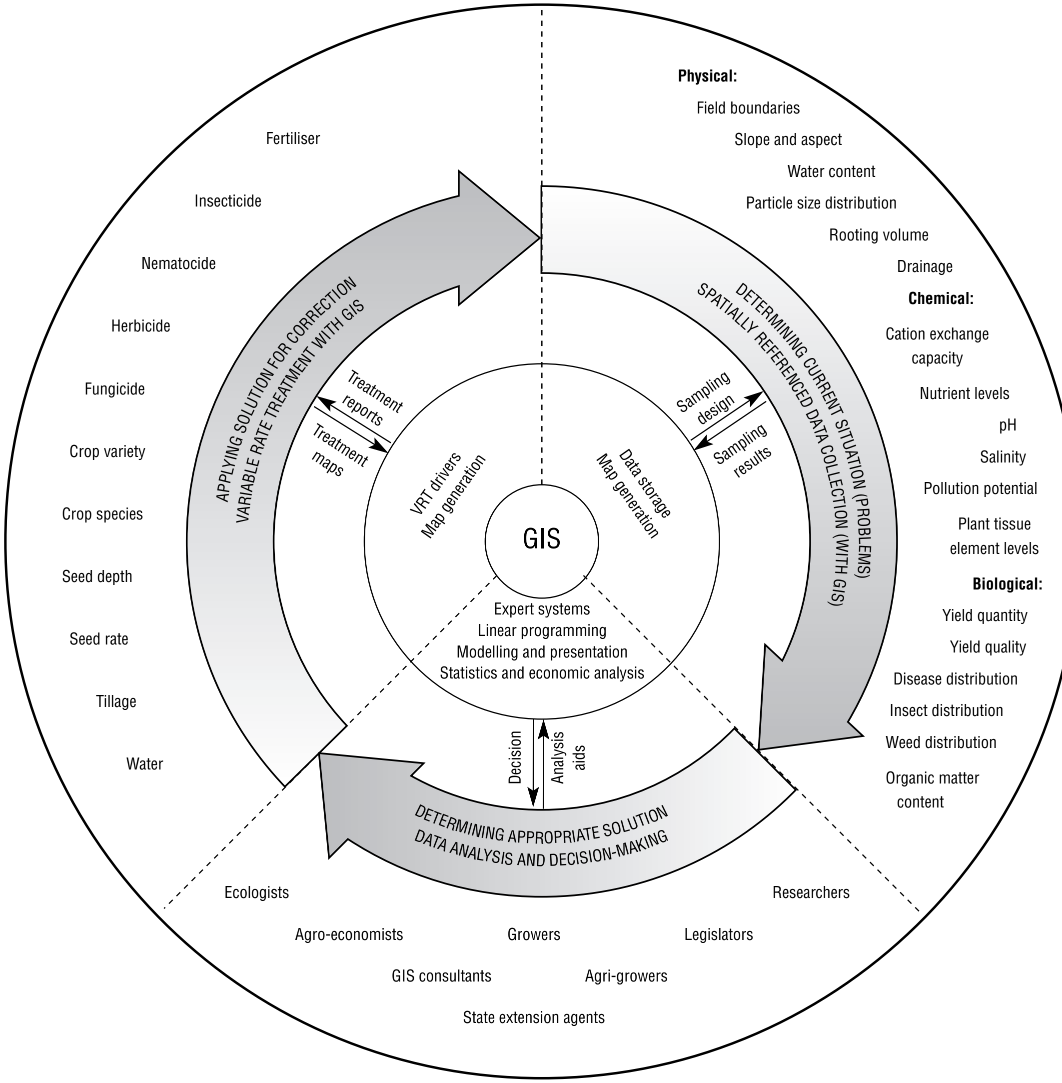


**Fig 3. The components of the NESPAL precision farming decision support system with a GIS as a central hub and GPS as the correlating base for geographical reference.**
*Source*: Usery et al 1995

Continuous yield sensors combine accurate location information collected using a GPS with the results of a variable flow rate sensor. They provide information about this year's crop performance that can be used to guide next year's crop management strategies (Long et al 1995). Such sensors represent a very important development and, so far, sensors have been successfully developed and tested for corn, wheat, cotton, and peanuts (Usery et al 1995). These sensors measure crop yield at harvest time and therefore they cannot help farmers make mid-season corrections to farming strategies or predict harvest quality. Additional information can be acquired with long range (aerial photography, Doppler radar, satellite imagery, etc.) and short range (ground penetrating radar, electromagnetic induction, etc.) remote sensing. These tools have been combined with DGPS and used to gather accurate information about field variability of soil texture, salt content, soil water content (Sudduth et al 1995), soil surface condition (Everitt et al 1989), vegetal condition and the presence of crop and/or weed species (Brown et al 1994), and plant stress and insect infestations (Everitt et al 1994). Hence, SPOT multi-spectral imagery (20 m spatial resolution) is acquired several times per month during the growing season, processed in 24–48 hours, and used to monitor the health of the sugar beet crop in North Dakota and Minnesota, USA in one such commercial application.

Direct field attribute measurement, although costly and time consuming, is still needed for many agronomically important variables (Usery et al 1995). The level of accuracy of the final map depends on the sampling and interpolation procedures that are used. Good interpolation starts with representative samples and several different sample designs are used. Many commercial systems and some researchers use grid samples (e.g. Mulla 1991). Others use stratified random or random samples: for example, NESPAL uses the systematic stratified random sampling method of Berry and Baker (1968) because this method maintains systematic coverage of the target area while providing randomness in sub-areas (Congalton 1988; Spangrud et al 1995; Wollenhaupt et al 1994). The interpolation process, which is required to construct maps and/or to generate data at the same locations in a series of connected layers irrespective of how the source data are collected, has important implications for the types of operations that are needed in the GIS and may represent the weak link in most site-specific farming systems (Bouma 1995; McBratney and Whelan 1995; Nielsen et al 1995).

Schüller (1992) advocated using GIS as a central hub in site-specific farming systems because of their data management, integration, and display capabilities. Furthermore, three-fifths of the researchers who responded to the site-specific farming survey conducted by Usery et al (1995) acknowledged that they already used GIS for these tasks. These researchers also observed that the available software systems (ARC/INFO, GRASS, Idrisi, MapInfo, etc.) contained too many superfluous functions, lacked several important functions, and were difficult to use for site-specific farming applications. The launch of several new desktop GIS software products (e.g. CROPSIGHT, FARM TRAC; VISAG; VISION SYSTEM) that are aimed at site-specific farming applications is likely to alleviate some, if not all, of these problems. Several of these products convert generic desktop GIS software (ArcView3, MapInfo, etc.) and database products (Access, dbase, etc.) into user-friendly farm management systems. They perform some spatial analysis functions (e.g. distance, area calculations, Boolean overlays, buffering, and reclassification); however, they omit most of the Kriging-related geostatistics, multivariate analysis, trend surface analysis, clustering, principal components analysis, and fuzzy-logic statistical tools that many of the researchers who responded to the site-specific farming survey of Usery et al (1995) thought were needed to integrate and interpret site-specific data (see Eastman, Chapter 35, for a review of multicriteria decision- making in related contexts).

Site-specific application rates might be ascertained on the basis of correlation measures between (easily-measured) soil attributes and the fertility requirements of individual crops (Long et al 1995), and the spatial patterning of soil data (Cahn et al 1994; Sawyer 1994). However, there is no clear consensus about the sample spacings and interpolation methods that should be used in specific instances (see Getis, Chapter 16, for a review of spatial statistics, including Kriging and the identification of local 'hot spots' of spatial association). Two studies are described here to illustrate the scope and nature of this problem.

Gotway et al (1996) grid-sampled two field research sites in Nebraska and used the data in a prediction-validation comparison of ordinary point Kriging and inverse distance methods using $p = 1$, 2, and 4. The sample configuration (regular grid) and extent of the search neighbourhood were held constant and two variables, soil $NO_3$-N (nitrate–nitrogen) and SOC that are used in Nebraska to predict nitrogen fertiliser rates, were examined in this study. The accuracy of the inverse-distance methods tended to increase with the power of the distance for datasets with a coefficient of variation less than 25 per cent (typical of SOC). However, the inverse distance methods generated inaccurate predictions for datasets with greater variation (such as $NO_3$-N). The accuracy of the Kriged predictions was generally unaffected by the CV and was relatively high for all of the sampling densities that were examined. The Kriged results also provided information about error (which can be translated into uncertainty in nitrogen fertiliser recommendations) and there is the possibility that more sophisticated Kriging methods (choice of semivariogram model, use of nested structure and anisotropic methods, etc.) might increase the accuracy and reduce this error further in some instances. Larger sample sizes would have increased the quantity of information and reduced the error (uncertainty) in the maps constructed by each method as well.

Cahn et al (1994) evaluated the spatial variation of SOC, soil water content, $NO_3$-N, $PO_4$-P (phosphate-phosphorus), and K (potassium) in the 0–15 cm layer of a 3.3 hectare field in central Illinois cropped with maize and soybeans. The results showed: median polishing detrending and trimming of outlying data were useful methods for removing the effects of non-stationarity and non-normality from the semivariance analysis; soil fertility parameters had different ranges of spatial correlation within the same field; and soil $NO_3$-N data may be of limited value to site-specific farming applications because the spatial pattern displays a short correlation range (less than 5 metres) that changes throughout the growing season. Cahn et al (1994), for example, calculated that as many as 400 randomly selected samples per hectare may be needed to develop an accurate soil $NO_3$-N map and that an applicator travelling at 8 km/hr would need to modulate fertiliser rates every 2.25 seconds to match nitrogen fertiliser rates to soil $NO_3$-N needs. This goal is almost certainly unrealistic in the absence of real-time $NO_3$-N sensors from a cost-benefit point of view.

The results from both of these projects indicate why farmers and/or consultants are looking for soil data that exhibit long ranges of spatial correlation, large scale variation, and spatial patterns that are temporally correlated when they have to use direct field attribute measurement (Cahn et al 1994). These projects are instructive as well because they demonstrate the complexity of the statistical methods that may be required and therefore the difficulty involved in producing user-friendly and appropriate analytical tools in a GIS and/or a spatial decision support system for these types of applications. The need for systems containing these types of analytical tools will increase in the next few years as the use of continuous data collection techniques and remote sensing becomes more widespread.

## 5 CONCLUSIONS

The past decade has witnessed a tremendous growth in agricultural applications of GIS at a variety of scales. These applications have benefited from technological advances connected with GIS and several related technologies (as discussed throughout the Technical Issues Part of this volume – including GPS, remote sensing, continuous data collection techniques, geostatistics, etc.). In addition, the growth in popularity of site-specific farming as a way to improve the profitability and/or reduce the environmental impact of modern agriculture has promoted the development of desktop GIS that are customised for these types of application (see Elshaw Thrall and Thrall, Chapter 23 for a general review). The use of these advanced technologies in agriculture offers at least four advantages: they provide data cheaply and quickly at a variety of (fine) resolutions; they use repeatable methods (to the extent they generate metadata on data sources and analytical procedures); they provide improved diagnostics for error detection and accuracy (uncertainty) determinations; and they generate information that can be used with the visualisation tools commonly found in GIS to develop customised maps and/or tabular summaries.

These advantages may be partially offset to the extent that these technological innovations have outpaced our knowledge of soil/crop (cause-effect) relationships, spatial interpolation techniques, and model/database validation. Further work is urgently needed to improve our understanding of these aspects of science at a variety of scales to confirm the potential use of GIS and related technologies in routine surveillance and assessment activities ranging from site-specific farming systems to global food production and security issues.

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