Lecture Notes: "Land Evaluation"

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Part 6 : Data Sources for Land Evaluation

Contents for Part 6 : “Data Sources for Land Evaluation”

Land evaluation is based on *land resources data*. This unit discusses various kinds of data (soils, climate, hydrology), how it is collected, especially by *remote sensing*, and how it is processed in the computer.

1. Remote sensing for land evaluation

An important source of information on land characteristics is *remotely-sensed* data, especially satellite imagery. In this set of lectures we study the principles of remote sensing only as they apply to land evaluation. There are a great many other applications, e.g. crop monitoring, natural resource survey and monitoring, map making and map updating. The main application we consider is *land cover classification*.

Bibliography: Introduction in (EUROCONSULT, 1989) §3.7 (p. 203-212). The authoritative reference is the Manual of Remote Sensing (American Society of Photogrammetry, 1983). An excellent survey is (Lillesand & Kiefer, 1987). More on digital image processing is presented by (Jensen, 1986). For environmental applications see (Barrett & Curtis, 1992), for soil science see (Mulders, 1987), for agriculture see (Gastellu-Etchegorry (ed.), 1990).

1.1 Definition of remote sensors

Devices which can collect information about an object from a distance, without touching it, except perhaps with energy emitted from the sensor.

'Near' remote sensors are 'close' to the object, e.g., infrared heat detectors for home insulation, ordinary photographs.

We will consider 'far' remote sensors (from aircraft and spacecraft) that study areas of the earth's surface, since land evaluation is always concerned with such areas.

Key point: The products of remote sensing are usually *not* direct samples of the phenomena of interest, so must be *calibrated* against reality in order to be useful. This process is called *interpretation* or *ground truthing* and may be manual or automated.

1.2 Resolution

This refers to the level of detail of the image, in two senses:

Radiometric: number of energy levels that can be distinguished. Can be practically infinite in photographs, but limited in digital images

Spatial: smallest object that can be distinguished in the image.

1.3 Types of remote sensors

1.3.1 Photographic film

— generally from aircraft but can be from spacecraft (Shuttle)

— the sensor is silver halide crystals, sensitive to light (visible electromagnetic energy)

— *panchromatic* (several colors) or *single-color*, which may not be visible e.g. Infrared

— the product is a photograph

1.3.2 Passive electromagnetic devices

— generally from satellites but there are specially-equipped aircraft

— the sensor is an electronic detector, sensitive to electromagnetic energy from a definite part of the spectrum (UV through mid-IR)

— product is a digital record of the sensor response, which can be converted to photographs

— 'digital cameras' use similar technology but are aimed at the same uses as photographic film for 'near' remote sensing. The distinction between these and photographs will disappear soon.

1.3.3 Active electromagnetic devices

— generally from aircraft but can be from satellites

— the apparatus directs energy towards the earth and receives a part of it as a *return signal*; the energy level, time differential, or phase differential are recorded in digital form

— example: radar

— product is a digital record of the sensor response, which can be converted to photographs

1.3.4 Active non-electromagnetic devices

— from aircraft, spacecraft are too far to receive a non-electromagnetic return signal

— the apparatus emits non-electromagnetic energy, e.g. sound waves (sonar), and receives a part in return; the time and phase differentials are recorded

1.4 Advantages of remote sensing for land evaluation

1. Relatively *cheap* and *rapid* method of acquiring *up-to-date* information over a *large* geographical area. Example: Landsat 5 covers each area of 185x160km at a ground resolution of 30m every 18 days, cost of the original digital data is $5 000 (6 200 ha $\$^{-1}$, each hectare contains approximately 11 observations. Even with the cost of ground truthing this is very economical.

2. It is the only practical way to obtain data from *inaccessible* regions, e.g. Antarctica, Amazonia.

3. At small scales, regional phenomena which are invisible from the ground are clearly visible. Examples: faults and other geological structures. A classic example of seeing the forest instead of the trees.

4. Cheap and rapid method of constructing base maps in the absence of detailed land surveys.

5. Easy to manipulate with the computer, and combine with other geographic coverages in the GIS.

1.5 Disadvantages of remote sensing for land evaluation

1. They are *not direct samples* of the phenomenon, so must be *calibrated* against reality. This calibration is never exact, a classification error of 10% is excellent.

2. They must be *corrected geometrically* and *georeferenced* in order to be useful as maps, not only as pictures. This can be easy or complicated.

3. Distinct phenomena can be *confused* if they look the same to the sensor, leading to classification error. Example: artificial & natural grass in green light (but infrared light can easily distinguish them).

4. Phenomena which were not meant to be measured (for the application at hand) can interfere with the image and must be accounted for. Examples for land cover classification: atmospheric water vapor, sun vs. shadow (these may be desirable in other applications).

5. Resolution of satellite imagery is too coarse for detailed mapping and for distinguishing small contrasting areas. Rule of thumb: a land use must occupy at least 16 pixels (picture elements, cells) to be reliably identified by automatic methods. However, new satellites are being proposed with 1m resolution, these will have high data volume but will be suitable for land cover mapping at a detailed scale.

1.6 Principal uses of remote sensing in land evaluation

1. Produce land use & land cover maps;
2. Identify land mapping units such as geomorphic forms and ecological zones;
3. Update base maps without full field survey: new roads, canals, field patterns, urban areas, etc.;
4. Locate specific points of interest to the evaluation, e.g. settlements;
5. Provide *time series* for temporary or seasonal phenomena, e.g. crop growth, vegetation intensity.

1.7 Principal platforms and their sensors for land evaluation

1.7.1 Low-flying aircraft with photographic cameras

This platform has rich history (American Society of Photogrammetry, 1983). Well-developed techniques for *photointerpretation* for a wide variety of purposes (vegetation, landforms, soil survey, geology, infrastructure...).

Scale of original photography on the order of 1:6 000 to 1:60 000, depends on flying height and focal length of camera.

Excellent resolution, limited only by the sensitivity and resolution of the film.

Usual procedure: *manual interpretation* and drawing of polygons, lines or points, followed by *digitizing* (or scanning of the hand-drawn lines) for use in the GIS.

Rectification and gereferencing can come before (orthophotos) or after interpretation.

Can be *scanned* and converted in digital images with any desired radiometric (bits per pixel) and spatial (pixels per inch of photograph) resolution, then processed like satellite data.

1.7.2 Low-flying aircraft with passive electromagnetic sensors

Same as above, but using charge-coupled diodes (CCDs) or digital cameras. Products go directly to the image processing system without scanning, then are processed digitally. *Soft-copy photogrammetry*.

1.7.3 Earth observation satellites

A product of the space age. Early appreciation by earth scientists of the potential of satellites after seeing results from Gemini. Development of electromagnetic sensors and digital systems for non-recoverable craft (i.e. couldn't recover photographic film).

Most used systems: LANDSAT TM ('Thematic Mapper') and SPOT (Sistème Pour l'Observation du Terre): *thematic multispectral mappers*. Earlier LANDSAT system was MSS ('Multispectral scanner'), lower spatial and radiometric resolution but similar in concept.

— "Thematic" : intended for making thematic maps, not cartographic products as such.

— "Multispectral": has several *bands*, each sensitive to electromagnetic radiation of specific wavelengths in and near the visible (e.g. blue, red, green, infrared), micrometric wavelengths: 1 µm = 10**-6m, corresponding to a frequency of 3x10**5 GHz (1 GHz = 10**9 Hz).

Landsat TM bands:
1 : blue visible (0,42 - 0,52µm) 2 : green visible (0,52 - 0,60µm) 3 : red visible (0,63 - 0,69µm) 4 : near infrared (IR) (0,76 - 0,90µm) 5 : medium IR (1,55 - 1,75µm) 6 : thermal (10 - 20µm) - note longer wavelength than band 7 7 : medium IR (2,08 - 2,35µm)

— *Passive* sensors: receive, but do not emit, energy

— Radiometric resolution of 256 levels = one 8-bit byte of computer memory per cell. (MSS had 128-level, i.e., 7 bit, resolution)

— Electromagnetic energy is emitted by the earth's surface and objects on it, principally *reflected* from direct or indirect sunlight (but the thermal is longwave radiation)

— Spatial resolution of 30x30m in TM band 1-5 and 7, 120x120m TM band 6 (MSS was 79x79m)

— Spatial resolution of 20x20m in SPOT multispectral bands, 10x10m panchromatic

— The technology is easily capable of 5x5m, spy satellites are reportedly 1x1m, but the quantity of data becomes enormous

— practically without problems of relief displacement because they are taken from 700km to 900km altitude, i.e., scale is fairly constant across the image

— it is possible to create a stereo model from adjacent pairs of SPOT images

— scene size approx. 180km x 160km

1.7.4 High-flying aircraft with airborne radar

'Side Looking Airborne Radar' (SLAR)

— Centimetric wavelengths (10.000 times longer than visible light detected by TM)

Some radar bands
K : 1,1 - 1,67cm (26,5 - 18 GHz)
X : 2,4 - 3,75cm (12,5 - 8 GHz)
C : 3,75 - 7,5cm (4 - 8 GHz)
S : 7,5 - 15cm (4 - 2 GHz)

— *Active* sensors: emit radio waves and measure the time and intensity of the return signal.

— Penetrate vegetation because the waves are too long to be reflected.

— Complex and poorly-understood effects of material surfaces on the return signal, so interpretation is a high art.

— Must be corrected for relief displacement, because they are from aircraft.

1.8 Principal characteristics of thematic-mapper type digital images

We now concentrate on this kind of imagery, since it is the most prevalent in land evaluation. Some of these points recap what was presented above.

1. *Grid* ('raster') data, fixed *spatial resolution*, from 1100m x 1100m (AVHRR), 160m x 160m (TM band 6), 80m x 80m (Landsat MSS), 30x 30m (Landsat TM bands 1-5, 7), to 10m x 10m (SPOT panchromatic)

2. Each sensor detects the *radiance* in discrete grades (*radiometric resolution*), typically from 0 (no radiance) to 255 (the sensor is saturated). The number of levels depends on the sensitivity of the sensor and the amount of storage to be dedicated to each observation (1 byte = 8 bits = 2^8 = 256 levels).

3. The spatial and radiometric resolution determine the *storage requirement* for the digital image. For each km² of ground coverage, the requirement is:

$$(1000/r)^2 \cdot b \cdot c$$

where r is the lineal resolution in meters, b is the number of bands, and c is the number of bytes per cell. For example, for Landsat TM, the requirement is $(1000/30)^2 \cdot 7 \cdot 1$ = 7,777.8 = 7.595Kb approx. bytes per km². For a complete scene of 180x165km, or 29 700 km², this is 231 000 000 bytes or approx.

220Mb. (note: 1 024 bytes = 1 Kb, 1 024 Kb = 1 Mb). About 3 scenes can fit on one 700Mb CD.

Note that *doubling* the lineal resolution *quadruples* the storage requirement, etc. Since each cell must be processed at least once, the processing requirement at least quadruples and usually is increased by a larger factor. For example, to go from a 30m resolution Landsat to 5m 'Military Spec' resolution would increase the storage requirement by $(30/5)^2 = 36$ times, i.e., a scene of the same size would require approx. 7.73 Gb (note: 1 024 Mb = 1 Gb). About 10 700Mb CDs would be required for one scene!

4. Each cell contains only one radiance value for a band, which *integrates* the radiances of the actual objects within the cell. This causes problems when there are contrasting objects in the cell: the sensor averages them, which represents neither! For example, a white-sand beach (very reflective of red light) adjacent to a deep blue ocean (absorbs almost all the red), the cell will look like moderately dense vegetation (medium reflectance of red lights) even though that is neither of the actual uses! Similar problem: a black car in a white-concrete parking lot.

5. The image has errors due to the spacecraft's orientation, the rotation of the earth under it during the imaging, and the shape of the earth. The cells are not really square, must be *re-sampled* (next section).

1.9 Image processing

The digital image as received may be manipulated in several ways. Some of this may have been done by the image supplier.

1. Change the file format to that of the image processing system. Grid images are very easy to transform. E.g. ERDAS provides modules to read LANDSAT tapes and store the image in ERDAS format.

2. Radiometric correction for differences between within the same band (IDRISI command DESTRIPE)

3. Radiometric correction for the effects of haze or known system gain (IDRISI commands SCALAR, STRETCH)

4. Filter to reduce noise and interpolate where there are missing values due to sensor failure (IDRISI command FILTER, 'mode' option)

5. Restitution and transformation to a standard projection, e.g. UTM or Lat/Long, from the satellite's coordinate system (e.g. Space Oblique Mercator) (IDRISI command RESAMPLE): ground *control point*s must be known and distributed fairly evenly around the image. The system computes a transformation matrix, including rotation, translation, and scaling, from a least-squares fit to the control points.

6. Change of resolution to match other coverages in a GIS (IDRISI commands RESAMPLE, CONTRACT, EXPAND)

7. Enhance the contrast for visualization (note: this does not increase the information content of the image) (IDRISI command STRETCH, histogram equalization)

8. Eliminate extreme values for visualization (reduces information content, not a good idea for land cover classification) (IDRISI command STRETCH, linear with saturation)

1.10 Georeferencing an image

Basic procedure to georeference an image: (IDRISI module RESAMPLE).

(1) Identify a set of *control points* which can be identified on the source map and on the ground (by ground survey or GPS) or on a *base map* of known quality.

(2) Determine the *map coordinates* (row/column) in the source image for each of these control points. For example, Column (X) = 50, Row (Y) = 200.

(3) Determine the *geographical coordinates* of these control points in the desired coordinate system. For example, UTM_E (X) = 675000, UTM_N (Y) = 11230250. One way to do this is to register a paper map to a digitizer and digitize the control points into a point 'vector' file.

(4) Enter a table of *correspondences* between map and ground: ordered pairs of coordinate pairs: $\{(c_i, r_i), (x_i, y_i) | i \in C\}$ where C is the set of control points.

(5) The computer calculates a geometric *affine transformation* which includes:
- — scaling;
- — translation; and
- — rotation.

(6) The computer creates a blank image to contain the new image.

(7) fill in the cells with values from cells in the original map that include the area of the new cell.

If the image was already geometrically correct and no rotation is necessary (extremely unlikely), there will be no error, otherwise there is a *re-sampling* problem.

1.11 Transformation to principal components

Usually there is an information-theoretic *redundancy* between the various bands, i.e., some information about a pixel is repeated in several bands. For

example, visibly black/gray/white objects have similar radiances in each of the three visible-light LANDSAT bands. Considering the radiance values at a certain location (cell) to be a multivariable, the techniques of *principal components* can be used to *reduce the dimensionality* of the multivariable. This is a powerful technique for bringing out the maximum information in a multi-band scene. See (Lillesand & Kiefer, 1987) pp. 655-660 for a simple introduction.

Basic idea of principal components: transform from a multi-dimensional space (i.e., the bands of the original scene) to another of the same dimension, producing *synthetic bands*, such that each axes of the new space is *orthogonal* (i.e., there is *no correlation* between the transformed 'bands'), and such that the first axis contains the *maximum variance* (i.e., the maximum information content) and so on.

This is just the calculation of the *eigenvalues* and *eigenvectors* of the original multidimensional matrix made up of the radiance values for each cell of the image (rows X columns X bands).

Advantage: reduces the dimensionality, so that the first three components usually contain almost all the information (higher-dimension bands are mostly noise).

Advantage: the synthetic bands are un-correlated, so that what can be seen in one is independent of what can be seen in another.

Advantage: higher-dimension bands reveal *interactions* between the original bands, and can be diagnostic for certain land cover types. Sometimes most of the higher-dimension synthetic band is noise but in a few spots, an otherwise-hidden phenomenon can clearly be distinguished.

Disadvantage: a synthetic band does not represent any simple physical phenomenon (e.g., reflection from a certain type of object).

2. Land cover classification from remotely-sensed data

The most common application of remotely-sensed images in land evaluation is a *land cover classification*, also called a *land use map*. The basic ideas is that the spectral characteristic in a multi-band image can separate different land uses. Satellite-based land cover classification is often the only practical ways to do this over large areas.

Key point: the *spectral characteristics* of the different land covers must be associated with each land cover class, then the entire image can be classified.

Land cover can be classified in many ways, depending on the needs of the evaluation. We can distinguish between *general-purpose* and *special-purpose* classifications, each of which may be *standard*.

Why is land cover classification important in land evaluation?

1. Many uses depend on the presence or absence of certain land cover. Example for *presence*: extractive forestry requires an existing forest with a definite composition of species and ages. Example for *absence*: in the US, it is generally prohibited to use existing wetlands (mainly defined by hydrophlic vegetation, which can be a land cover class) for agriculture.

2. The present land cover can itself be diagnostic for suitability. Example: natural vegetation indicative of a certain hydrologic status, indicating suitability for another use that requires the same status: example from Ecuador: shrimp hatcheries replacing mangrove swamps.

3. Predictive models for land evaluation may require land cover information. Classic example: 'C' factor in the USLE. Also, predicting runoff from storms using the SCS Curve Number method depends heavily on current land cover (see (Pilgrim & Cordery, 1993) §9.4.2).

2.1 General-purpose land cover classifications

These are intended to classify land cover at a certain level of detail. An example is the USGS land cover classification (Anderson *et al.*, 1976, United States Department of the Interior - U.S. Geological Survey, 1990). This has three levels: (1) general kind of land use (urban, agricultural, rangeland, forest, water, wetland, barren land, tundra, and perpetual snow & ice), (2) major land use (e.g., residential, cropland). (3) specific kind of land use (e.g., single-family detached dwellings, winter small grains). Each level is appropriate to a particular spatial, temporal, and spectral resolution of the supporting imagery. Here is the Anderson Level 1 & 2 classification:

Land use codes for LUDA data, Levels 1 and 2		
1 Urban or Built-up Land 11 Residential 12 Commercial and Services 13 Industrial 14 Transportation, Communication, and Utilities 15 Industrial and Commercial Complexes 16 Mixed Urban or Built-up Land 17 Other Built-up Land 2 Agricultural Land 21 Cropland and Pasture 22 Orchards, Groves, Vineyards, Nurseries, & Ornamental Horticultural Areas 23 Confined Feeding Operations 24 Other Agriculture Land	3 Rangeland 31 Herbaceous Rangeland 32 Shrub and Brush Rangeland 33 Mixed Rangeland 4 Forest Land 41 Deciduous Forest Land 42 Evergreen Forest Land 43 Mixed Forest Land 5 Water 51 Streams and Canals 52 Lakes 53 Reservoirs 54 Bays and Estuaries 6 Wetland 61 Forested Wetlands 62 Non-forested Wetlands	7 Barren Land 71 Dry Salt Flats 72 Beaches 73 Sandy Areas other than Beaches 74 Bare Exposed Rock 75 Strip Mines, Quarries, and Gravel Pits 76 Transitional Areas 77 Mixed Barren Land 8 Tundra 81 Shrub and Brush Tundra 82 Herbaceous Tundra 83 Bare Ground Tundra 84 Wet Tundra 85 Mixed Tundra 9 Perennial Snow or Ice 91 Perennial Snowfields

Notice that this classification would be useless for many purposes, e.g. differentiating small-holders practicing traditional agriculture from market-oriented large farmers. The classification must fit the purposes of the evaluation.

Another example is the ecological classification of Holdridge (1967), widely used in Latin America to distinguish 'life zones' that have a well-defined set of possible uses and limitations as well as human ecology.

2.2 Method 1 : Vegetation indices

This is not really a complete land cover classification, but if the type of vegetation is the primary concern, these are very useful and often sufficient. For example, the 'cover' factor in a hydrologic model is often directly related to vegetative density and vigor.

NDVI: *Normalized Difference Vegetation Index*

$$NDVI = \frac{NearIR - R}{NearIR + R}$$

Landsat TM: NearIR = Band 4, R = Band 3; AVHRR : Bands 2 and 1.

Values from -1 (no NearIR reflectance, complete R reflectance, typical of bare soil or water) to +1 (complete NearIR reflectance, complete R absorbance, typical of healthy chlorophyll).

This has a good theoretical basis, i.e., the difference in reflectivity of chlorophyll.

Analysis of time sequences for classification of vegetation *patterns* (Eastman & Fulk, 1993): the sequence of 'greenness' reflects the seasonality.

2.3 Method 2 : Supervised classification

Basic idea: train the computer to recognize landscape elements by their *spectral signatures*, assuming that we know what is where in some *training sites*.

Advantage: can classify the image according to an existing, possibly standard, classification, e.g. USGS Land Use / Land Cover (Anderson *et al.*, 1976) or for a specific use of interest (e.g. mangrove swamps, hydrophylic vegetation).

Disadvantage: selection of training sites (see below) may be *biased*, leading to a biased classification.

Warning! The classification may be less than completely successful, because of inherent problems in the image. These are of two types: omission (can't differentiate classes) and commission (differentiate spurious classes).

Errors of *omission*: It may be impossible to differentiate some classes of the classification system. Example: for an image taken in midwinter in the SE USA, pasture vs. winter small grains.

Errors of *commission*: areas of the same use according to the classification system may look very different in the image, due to management differences. For example: sugar cane in full growth vs. just harvest vs. burned, all are the same land use. The solution is to subdivide the class according to these differences during the classification, then join them for the final map.

General procedure:

1. The analyst selects the land use/land cover legend (may be an existing system). If on inspection of the image it is obvious that some classes are divided into several spectral groups, the legend may be split accordingly. Example: forest in sun and shade. These will be classified separately and then combined in the final map.

2. The analyst identifies sets of sites *on the ground* (or possibly on other maps) which correspond to each class. These are called the *training sites* since they will be used to 'train' the automated system. These are *digitized* and referred to the same coordinate system as the image. They can be digitized

on-screen (IDRISI command COLOR 'd') if the use is obvious in the image, or from a secondary map of land use in the selected sites, or boundaries obtained by field survey (e.g. GPS) can be entered directly from the keyboard.

3. The system calculates the *spectral signatures* (multivariate range, mean, standard deviation) of each land use class from the cells included in the training sites for that use (IDRISI command MAKESIG).

4. The analyst reviews the signatures to see which bands best differentiate the uses, and which classification method would give the best results (IDRISI command SIGCOMP)

5. The system allocates each cell in the complete image to one of the land use classes, based on its values in the selected bands, according to the classification method (maximum likelihood: MAXLIKE, minimum distance to centroid: MINDIST, bounding parallelepiped: PIPED).

6. Either the training sites or another set of sites with known uses, the *validation sites*, can be compared with the classification, using a *confusion matrix*, to determine the success of the classification. Errors of *commission* (the system states that a land use is present, when it isn't) vs. *omission* (the system states that a land use is absent when in fact it is present); overall classification accuracy can be judged with Chi-squared type techniques (IDRISI command ERRMAT).

2.4 Method 3 : Unsupervised (automatic) classification

Basic idea: the computer separates the image using information theory, into a classification that 'best' (in an information-theoretic sense) differentiates pixels.

Advantage: objective classification, the computer faithfully reflects the most important differences in an information-theoretic sense, without prejudice. Brings out the differences that the image can best reveal.

Advantage: does not depend on the (possibly biased) selection of training sites

Disadvantage: may not classify according to the land use classification we have in mind; maybe can combine classes, but maybe they are incompatible.

General procedure:

1. A set of (usually three) bands are combined into one *false color composite* (IDRISI command COMPOSIT). Note: If the *principal components* are used, almost all the information of the original image is retained.

2. The system divides the cells of the composite into classes which *maximizes* the *inter-class* variance and *minimizes* the *intra-class* variance (IDRISI

command CLUSTER). This is accomplished by analyzing the *histogram* of the composite image, and looking for peaks and valleys.

3. Each cell is classified by this division. If the classified image is too 'patchy', it can be smoothed by using a mode filter.

4. The analyst must now add a *legend* to the classified image, possibly combining classes which, although having different spectral characteristics, represent the same land use. This almost always involves a field visit or at least comparison with a known land-cover map or higher-resolution imagery (e.g. airphotos).

2.5 Evaluating the accuracy of a classification

The basic idea is to compare the predicted classification (supervised or unsupervised) of each pixel with the actual classification as discovered by *ground truth*. A good review of methods is given by (Congalton, 1991).

Four kinds of accuracy information:

1. *Nature* of the errors: what kinds of information are confused?

2. *Frequency* of the errors: how often do they occur?

3. *Magnitude* of errors: how bad are they? E.g., confusing old-growth with second-growth forest is not as 'bad' an error as confusing water with forest.

4. *Source* of errors: why did the error occur?

2.5.1 The Confusion Matrix

The analyst selects a sample of pixels and then visits the sites (or vice-versa), and builds a *confusion matrix*: (IDRISI module CONFUSE.). This is used to determine the *nature* and *frequency* of errors.

columns = ground data (assumed 'correct')

rows = map data (classified by the automatic procedure)

cells of the matrix = count of the number of observations for each (ground, map) combination

diagonal elements = agreement between ground and map; ideal is a matrix with all zero off-diagonals

errors of omission (map producer's accuracy) = incorrect in column / total in column. Measures how well the map maker was able to represent the ground features.

errors of commission (map user's accuracy) = incorrect in row / total in row. Measures how likely the map user is to encounter correct information while using the map.

Overall map accuracy = total on diagonal / grand total

Statistical test of the classification accuracy for the whole map or individual cells is possible using the *kappa* index of agreement. This is like a χ^2 test except that it accounts for chance agreement.

2.5.2 Sample confusion matrix

		Ground classification		
		A	B	C
Map Classification	A	1	2	3
	B	0	2	0
	C	4	1	1

Overall *accuracy*: (10+20+10)/(10+2+3+0+20+0+4+1+10)= 40/50 = 80%

Error of *commission* for class A: (2+3)/(10+2+3) = 5/15 = 33% error

Error of *omission* for class A: (0+4)/(10+0+4) = 4/14 = 29% error

2.5.3 Fuzzy accuracy assessment

There is a fundamental problem with the confusion matrix: the ground data may not be just 'correct' but 'somewhat correct'... a problem of classification. (Gopal & Woodcock, 1994) provide a good introduction to this problem and to the use of fuzzy sets to solve it.

Basic idea: an expert can classify ground truth using *linguistic variables* on a scale of 1-5: (1) absolutely wrong, (2) understandable but wrong, (3) reasonable, acceptable but there are better answers, (4) good answer, (5) absolutely right. Then the confusion matrix is expanded to answer two more precise questions:

(1) How frequently is the map category the best possible choice?

(2) How frequently is the map category acceptable?

Various fuzzy measures of correctness can be constructed to answer these questions.

A *fuzzy set A* over a universe of possible members *X* consists of members, a generic member being labeled as , along with a *membership grade* for each member *x*, defined either by enumeration or by a function:

$$A = \{(x, \mu_A(x)) | x \in X\}$$

where the membership function $0 \le \mu_a(x) \le 1$. Intuitively, 1 = totally in the set, 0 = totally not in the set. Traditional *crisp* sets only allow values of 0 or 1, corresponding to *false/true*, *out/in*, *wrong/right* etc.

In the context of map accuracy assessment:

X is the set of evaluation sites, i.e., polygons or pixels where we will compare the mapped and actual values.

There is a separate fuzzy set A_C for each class $c \in C$, where *C* are the classes, e.g. *C* = {"urban", "suburban", "deciduous forest", "evergreen forest", "mixed forest", "water"}. Note that this implies that a given site can be in *more than one class*, with varying degrees of correctness.

Suppose we have five accuracy evaluation sites: *X* = {a, b, c, d, e}

Then we might have A_{water} = {(a,.5), (b,0), (c,1), (d,.75), (e,.25)}, where the linguistic scale 1-5 has been transformed to a membership scale 0, ..25, .5, .75, 1. So site 'b' is absolutely not water, site 'c' is absolutely water, if site 'd' were classified as water it would be a good but not ideal answer, etc.

To measure the *magnitude* of errors, we can define a function to be evaluated at each site *x*:

$$\Delta(x) = \mu_{\chi(x)}(x) - \max_{C \in \mathbf{C}, C \neq \chi(x)} \mu_C(x)$$

where $-4 \le \Delta(x) \le +4$, if the linguistic variables range from 1 to 5. ±4 indicates maximum deviation, 0 is perfect agreement. These scores can be used to weight the confusion matrix or compute other functions.

Question: (1) How frequently is the map category the best possible choice?

Answer: Define:

$$MAX(x,C) = \begin{cases} 1 & \text{if } \mu_x(x) \ge \mu_{c'}(x), \forall c' \in \mathbf{C} \\ 0 & \text{otherwise} \end{cases}$$

I.e., *MAX(x,C)* is 1 iff C is the best answer among the answers given. Then use *MAX* in the confusion matrix.

Question: (2) How frequently is the map category acceptable?

Answer: Define:

$$RIGHT(x,C) = \begin{cases} 1 & \text{if } \mu_x(x) \ge \tau \\ 0 & \text{otherwise} \end{cases}$$

where τ is the *threshold* of 'correctness', selected by the expert to correspond to 'good enough'. Then use *RIGHT* in the confusion matrix.

2.6 Spectral heterogeneity in a land cover class (high-frequency features)

The above methods work on a pixel-by-pixel basis, and take no notice of the *spatial structure* of the image. A variety of methods have been developed that do account for this structure. The introduction to (Fung & Chan, 1994) provides a good review.

Spectral heterogeneity (rapid fluctuations in spectral values over short distances) is related to *high-frequency* features, caused by

(1) higher radiometric and spatial resolution of the sensor itself; and

(2) land use types with intimately-mixed land cover types, which can be distinguished by the sensor but which are really part of the same land use at the desired generality of classification.

A classic example is suburban land, which consists of intermixed houses, lawns, trees and streets. Supposing we are not interested in mapping pixels of each of these land covers, but rather in the land use 'suburban residential', some way must be found to include all these in one class.

In general, we refer to the *spatial composition of spectral classes* (SCSC). In addition to the radiance values themselves, we can investigate the SCSC of a land cover class. In functional notation:

$$LU_i = f\{SC_j, j = 1...n\}$$

where the SC_j are the spectral classes derived from a per-pixel classification (supervised or unsupervised). The function f can include frequency (rate-of-change across the image) and adjacency information. Then instead of classifying per-pixel, a *moving window* is used, and the set of per-pixel spectral classes in the window is used to determine the most likely function, and from this, the most likely land use class. The optimum window size depends on the resolution of the image vs. the frequency of the land use classes.

3. Data sources for land evaluation: soil surveys

The soil resource is important for most land evaluations. In fact, land evaluation originated with soil surveyors' desire to make their surveys useful to land users. In this lecture we will explain how a soil survey is made and what is can tell us about land characteristics. Modern name for soil survey: *soil resource inventory* (avoids the confusion with 'survey' meaning cadastral survey).

A good introduction to soil survey is (Dent & Young, 1981). The consulting company Booker Agriculture International has published their soil survey manual (Landon, 1984) which is aimed at tropical areas. A readable and practical introduction in the context of forestry is (Valentine, 1986). The original soil survey manual of the USDA (Soil Survey Staff, 1951) is the best single source; it is has been updated. The Agricultural Compendium (EUROCONSULT, 1989), pp. 125-139 introduces field survey techniques.

For land evaluation, the basic question is, given a soil survey, what use can we make of it? How reliable is it? How specific are its statements? To answer these questions we must understand the purposes and kinds of soil surveys, and how they were made.

3.1 Basic aim of soil survey

(Dent & Young, 1981) p. 1: "The practical purpose of soil survey is to enable more numerous, more accurate and more useful *predictions* to be make for *specific purposes* than could have been made otherwise [i.e., in the absence of location-specific information about soils]. To achieve this purpose, it is necessary to:

(1) *determine the pattern* of the soil cover; and to

(2) *divide this pattern* into relatively *homogeneous* units; to

(3) *map the distribution* of these units, so enabling the soil properties over any area to be *predicted*; and to

(4) *characterize the mapped units* in such a way that useful statements can be made about their land use potential and response to changes in management." (punctuation and emphasis is mine)

Note that the map and legend by themselves are not the aim of the soil survey. Instead, it is the *use* that will be made of these. (Of course, from the pedologist's point of view, the soils themselves are the objects of interest.)

A very severe sampling problem: The fundamental problem with soil survey is that we can directly observe only a tiny fraction of the soil, and this sampling

(by auger or shovel) is destructive, i.e., once we have sampled a site we have destroyed its original characteristics. In a few unusual circumstances we can observe some properties of the soil non-destructively and over the entire space (ground-penetrating radar, airborne imagery of the soil surface), but in general we must dig. In practice we rely on *associated* characteristics that we feel are associated with soil *genesis*, i.e., why the soil is there in the first place. Foremost among these are geomorphology (landform analysis). So, even though we have seen the soil itself in a minuscule proportion of its total volume, by relating soil properties to visible landscape features (if possible), we can reliably infer soil properties over the entire landscape.

3.2 Special-purpose and general-purpose soil surveys

Special purpose surveys: for a single well-defined objective. The classic example is an irrigation project. Another example is conservation-oriented farm planning. The advantage of a special-purpose survey is that we know the properties of interest for the special purpose and can concentrate on mapping these, so that the mapping is more rapid and can be done with less-skilled mappers (i.e., not just trained pedologists). But, we may not record properties that are vital for other uses.

Example: Brazilian system for directly mapping the physical environment.

General purpose surveys: provide the basis for a variety of interpretations for various kinds of uses, present and future, including some we can't anticipate now. The advantage is that the survey can be re-used for many purposes. The disadvantage is that the survey isn't ideal for any purpose; also we may not anticipate future needs. Example: 'general purpose' surveys pre-1970 applied to ground-water contamination studies.

The trend has been towards general-purpose surveys, sponsored on a 'speculative' basis coordinated by a national mapping agency (e.g., in the USA, the Soil Conservation Service has formed a National Cooperative Soil Survey). However in countries with less resources and immediate needs, the special-purpose survey prevails.

3.3 Scale and order of the soil survey

See Table 6.1 in (Dent & Young, 1981). The basic questions are: (1) What is a typical *map scale* (implies the *optimum legible delineation* corresponding to 1cm² on the map)?; (2) What is the *intensity* of the survey (density of observations and means of making them)?; (3) What is the *range of properties* (or, the degree of homogeneity) of the mapping units?; (4) What are the mapping units?; (5) What is the *purpose* of the survey?

Main issue for land evaluators: make sure the survey was made at the correct scale for the purposes of the evaluation. See (Forbes, Rossiter & Van Wambeke, 1982) Ch. 1 for a discussion of how to evaluate the scale.

Exploratory: 1:1'000.000 and smaller, OLD 100km²; no field observations (compilations of more detailed maps); very heterogeneous; dominant soil orders; national atlases or wall displays, not useful for planning.

Reconnaissance: 1:250.000 to 1:100.000, OLD 6.25km² to 1km²; widely-spaced observations usually at convenient points, no systematic coverage; heterogeneous; landform groups; resource inventory at regional level, preliminary project location. This has been the preferred scale for the first soil survey of an area in most LDCs.

Semi-detailed: 1:50.000, OLD 25ha; systematic observations every approx. 500m; associations of more-or-less homogeneous classes; associations of phases of soil series; regional land-use planning or project planning for extensive uses. This has been the preferred scale for general-purpose surveys in forest and range areas in the USA and Canada.

Detailed: 1:20.000, OLD 4ha; systematic observations every approx. 200m; more-or-less homogeneous; phases of soil series; farm planning and suburban (low-intensity) planning. This has been the preferred level for general-purposes surveys in agricultural areas in the USA, Canada and Europe. Scales vary from 1:15.000 (OLD 2.25ha) to 1:25.000 (OLD 6.25ha)

Intensive: 1:5.000 to 1:10.000, OLD 2500m² (0.25ha) to 1ha; systematic observations, often on a regular grid, every 50m; homogeneous; phases of soil series or individual soil properties; engineering works

3.4 How is the survey actually made?

A good review of survey methods and sampling strategies is by (Avery, 1987).

Reconnaissance: boundaries are determined from other maps such as geology and physiography. Widely-spaced field checks are used to determine typical soil properties. No estimate of internal variability.

Semi-detailed: airphoto interpretation of landforms, followed by field checking of map unit composition. Sampling is biased towards 'typical' landscape positions, so only crude estimates of internal variability.

Detailed: same as semi-detailed, but at a more detailed level of airphoto interpretation and with field checks of boundary positions. The surveyor actually walks most of the landscape, usually in *free survey*, concentrating on problem areas. In areas with poor correlation of geomorphology to soils (e.g., blankets of volcanic ash in Ecuador, recently-emerged polder soils), the field observations themselves are used to locate the boundaries. There are enough observations, albeit usually biased, to obtain a fairly good estimate of internal variability.

Intensive: systematic field observations on a regular grid, either alone or to supplement the methods used in detailed survey. Sometimes geostatistical methods are used to determine boundaries. In the extreme case, a soil property is presented as a continuous map. Unbiased estimates of internal variability of map units.

3.5 Mapping legends

Each of the more-or-less homogeneous areas of the map must be given a *name* and its properties *described*.

Mapping legend The set of map unit names is the *mapping legend*. This provides names by which we can refer to areas on the map. E.g., "This polygon represents an association of Cazenovia silt loam, 0-3% slope, and Palmyra gravely loam, 3-8% slope."

Descriptive legend: the set of descriptions of their properties is the *descriptive legend*. This is the link between the map and statements that we can make about the map units. E.g., "In this polygon, the water table is always deeper than two meters."

Interpretative legend: a statement about the map unit for a specific purpose, i.e., a result of land evaluation. E.g., "This area is highly suited to intensive mechanized irrigated grain crop production".

Special-purpose legends: the map units are described by their properties; i.e. there is no mapping legend, only a descriptive legend. Each delineation receives a symbol that directly indicates the mapped properties. Example: '3a-d-1' might mean 'texture class '3', slope class 'a', depth class 'd', erosion class '1'. This is appropriate for special-purpose surveys: the legend addresses exactly what the survey is intended to map.

General-purpose legends: the map units are considered to represent *soil classes* that between them divide up the universe of possible soils. Each class is a coherent conceptual grouping of similar soils. It has similar *morphology*, *landscape pattern*, and *genesis*. This is appropriate for general-purpose surveys: from the map unit name, we can infer many different properties, and hence make predictions for many different uses.

3.6 Soil classification: generalities

The classes of a legend can be *locally* defined, or taken from some external *systematic classification*:

Local classifications: the classes are established locally based on observed differences between soils as they occur in the field. They are generally given local names. Advantage: as precise as possible given the local data.

Disadvantage: difficult to compare with other areas. (Butler, 1980) argues the case for this sort of 'bottom-up' classification quite persuasively, and presents a methodology for realizing it.

Systematic classifications: the classes are established in some *hierarchical taxonomy*, and the local soils must be fit into one of the existing classes. Sometimes there is flexibility in that the most detailed level can be defined locally. Advantages: allows comparison of different areas (if the same classification was applied in the same way in both areas - the *correlation* process should ensure this); removes much of the burden of legend-making from the local survey thereby speeding up the survey. Disadvantage: the established concepts may not match the reality of the soils in the survey area.

> Unlike living organisms, soils have no real 'genetics', so no 'true' lineage, therefore any classification is a human construct, and one can only compare classifications on the basis of their utility, not on their intrinsic merits.

Or, as the French soil scientists say, 'the soil has no sex'.

The Agricultural Compendium (EUROCONSULT, 1989), pp. 110-125 presents the basics of various classification systems including the USDA Soil Taxonomy and the FAO Soil Map of the World.

3.7 Soil classification : USDA Soil Taxonomy

Original reference: (Soil Survey Staff, 1975); the system has been revised several times, with new keys. Severe philosophical criticism, e.g. (Webster, 1968) has never been satisfactorily rebutted. See (Buol, Hole & McCracken, 1989) p.208-219 for a good introduction to the system's principles and realization.

A widely-used system with pretensions to universality. It was specifically developed to *support soil survey* in the USA, with some international consultation (more in recent years). It is used in many mapping legends; for example Venezuela uses it as the mapping legend for all soil surveys (despite major soils of Venezuela not being included, e.g. subgroups of Paleustults). Several recent works on systematic soil science (e.g., (Buol, Hole & McCracken, 1989, Van Wambeke, 1992)) are organized around this classification, precisely because its hierarchical nature provides a ready-made outline for discussing soils.

Soil Taxonomy is a *hierarchical* system with six levels of detail, each contained in the next-highest category. Each class has a *central concept* and *range* of properties, these are strictly defined with rigid limits. So to infer soil properties from map unit names, we can follow the keys and see what *diagnostic criteria* the soil must meet to be so classified.

Dirty secret: worldwide, most classification with Soil Taxonomy is done on the basis of central concepts and the supposedly 'rigid' limits are not always

observed. This is the only practical way to use Soil Taxonomy as a mapping legend. There have been attempts to use continuous classification (fuzzy logic) instead of the rigid limits that are conveniently ignored by the practicing classifier. More fundamental objections are to the actual definitions of categories and the single hierarchy.

Names are composed from a series of neoLatin etc. roots (University of Illinois classics professor), except for the lowest categorical level (the series) which is named for a locality near where it was first described. A soil name, including a series, can be used far from where it was first described, if the soils are similar enough. Example: The Matanzas series from W. Cuba is mapped in Hispaniola and Puerto Rico.

The Soil Taxonomy hierarchy

Each level is meant to be defined on increasingly-specific criteria. The higher levels are meant to group 'similar' soils into increasingly-general classes.

Order [11]: Defined by the presumed presence of major soil-forming processes as indicated by *diagnostic horizons* or properties of over-riding importance. Alfisols, Andisols, Aridisols, Entisols, Histosols, Inceptisols, Mollisols, Oxisols, Spodosols, Ultisols, Vertisols. Why not 'Aquasols' (FAO Gleyosols)?

e.g., Alfisols (high-base status soils with illuvial clay in the subsoil)

Suborder [≈ 60]: Subdivision of orders according to soil moisture regimes, wetness, major parent material

e.g., Udalfs (usually-moist but not wet Alfisols)

Great group [≈ 250]: Subdivision of suborders based on kind and arrangement of horizons and presence or absence of secondary diagnostic horizons

e.g., Hapludalfs (typical of the Udalfs, as opposed to e.g., Fragiudalfs = with a fragipan)

Subgroup [≈ 1,500]: *Central concept* of a great group or intergrades to other great groups, or extragrades to 'not soil'

e.g., Aquic Hapludalfs (Hapludalfs saturated with water for a small portion of the year, as opposed to Typic Hapludalfs

Family: Subdivision of subgroup based on general textural class of entire soil, dominant mineralogy, and soil temperature regime

e.g., fine-loamy, montmorillonitic, mesic Aquic Hapludalfs (includes soil texture, climate and mineralogy)

Series [≈ 15,000 in the USA and PR]: Detailed arrangement and properties of horizons

e.g. Lima

In addition, each of these may have one or more phase modifiers in the actual mapping legend. These modifiers refer to non-taxonomic criteria (i.e., not important to soil genesis) which are important for the use of the map unit. Examples: stoniness, slope, surface soil texture.

Complication: the soil series as *mapped* generally has a different range of properties than the *taxonomic* soil series, even if it is quite homogeneous. The problem is that the soil series must fit into the higher levels, i.e., family and above, and these may impose artificial limits on the series.

Example: The Cecil series (typical Piedmont 'red clays') as mapped in its original location in Maryland has a base saturation in the clayey subsoil of 30-40%, even within one delineation (i.e., can't separate by more detailed mapping). This is a reasonably narrow range, sufficient for reliable interpretations, yet it overlaps the rigid boundary between two soil orders (highest category) 'Alfisols' (>35%) and 'Ultisols' (<35%).

3.8 Soil classification : FAO-UNESCO Soil Map of the World

See (EUROCONSULT, 1989) §2.7.3 for a brief introduction.

In many areas of the world, the FAO Soil Map of the World at 1:5'000.000 is the only source of soils data. Also, it has been digitized and is available through the GRID program of the UN. Many FAO and related projects use this system also, so the land evaluator should understand how to interpret its names. The purpose of this classification was only to serve as a legend of the Soil Map of the World, it was never intended to be a field mapping legend. The categories are not strictly defined as in the USDA system. The system uses diagnostic horizons, but again these are not so strictly defined. So, only general properties of the soil can be inferred from this legend.

This map has been published in 10 volumes (19 map sheets) with a descriptive legend that describes each soil group (Food and Agriculture Organization of the United Nations, 1974). The legend has recently been updated to provide a third (more specific) level of information (Food and Agriculture Organization of the United Nations, 1990).

Two levels of detail: 26 *major soil units* (similar in detail to USDA suborders) and 106 *soil units* (similar in detail to USDA great groups). Names are a mixture of traditional, national (especially Russian), and USDA. Examples: Af = Ferric Acrisols; Pg = Gleyic Podzols. Some major soil units are not subdivided, i.e., E = Rendzinas, U = Rankers and I = Lithosols. Each delineation on the map has a symbol made of its dominant soil, the type and proportions of its constituent soils, its general textural class (coarse, medium or fine) and its dominant slope class (0-8%, 8-30%, >30%). Example: 'Lc5-3a'.

Key points: The categories are not strictly defined, there was no binding correlation of names, the sheets were made on the basis of experience, not necessarily mapping (n.b., each sheet comes with a key map indicating how

much actual field mapping was done for each area), the OLD is very large: 2,500 km². Still, useful information can be extracted, especially on major soil limitations to land use.

3.9 Soil classification: national systems

Many countries with well-organized soil surveys have developed their own classification systems. Examples: Canada, South Africa, Brazil, England & Wales, France, the Netherlands, Australia, New Zealand. The reference manual for these systems provides a wealth of information about soil properties.

Other countries map soil series (often at different levels of detail) alone or in associations, e.g. Philippines.

Francophone African countries use a strongly pedological legend developed by ORSTOM.

(Buol, Hole & McCracken, 1989) Ch. 14 provides a summary of, and references for, most of these systems.

3.10 Soils databases

The large quantities of information on soils, both in maps and tables, is slowly being organized into computerized databases. The most advanced systems are in the Netherlands, Canada, and the USA. Tabular data is easier to computerize than maps, because many soil maps were made without regard to map accuracy standards. Soils databases should be organized as a group of *relational tables*. Each table contains information relevant to the entity at that level of abstraction, and links to other tables.

A typical soils database structure is:

1. *Map units*, i.e., what is actually shown on the soil map: key: Map Unit ID; data: Component ID & their percentages within the map unit, attributes of map units such as total area of all delineations, descriptive name

2. *Components* of map units: key: Component ID; data: landscape position within Map Unit

3. *Pedons* (representative soil profiles): key: Component ID + Pedon ID; data: location, site characteristics, whole-pedon attributes such as depth to water table

4. *Layers* of pedons: key: Pedon ID + Layer ID; data: depth from surface, measured properties, morphology

In this data model, a component can be part of various map units (many-many relation) but layers are within pedons (many-1) and pedons are within components (many-1). In addition, if there is a geographic information system showing individual delineations, there will be another table (many-1 with the map unit table):

5. *Polygons* (or, delineations): key: Polygon ID (over the whole map); data: Map Unit ID, delineation attributes such as area

We use the relational database manager to answer *queries* (questions) about different entities in the database.

To make statements about a *pedon*, we may need to aggregate information about *layers*. E.g., hydraulic conductivity of the pedon is generally the slowest of its layers; total available bases in the pedon is the sum of the bases in its layers.

To make statements about a map unit *component*, we may need to aggregate information about its representative *pedons*. E.g., average depth to bedrock in the component is the average of that data field in the pedons that represent the component.

To make statements about *map units*, we may need to aggregate information about its *components*, but if the components are supposed to occur on different landscape positions, we may prefer to make separate statements about each component.

To make statements about *delineations* (polygons), we look at the related *map unit* in which it is included.

4. Data sources for land evaluation: climate and hydrology

Probably the most important factor for land use is the climate. Almost all land uses are substantially affected by rainfall, temperature, air humidity, and especially the timing of these events. Geographers have been recording this information for a long time, and the variety of measurement and recording techniques can be confusing.

Hydrology data (the location and amount of water in its various forms) is very important for land uses that make use of water resources other than precipitation.

4.1 Climatic regions

For some land evaluations, we don't need weather data *per se*, rather, we need a *zoning* or division of the study area according to its overall *climate*. If we can find a climatic classification that suits our purpose, we can save a lot of work by using the results of climatologists and geographers. Maps based on these systems can be found in most general atlases, usually at scales of 1:5'000,000 or smaller, but the principles can be used to produce maps with more cartographic detail.

Climatic regions are especially useful for regional-scale land evaluation where the broad climatic differences are of overriding importance. Example: slash/mulch systems seem to be suitable in Köppen region Af but less successful in region Aw (see below).

Definition: "The term *Climate* is a generalized integration of weather conditions over a defined period of time in a given area." (EUROCONSULT, 1989) §1.1. So the climate records the most important general factors, and is a very useful zoning tool. It refers to *long term* averages.

4.1.1 Köppen classification

Summary: (EUROCONSULT, 1989) §1.1.1

Purpose: divide the world into general climate regions. Some countries, e.g., Mexico, have refined the system with lower categorical levels to give a finer description of climate in their national territory. The map unit boundaries are determined from analysis of long-term climatic data, and where data is sparse, from natural vegetation.

Main zones: A = Tropical rainy, B = Dry, C = Warm, temperate rainy, D = Cool, E = Polar

Subdivisions based on: (1) long-term mean temperature; (2) long-term mean precipitation; (3) rainfall distribution: a = annual, s = astronomical summer, w = winter; (4) driest, wettest, hottest, and coldest months

Examples: Aw : sub-humid tropical; Aw" : subhumid tropical with two rainfall maxima; Af : humid tropical; Afa : humid tropical with a hot summer (T_{hm}> 22° C); Bwh : subtropical desert

Local subdivisions can be even finer, e.g. (Duch Gary, 1991) in a study of the Yucatan follows the system of (Garcia, 1981) in dividing type Aw into subtypes Aw, Aw(w) and Aw(x'), where (x') corresponds to greater winter rainfall and (w) to lesser winter rainfall (although in both cases, winter is the dry season). These are in turn subdivided, e.g. Aw(x') into Aw0(x'), Aw1(x') and Aw2(x') on the basis of total rainfall within the subhumid climate, and then into regions based on other factors not reported, leading to formulas like Aw0"(x')(i')g. The question, of course, is whether these finer divisions match our land evaluation purposes. For natural vegetation they presumably do.

4.1.2 Holdridge's Life Zones

This system (Holdridge, 1967) was developed in Costa Rica and is very popular in Central and South America. The objective is to determine the natural ecological regions in which certain native floristic assemblages are to be expected. We can see this is in the life zone names, e.g. 'Humid tropical forest'. The idea is that these zones are 'natural' for certain human uses also. For example, natural grassland steppes are idea wheat areas. As with the Köppen system, map unit boundaries are determined from analysis of long-term climatic data, and where data is sparse, from natural vegetation.

Holdridge considers that plants are affected by *moisture availability*, which in turn is determined from *precipitation* and *potential evapo-transpiration* (PET) PET in turn is determined from *temperature*. In this system, there are three axes, any two of which are sufficient to determine the third, and the life zones are conceived as hexagonal regions on the graph.

In intertropical areas, the *altitude* determines the temperature; in other regions, the *latitude* determines the temperature.

4.1.3 Thornthwaite's moisture index

This simple index (EUROCONSULT, 1989 §1.1.2) relates mean precipitation and mean potential evapotranspiration, to obtain an overall indication of moisture deficit over a year.

Moisture index = $I_m = (100s-60d)/n$

where s = moisture surplus, d = moisture deficit, and n = PET, all in the same units. $I_m = 0$ indicates a neutral climate, >0 = humid, <0 = dry.

Problem: the '100' and '60' are empirical, from US data.

4.1.4 USDA Soil Taxonomy soil moisture and temperature regimes

Soil Taxonomy included soil climate as an important diagnostic criterion (not without considerable controversy, n.b. the FAO Soil Map of the World does not say anything about climate). In practice, soil climate is inferred from atmospheric climate with empirical models (although GAPS could be used for this purpose). Van Wambeke classified a large number of sites worldwide according to their soil climate, and proposed subdivisions of the original system.

The limits are meant to be important for soil processes and land use. Their names are connotative, e.g. Udic, Ustic, Aridic, Xeric moisture regimes; thermic, mesic, and frigid temperature regimes, iso- vs. non iso-.

If an existing map of soil climate is available, or if all soil map units have been classified according to their soil climate, this can be a very useful statement about long-term climate. Note that there are many atmospheric climate factors that are not included in soil climate (e.g., wind, dew, air humidity).

4.1.5 Agro-ecological zones (AEZ)

We will see the FAO AEZ in a later lecture. The basic idea is to classify climates directly for each land utilization type (in practice, a crop and management level) rather than rely on geographical or ecological climate classifications.

4.2 Types of weather and hydrology data

In many land evaluations, ready-made climatic classifications are not sufficiently detailed or are not suited to the purposes of the land evaluation, so that the evaluator has to use the original data. This section examines the kinds of data that are commonly measured and some problems in their use for land evaluation.

A good introduction is Part I 'Hydrological Measurements' in (Shaw, 1988). The Agricultural Compendium (EUROCONSULT, 1989) discusses data collection methods (§1.3), precipitation data (§1.2.5), evaporation (§1.2.3), temperature (§1.2.1), and wind (§1.2.2).

A very real problem is that measurement methods vary, and give substantially different results. Careless calibration or observational technique can compound this problem. (Shaw, 1988) Ch. 9 'Data Processing' has a nice discussion of quality control and assurance. She makes obvious but vital points such as: "The worth of rainfall data depends primarily on the instrument, its installation, its site characteristics, and its operation by a responsible observer. It is essential for a hydrologist using the data to have direct knowledge of a rain gauge station..." The land evaluator should certainly not trust climate records presented as-is, unless supplied by an agency with a known quality control record.

4.3 Time series

Weather data is only useful when it is collected over time. The sequence of data for the same variable over time is called a *time series*. Special statistical tools are used to analyze time series; (Shumway, 1988) is an accessible reference. The point is to characterize the entire sequence of observations by a few parameters that do not lose the time element (as do aggregate statistics such as annual totals).

Time series show *periodicities* of various *frequencies*. A time series presented in the *time domain* (original data) can also be viewed in the *frequency domain*, i.e., as a series of trigonometric functions of various frequencies. In climate and hydrology, there is almost always an annual frequency component. Longer-term cycles are also interesting, e.g., El Niño-Southern Oscillation (ENSO).

4.4 Frequency analysis

Especially for risk analysis, we very often want to know a complete *probability distribution* of rainfall amounts (and, less commonly, other meteorological variables). In practice this is obtained from long-term time series. Even in the areas of least temporal variability, 20 years is an absolute minimum for making any kind of reliable statement about the frequency distribution. 30 years is acceptable in many areas, although to capture extreme events in the tails of the distribution (e.g., very dry or very wet years), 50 years or more are needed. Generally, longer records are needed in drier areas.

The probability distributions to be fitted are of three general types, in decreasing order of skewness: (1) J-distribution (approximately negative exponential); (2) lognormal with positive skew; (3) normal. The latter is typical of annual totals, the second of monthly totals, and the first of daily totals. A *binomial* distribution can be fitted to the number of days with/without significant rainfall, without respect to amount.

4.5 The problem of spatial variability and interpolation

For land evaluation, a major problem is that in traditional measurements, weather is observed only at specific points (weather observation stations), yet we usually want to know the weather at any point in the evaluation area.

Note: recent advances in sensors and data processing are aiming at complete-area weather knowledge. For example, in the USA, the NEXRAD weather radar, operating continuously and covering the entire lower 48 states, will be calibrated to give reliable rainfall amounts on a grid size of about 1km². Geosynchronous ('stationary') weather satellites already can provide cloud cover and some information about cloud type continuously on a 16km² grid. The big

problem here is data storage and processing; the amount of data is staggering, especially considering that it is captured more-or-less continuously.

4.5.1 Interpolation of rainfall amount

Rainfall is not measured continuously over space, yet we may often need an estimate of the rainfall at a *point* or over an *area*. In each case there are a variety of methods, all of which are 'valid' under certain assumptions and can give best results.

To compute rainfall at a *point* not sampled: (1) take the closest station with a record; (2) take an unweighted average of nearby stations that are presumed to have the same rainfall regime; (3) take a weighted average of nearby stations; (4) construct an *isohyetal* map and interpolate the value for the point between the isohyets.

To compute rainfall over a *region*: (1) take the unweighted average of all stations within the region; (2) take the area-weighted average of the stations, using the areas of their Theissen polygons as weights; (3) construct an isohyetal map and weight the midpoint value between isohyets by the area of the corresponding band.

The advantage of *isohyets* is that they can be drawn both from station records and from knowledge of terrain, including elevation, aspect, and local effects such as lakes and glaciers. The disadvantage is that they require specialist knowledge.

5. References

1. American Society of Photogrammetry. 1983. *Manual of remote sensing*. 2nd ed. Vol. 1. Theory, instruments and techniques; 2. Interpretation and applications. Falls Church, VA: ASP&RS. 2440 pp. +G70.4 .M29 1983 Engineering

2. Anderson, J.R., Hardy, E.E., Roach, J.T., and Witmer, R.E. 1976. *A land use and land cover classification system for use with remote sensor data*. US Geological Survey Professional Paper 964, Washington, DC: US Government Printing Office. QE75 .P96 No. 964 Engineering

3. Avery, B.W. 1987. *Soil survey methods: a review*. Technical Monograph No. 18, Silsoe: Soil Survey & Land Resource Centre. 86 pp. pp.

4. Barrett, E.C. & Curtis, L.F. 1992. *Introduction to environmental remote sensing*. 3rd ed. London: Chapman & Hall. xx, 426 pp. G70.4 .B27x 1992 Mann

5. Buol, S.W., Hole, F.D. & McCracken, R.J. 1989. *Soil genesis and classification*. 3rd ed. Ames, IA: The Iowa State University Press. xiv, 446 pp. S591 .B941 1989 Mann

6. Butler, B.E. 1980. *Soil classification for soil survey*. Monographs on soil survey, ed. P.H.T. Beckett, R.W.a.V.C.R. Oxford: Oxford Science Publications. 129 pp. S592.16 .B98 Mann

7. Congalton, R. 1991. *A review of assessing the accuracy of classifications of remotely sensed data.* Remote Sensing of Environment 37: 35-46. QC808.5 .R38 Engineering

8. Dent, D. & Young, A. 1981. *Soil survey and land evaluation*. London, England: George Allen & Unwin. S592 .14.D41 Mann

9. Duch Gary, J. 1991. *Fisiografía del estado de Yucatan: su relación con la agricultura*. Chapingo, México: Universidad Autónoma Chapingo. 229 pp.

10. Eastman, J.R. & Fulk, M. 1993. *Long sequence time series evaluation using standardized principal components.* Photogrammetric Engineering & Remote Sensing 59(8): 1307-1312.

11. EUROCONSULT. 1989. *Agricultural Compendium for rural development in the tropics and subtropics*. Amsterdam: Elsevier. 740 pp. S481 .A27 1989 Mann

12. Food and Agriculture Organization of the United Nations. 1974. *Soil map of the world*. Vol. 1 : Legend. Rome: FAO. vii, 59 pp. G3201s.J3 5000 F6 (Olin) ...F68 (Mann)

13. Food and Agriculture Organization of the United Nations. 1990. *Soil map of the world : revised legend*. World Soil Resources Report 60, Rome: FAO. 119 pp. S591 .F68 No. 60 Mann

14. Forbes, T.R., Rossiter, D. & Van Wambeke, A. 1982. *Guidelines for evaluating the adequacy of soil resource inventories*. 1987 printing ed. SMSS Technical Monograph #4, Ithaca, NY: Cornell University Department of Agronomy. 51 pp. S592.14 .F69 Mann

15. Fung, T. & Chan, K.-c. 1994. *Spatial composition of spectral calsses: a structural approach for image analysis of heterogeneous land-use and land-cover type*. Photogrammetric Engineering & Remote Sensing 60(2): 173-180.

16. Garcia, E. 1981. *Modificaciones al sistema de clasificación climática de Köppen*. 3a. ed. México, DF: Edición particular.

17. Gastellu-Etchegorry (ed.), J.P. 1990. *Satelite remote sensing for agricultural projects*. World Bank. 227 pp. S494.5.R4 S27x 1990 Mann

18. Gopal, S. & Woodcock, C. 1994. *Theory and methods for accuracy assessment of thematic maps using fuzzy sets*. Photogrammetric Engineering & Remote Sensing 60(2): 181-188.

19. Holdridge, L.R. 1967. *Life zone ecology*. Revised ed. San José, Costa Rica: Tropical Science Center. 206 pp. QK901 .H72 1967 Mann

20. Jensen, J.R. 1986. *Introductory digital image processing*. Englewood Cliffs, NJ: Prentice-Hall. 379 pp. G70.4 J54 Engineering

21. Landon, J.R. (ed). 1984. *Booker tropical soil manual : a handbook for soil survey and agricultural land evaluation in the tropics and subtropics*. New York: Longman. xiv, 450 pp. S599.9.T76 B72 1984 Mann

22. Lillesand, T.M. & Kiefer, R.W. 1987. *Remote sensing and image interpretation*. 2nd ed. New York: John Wiley & Sons. xiv, 721 pp. G70.4 .L72 1987 Engineering reserve

23. Mulders, M.A. 1987. *Remote sensing in soil science*. Developments in Soil Science 15, Amsterdam: Elsevier. 379 pp. S592.135 .M95 1986 Mann

24. Pilgrim, D.H. & Cordery, I. 1993. *Flood runoff,* in *Handbook of Hydrology,* Maidment, D.R., Editor. New York: McGraw-Hill. p. Chapter 9. GB 662 .5 .H23 Engineering

25. Shaw, E.M. 1988. *Hydrology in practice*. 2nd ed. London, England: Van Nostrand Reinhold (International). xiii, 539 pp.

26. Shumway, R.H. 1988. *Applied statistical time series analysis*. Prentice Hall Series in Statistics, ed. Wichern, R.A.J.a.D.W. Englewood Cliffs, NJ: Prentice Hall. 379 pp.

27. Soil Survey Staff. 1951. *Soil survey manual*. Agriculture Handbook 18, Washington, DC: US Department of Agriculture. 503 pp.

28. Soil Survey Staff. 1975. *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*. Agricultural Handbook 436, Washington, DC: US Department of Agriculture Soil Conservation Service. 754 pp.

29. United States Department of the Interior - U.S. Geological Survey. 1990. *Land use and land cover digital data from 1:250,00- and 1:100,000-scale maps: Data users guide 4 (US GeoData - National Mapping Program Technical Instructions)*. Reston, VA: United Stes Department of Interior, U.S. Geological Survey. iv, 33 pp. GA118 .L25 1990 Mann Reference

30. Valentine, K.W.G. 1986. *Soil resource surveys for forestry: soil, terrain, and site mapping in boreal and temperate forests*. Monographs on soil and resources survey 10, ed. Beckett, P.H.T. Oxford, England: Clarendon Press. x, 147 pp. SD390 .V15 1986 Mann

31. Van Wambeke, A. 1992. *Soils of the tropics: properties and appraisal.* New York: McGraw-Hill. ix, 343 pp. S599.9.T76 W24 1992 Mann Reserve

32. Webster, R. 1968. *Fundamental objections to the 7th approximation.* J. Soil Sci. 19: 354-366.