LANDSCAPE - GUIDED CLIMATIC INVENTORY USING REMOTE - SENSING IMAGERY
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AN ECOLOGICAL METHOD TO DEAL WITH CLIMATIC POINT DATA, PARTICULARLY IN CASE OF LOW DENSITY NETWORKS USING SATELLITE IMAGERY OR AERIAL PHOTOGRAPHY

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PREFACE

The production of food and other crops is dependent to a great extent on climate and soils. The Food and Agriculture Organization has since its inception paid attention to increasing knowledge of climatic conditions in the developing countries. In recent years, the Organization has greatly benefited by the use of a range of remote sensing technologies for a wide range of purposes.

The landscape guided method for climatic inventory described in this report was initially designed to overcome shortcomings in other climatic mapping techniques, under conditions of scarce data availability in developing countries, for national land resource inventories. The results of this pilot study in Kenya provide evidence which indicates that landscape features shown on satellite imagery and on aerial photography offer information that could be useful in a variety of climatological applications.

The methods were developed as a result of close cooperation between the Remote Sensing Centre (AGRT), the Land and Water Development Division (AGLS), and the Climatic Service of the Plants Division (AGPC).

The method was developed and tested by Franke van der Laan, who wrote this report, with technical cooperation from A.H. Kassam and H. Van Velthuizen. Local technical and administrative assistance were kindly provided by V. Odenyo, Director, and S. Kalyango, of the Regional Remote Sensing Facility in Nairobi, Kenya. Support and encouragement were provided by G.M. Higgins, Chief, Soil Resources, Management and Conservation Service, J.A. Howard, Chief, Remote Sensing Centre, and M. Frère, Chief, Climate Service.

The report is published as an example of a method which could prove useful in refining the knowledge of climatic conditions in many countries. It would be appreciated if the comments of readers, particularly those who use or adapt the methods described, could be sent to either Dr. Howard or Mr. Higgins at FAO Headquarters in Rome.
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SUMMARY

In the last 10-15 years, satellite imagery and aerial photographs have become available at almost any scale and from almost every part of the world.

This report attempts to show that landscape features on imagery can be as useful an indicator for climate in climatic inventory as for soil, vegetation and geology in which fields imagery is already widely used.

Attention is focused on the use of one or a limited number of images as a base for interpretation of climatic point data, according to the landscape guided approach. The results that can be obtained with this method are illustrated using mean annual rainfall data and Landsat imagery from a part of Kenya.

It is to be hoped that the results are convincing enough to stimulate further applications in other parts of the world and in other types of climatic studies.

The landscape-guided approach is suggested as an alternative to current methods of assessing the spatial impact of climate, such as the arithmetic mean, Thiessen polygon, isohyetal method, etc., and particularly for moisture related patterns. By plotting the point reference data on the imagery, the holistic overview of the landscape makes it possible to judge the value of the data from each station and to understand the relationship between landscape gradients and climatic gradients. This permits the use of landscape features to a certain extent to extrapolate climatic conditions, leading to a better spatial and geographical accuracy than in the other methods.

The possibility of critical comparison of the trends indicated by stations and the imagery led in a case study to a surprising number of additional improvements such as detecting human errors, recognition of unrepresentative siting of stations, etc.

Although testing of the method is still required, it shows a promising application in a wide range of conditions.

In this report, the relationship between climate and relevant features on imagery is discussed. Imagery shows topographic features which are the cause of much of the local climatic variation and vegetation and land use patterns which are to a large extent determined by climatic variation. Vegetation patterns, in particular, have a very high indicative value. In spite of the fact that the absolute amount of vegetation varies widely seasonally, and due to the impact of various other ecological factors, it was found that the relative differences indicating the beginning, end, direction and steepness of the landscape gradients remain visible. These differences give the clue to understanding the spatial variation in climatic conditions. The relationship between landscape and climatic gradients can be discovered by plotting the stations on the imagery. Any one image can
assist in achieving the majority of the improvements, although using images of more seasons or years can improve the understanding further.

Imagery is a general tool which can always be useful in studies concerning any climatic parameter, since it permits critical analysis of the data and supplies a continuous reference matrix for interpolation. However, under certain conditions it is more valuable than under others, such as in the following cases:

- if the station network is too open to "catch" the landscape complexity. In complex landscapes the method pays off quicker than in flat regions;

- for reconnaissance scales (1:100 000 - 1:2 000 000) because Landsat imagery supplies the best overview and detail of all imagery;

- if climatic data are expected to be of doubtful quality.

Additionally, imagery is useful to evaluate the representative value of the siting of stations and it is the best tool for integration of climatic maps with any other geographical data (soil, vegetation, landuse maps, etc) in building geographical data bases.

The types of imagery that permit fruitful landscape guided analysis for climatic inventory are discussed. Considering the importance of discrimination of subtle vegetation gradients, false colour imagery is a first requirement. A too large scale (< 1:50 000) lacks overview over the large trends, whilst a too small scale (> 1:5 000 000) lacks detail to determine landuse aspects and drainage patterns. High altitude aerial photography, Landsat imagery, NOAA false colour composites are the most useful products presently, with SPOT and Metric camera to come in the future.

A step-by-step method for the landscape guided approach is indicated in Annex II.

Van der Laan 1985C is a training module on the landscape guided method and includes a series of exercises and examples.
1. **INTRODUCTION**

The results of any study related to climate are bound to be limited by the density of the network of climatological stations.

The fact that point samples are the only source of climatic data has led to an almost unsatisfiable need for denser sampling networks and the development of numerous techniques to "make the best" out of the data. The most common current techniques are sketched in Annex I.

Still, particularly if quantitative results are required, the number of stations is felt to be insufficient or, in other cases, the data bank becomes too big to handle.

Mainly in developing countries, where the networks tend to be rather open, the feeling of dissatisfaction can grow to deep frustration if policy decisions with long term impact, e.g., on land resources management, hydrological engineering or soil conservation have to be made.

The most precise method (Shaw 1983) to bridge the gaps between point data is interpolation using contour lines on topographic maps (see also Annex I).

However, the impact of topography on climate is not easy to assess from these lines, and particularly on reconnaissance scales, the datagaps can be as big or bigger than the distances between the stations.

As a new alternative, it is suggested, where relevant (see chapter 7), to use landscape features as they show on satellite imagery or (false colour) aerial photography.(1)

Imagery is suggested for the following reasons:

- the availability and accessibility of imagery on any scale has become almost worldwide nowadays;

- landscape (or ecological) features are less artificial and abstract than contourlines and often have a more direct relationship with climatic patterns, which makes them easier to use;

- landscape gradients on imagery show as a continuous pattern, forming a convenient reference matrix to evaluate the position and measurements of any station in relation to its surroundings and in relation to the other stations.

(1) Throughout this report, the word "imagery" will be used for any product that gives a holistic view over the landscape, i.e. satellite imagery, aerial photography, radar imagery, etc.
1.1 Objectives

This report deals with climate/landscape relationships. Its objective is to show that landscape features on imagery can be as useful for climatic inventories as for other types of inventories (e.g., vegetation and soil) for which imagery is already commonly used.

This is a first attempt to establish functional relationships between landscape and climatic patterns. The relationships will be illustrated with an example. In this example, the attention will be on the usefulness of Landsat imagery for reconnaissance scale mapping of mean annual rainfall patterns in a part of Kenya.

It is believed that the results obtained are sufficiently convincing to stimulate the use of the landscape guided approach on a wider scale, both thematically (for different climatic parameters and applications) in time (short/long-term studies) and in space (different parts of the world).

1.2 Scope

The importance of a better understanding of climate/landscape relationships is stressed in this report, because imagery has become available almost worldwide in the last 10-15 years, allowing the application of this knowledge fruitfully.

Some major spin-offs and applications could be:

i. The improvement of the spatial accuracy of climatic inventories, particularly in areas where the climatic data are scarce and can be of doubtful quality as is often the case in developing countries. The continuous landscape gradients on imagery serve as a matrix that can assist in filling data gaps and in verification of data quality.

ii. The preparation and integration of map data for computerized, geographically referenced, land resources data bases. In such data bases the climatic data form a major input. The geographical matching of the data in the various data layers can only be achieved using a common holistic landscape matrix as a base (AIS, 1982).

iii. The use of imagery makes it possible in many cases to establish the functional relationship between landscape, climate and sampling points. This permits the re-evaluation of the efficiency of the existing networks. This can lead to detecting crucial gaps and stations that are superfluous and on confusing sites. The general impact is that better results can be obtained with an equal or lower number of stations.

iv. NOAA Vegetation Index Imagery is increasingly being used for national and continental-wide monitoring. In the interpretation of this imagery, the understanding of landscape/vegeta-
tion/climate relationships is as essential as in the landscape guided method for climate inventory. However, as monitoring (dynamic) and inventory (static) have different applications and require different techniques, this report will not deal with NOAA Vegetation Index imagery. This report can be considered as an introduction to one on monitoring, to follow.

1.3 The rationale of the use of landscape features on imagery for climatic inventory (1)

The term 'landscape' features refers to the characteristics of an area as they show up on imagery.

As these features are the result of, and contain, information on the impact of all ecological conditions (i.e., climate, geology, soils, drainage, vegetation, landuse, etc) together, imagery is said to give a "holistic" overview of the landscape (Zonneveld 1975).

Although the impact of one of these conditions cannot easily be separated from that of the others, the holistic overview has proven very useful in various types of inventories (soil, vegetation, geological, etc) as it permits discrimination between areas with similar and with different characteristics and to determine their position and extent. This improves the sampling efficiency in the field verification, during which the image features are translated into the relevant characteristics.

In climatic inventory, optimum sampling density and representation site selection are as important as in other types of inventories. However, it is an aspect which has been rather neglected up to the present (Shaw 1983). It will be shown in Chapter 6 that imagery contains equally useful information on the variation in climatic conditions as it does on variation in soils, vegetation, etc.

The main difference in the use of the landscape guided method for climatic inventory is that the field work stage is replaced by plotting data from meteorological stations on the imagery.

Crucial in the use of aerial photographs or imagery is that a logical relationship between the landscape features and the climatic parameter under study can be established. It is to the assessment and clarification of this relationship that most of this report is dedicated.

(1) Climatology in this report is considered as the study of long-term and retrospective studies as against meteorology studies which are aimed at predicting (short term) future conditions.
2. **MECHANISMS CAUSING SPATIAL VARIATION IN CLIMATIC CONDITIONS**

Climatic conditions form patterns of continuously changing gradients due to the constant movement of air masses, and the acting of various forces on them on the way.

It is the change in steepness of these climatic gradients (either in the short or in the long term) that form the subject of this report. The report does not deal with data collection nor data manipulation nor trend analysis.

The factors that determine climatic conditions are quite well known. It is their interaction in four dimensional space that make it difficult to predict the outcome at a certain moment and place. In order to carry out climatic inventories, an understanding of these factors is required in general, and of the situation in the area of interest in particular.

It is not the objective of this report to deal with the complex of weather determining factors in detail. The interested reader can find this in many handbooks, e.g. Shaw 1983, Ven te Chow 1964, or WMO 1969.

Without topographic disturbances, weather patterns are determined by worldwide movements of air masses, the chances that cold and warm air meet, local convection patterns and the degree of moisture saturation of the air. The final cause of rain is condensation by cooling and the formation of drops large enough to fall effectively. The necessary cooling is almost exclusively due to upward movement of air and the impact of horizontal winds on sloping ground. The original water vapour content of ascending air and the presence of small particles determine how soon condensation will take place (after Cochème 1969).

There is a general consensus on the fact that apart from daily and seasonal fluctuations, the average temperature conditions can be lineally correlated to altitude (Nicholson 1982, Cocheme 1969, Shaw 1983, Kassam 1980).

3. **GENERAL PRINCIPLES FOR ANALYSING LANDSCAPE FEATURES ON IMAGERY FOR CLIMATIC INVENTORY**

Climatic factors play a dominant role in the determination of the ecological conditions. The patterns of natural vegetation on imagery form the best indicators of the variation in ecological conditions in reality.

In areas where the vegetation is disturbed by human activity, landuse patterns take over this role (see section 5.3.6, 6.4.4 and 8.1.9).
The local variation in climatic conditions within the context of the worldwide or regional patterns (e.g. tropics, subtropics) is largely determined by topographic variation in the landscape (see e.g. section 5.1, 5.3.3, 6.4.2).

To a large extent, the topographic variation determines the climatic variation, while vegetation and landuse patterns are deeply influenced by climatic patterns. The imagery thus contains information on causes as well as effects of climatic patterns.

The usefulness of imagery as a supplement to climatic point data is that it contains information on every point in the landscape.

Due to numerous other factors such as soil type and depth, run-off, run-on etc., the landscape features only form a qualitative indication of the direction and steepness of the ecological gradients. These gradients need translation in climatic terms and calibration with quantitative data. This is achieved by plotting the climatic station data on the imagery. By studying the trends indicated by the landscape features on the image and the climatic gradients indicated by the stations, an understanding of the characteristic climatic conditions for these landscape features can be achieved. This permits, to a certain extent, the use of landscape features to extrapolate climatic trends.

3.1 Converging Evidence

A major principle in the use of landscape information on imagery is that never a single feature, whether topographic information or vegetation alone, determines the judgement of a particular situation. It is the converging evidence from all features, including drainage patterns, shadows, vegetation, climatic reference data, landuse etc. that determines this. Any contradictory evidence will lead to critical investigations.

4. ADVANTAGES OF A LANDSCAPE GUIDED APPROACH

Most of the advantages of the use of landscape features for climatic inventories originate from the following conditions:

d. The landscape patterns visible on Landsat form a continuous reference matrix. The plotting of the climatic data in this matrix leads to an understanding of the relative importance of each station and the direction and steepness of the ecological gradient in which it fits. This understanding of landscape climate relationships permits interpolation, where necessary, to extrapolate trends, to fill data gaps and even to recognize any map changes in climatic gradients that are not indicated by climatic stations at all. This leads to a higher spatial and better geographical accuracy in the mapping process.

ii. As the landscape gradients form an independent source of information on climatic gradients, a critical comparison with
the trends shown by the climatic network is possible. This possibility of critical analysis is new in climatic inventory where climatic point data are generally the only data available and have to be taken as the truth.

This increased critical awareness permits, for example, the evaluation of the layout of the station network which leaves, as Shaw (1983) already mentioned, much to be desired both in developed and developing countries. The possibility of comparison also permits the detection and correction of errors which otherwise might go unnoticed. The bigger the error, the easier it is to detect. The following types of errors are relevant:

a) detecting measurements of doubtful quality. This is important in developing countries where sometimes data records of 2-10 years are the only data available and thus must be used, and where often not fully competent people are found stationed in outposts;

b) detecting human errors in data computation, typing and plotting. Also, this is not irrelevant in climatic inventory where often data for over hundreds or thousands of stations and decades of years needs to be processed.

4.1 Advantages over the use of contourlines

Advantages of the use of imagery over contourline maps are that contourline patterns form rather abstract discontinuous patterns on artificial distances. On reconnaissance scales the intervals are generally very large. Further, the altitude gradient is only one factor that determines climatic patterns. It is probably this reason that explains why neither the orientation nor steepness of climatic gradients need to correspond to altitude gradients (section 6.5.2). Alternatively, vegetation patterns show the ecological gradients in a continuous way. These gradients generally fit better with climatic gradients and are easier to interpret.

5. THE INFORMATION CONTENT OF LANDSCAPE FEATURES ON IMAGERY FOR CLIMATIC INVENTORY

As indicated in sections 2 and 3, the information on topography, vegetation and landuse is most relevant for the understanding of variation in climatic conditions.

5.1 The effect of topographic variation

Differences in topography can be inferred from most imagery from shadows, drainage patterns and vegetation patterns.

The stereoscopic view on aerial photographs, metric camera and the future SPOT imagery, permit a more precise assessment of the topography. The effect of topography on climatic conditions can be inferred from imagery only indirectly.
The temperature gradient corresponds to a gradient in evapotranspiration. The decreasing evapotranspiration means that more water can be available for plant growth. The effect of the temperature gradient on imagery thus shows as a vegetation gradient. For this reason, higher altitudes tend to carry a denser vegetation until a critical low temperature is reached that limits plant growth in its turn.

If, due to topographic differences, air masses are forced to rise, the lower temperatures at higher altitudes trigger condensation. The unequal distribution of rain will tend to correspond to unequal vegetation development as well. The average distribution of the rain will depend on the average moisture saturation degree of the air masses and on the steepness of the slope. Depending on this saturation degree, below and above a certain altitude, relatively little rain will fall.

The direction of the major rain-bringing wind can be read from imagery from the distribution of vegetation around elevations. On slopes towards the rain-bringing winds more rain tends to fall, while on leeward slopes there is less rain.

5.2 Vegetation patterns on imagery

The correct interpretation of vegetation patterns, and their potential indicative value for the variation in climatic conditions in the landscape, is of paramount importance.

For the landscape guided inventory, only imagery and aerial photography can be used that permit separation of vegetation patterns from soil and other patterns. In general, this means that only false colour aerial photography or false colour composite satellite imagery can be used. This aspect will be treated in detail for the relevant types of imagery in chapter 8.

In false colour imagery, living vegetation shows up in shades of red. The intensity of the red is not directly proportional to the green biomass, but depends on the type of vegetation (annual/perennial), the position and the shape of the leaves and on the view angle of the satellite (Tucker 1983). The view angle effect is particularly important in case of NOAA imagery. On imagery with an almost vertical view angle (e.g. Landsat), this effect can be neglected.

In spite of the fact that the relation is not directly proportional, an increasingly dense vegetation will show in an increasingly red shade.

5.3 The impact of ecological conditions on the information value of vegetation patterns

Considering the many factors influencing vegetation development, one cannot expect to find a straightforward relationship between the red tone and the various climatic parameters.
One of the most important criteria for vegetation development is the moisture availability in time. This availability is influenced by rainfall (amount + distribution in time), temperature, the waterholding capacity of the soils, rooting depths of the vegetation itself, seepage, run-off/run-on patterns, etc.

Other factors that influence the indicative value of vegetation distribution as visible on imagery are, for instance, human disturbances (e.g. landuse patterns) and the momentaneous character of an image.

In order to use vegetation patterns for climatic inventories, the impact of these factors must be well understood so that artefacts can be separated from valuable indications.

5.3.1 Short and long-term climatic impact

The amount of vegetation that is recorded by imagery on a certain spot depends both on long and short term conditions.

The long-term availability of water and its distribution over the year will determine the potential biomass that can develop. This is not only due to direct moisture supply (rainfall) to vegetation, but also because the soil will be better protected against erosion. It will become deeper and thus build up a higher water holding capacity under moister conditions. If the rainfall is low or very irregular, less suitable soil conditions will develop and less biomass can maintain itself. Thus, even if the conditions in generally dry regions have been favourable before an image is made, the vegetation cover in generally dry areas can be differentiated from generally moist areas nearby.

5.3.2 Rainfall reliability

In the sequence from humid via semi humid to semi arid and arid conditions, the reliability of the rainfall tends to decrease both in its distribution over the season and in quantity. Due to this, the vegetation in humid regions tends to be more and more dominated by perennial vegetation (with continuous water requirements) while towards more arid conditions the annual vegetation tends to dominate. (Annual vegetation can respond to irregular water availability via dormant seeds.)

For this reason, vegetation in humid regions has a higher indicative value, since the biomass developed indicates the average climatic conditions. Vegetation in arid or semi arid zones, dominated by annual species can develop after an erratic rain shower, giving a very vegetated thus "moist" impression on a single satellite image. As both the reliability of the rainfall and the indicative value of the vegetation decreases towards semi-arid and arid regions, the interpretation of vegetation patterns in drier zones should thus be made with more care.
5.3.3 The influence of topography

Generally speaking, the greater the altitude difference over a slope, the more dominant the climatic influence on vegetation will be over other ecological factors, and the easier it can be recognized on imagery.

This means that the indicative value of vegetation patterns is partly a function of the topographic complexity.

5.3.4 Run-off and run-on

The distribution of vegetation is influenced by run off and run on patterns. It is the overview of the imagery in relation to the scale of these patterns that determine how easily a correct judgement of the effects of these processes can be made. As the effects are generally very local (determined by minor landscape gradients) or site specific, while climatic processes are generally related to larger landscape gradients, run-off and run-on patterns will seldom lead to difficulties in the interpretation. Examples of run-off/run-on patterns are vegetation edging rivers, gullies or pools forming marshes or particular patterns, as in case of the "brousse tigree" in the Sahel (Penning de Vries 1982).

5.3.5 Soil related aspects

The waterholding capacity of soils is one of the most important factors for vegetation development. It is not only a function of the soil texture and depth, but also of the rooting depth of the vegetation itself. The situation is different for soils of alluvial origin and soils derived from bedrock and for coarse and fine soils.

Alluvial and colluvial soils tend to be flat and of rather limited extent. In general, due to its flatness, the impact of soil difference on vegetation patterns is therefore bigger than climatic factors. Furthermore, the moisture supply is often not due to climatic factors only. The usefulness of imagery for climatic inventories in areas with extensive alluvial plains needs further investigation, since such plains did not occur in the case study.

Soils derived from bedrock, especially in geologically old regions, tend to enhance the impact of climate on vegetation, (as described in 5.3.1).

Where gradients in soil texture or depths occur due to differences in geology, the study of vegetation patterns for information on climate needs closer attention. The analysis method is described in section 8.3 and Annex II.

Under moist conditions, vegetation can make full use of the higher waterholding capacity of fine textured soils. These soils thus tend to support a denser vegetation than coarse textured soils.
However, under semi-arid and arid conditions, coarse textured soils tend to be "ecologically" moister (Wild 1967). This is due to the fact that such soils lose less water due to run-off and evaporation (surface effect) and roots (of perennial vegetation) can often penetrate deeper and make full use of the water storage (depth effect).

For the landscape guided method, soil fertility differences are seldom relevant for the general vegetation distribution pattern. Even on poor soils, in time a very lush vegetation can develop if it is not disturbed and moisture is available, as is the case with the tropical rainforests.

5.3.6 Landuse patterns

Landuse patterns can severely disturb the recognizability of climatic gradients, but can also enhance them, depending upon the situation.

Where agriculture, particularly small scale agriculture is the main landuse, landuse patterns can be as indicative as natural vegetation zones. An example of this, concerning the Aberdare Mountain, is discussed in section 6.4.3. Also the changing size of fields can be an indication of the change of climatic conditions. Some familiarity with the crop systems and management conditions is, therefore, convenient for the interpretation.

In drier regions, where grazing becomes a major landuse, the climatic evidence that is available in the vegetation can be destroyed over large distances. Burning practices can make interpretation impossible, especially in the dry season, but also without burning, overgrazing and removal of perennial vegetation can severely disturb the overview of the potential impact of ecological factors on the vegetation.

5.3.7 The momentaneous character of imagery

The picture that imagery shows is necessarily that of the conditions of a particular moment. This implies that conditions as shown on the picture do not necessarily need to be representative of the dominant conditions.

A crucial question in the use of the landscape features for a climatic inventory is if the use of imagery from different years or seasons will result in the same end product. As topography does not change relevantly in time, the main focus will be the change in the indicative value of vegetation and landuse patterns, seasonally and over the years.

This subject is treated in detail in section 6.4 and illustrated with the comparison of Images 1, 2 and 3. The conclusion of the comparison is (section 6.4.6) that the ecological gradients remain visible on imagery in any season and year. It is only the absolute amount of vegetation that fluctuates. The relative differences
(beginning, ending, steepness, direction of ecological gradients) that are required to complete the picture, set by the climatic point data, remain constant throughout the seasons and years.

Thus, as long as some reference stations per major landscape, or preferably by ecological gradient, are available, imagery from any time in the year can improve the understanding of the correlation between landscape and climate.

6. ILLUSTRATION OF RESULTS

There is no way to verify the result of a climatic map in an absolute way. What can be done is to indicate the greater or lesser logic and accuracy between different approaches in climatic mapping. It is this comparative approach that is chosen to illustrate the results of the landscape guided interpolation method. The results of 3 interpolation methods will be compared:

- the straightforward interpolation (1)
- the interpolation method using additionally the information of contourline patterns (at present the most common technique);
- the landscape guided interpolation method

As a general reference, both the satellite image and the station data have been printed together with the results of the various methods. This permits assessment of the logic, the accuracy and the type of mistakes made in each approach and the determination of the value of the use of the imagery.

6.1 Choice of demonstration material

The demonstration of the results of the landscape guided interpolation method will be carried out with mean annual precipitation in the area around Nairobi, Kenya. This area is selected because the impact of many factors can be well illustrated, i.e.

- the impact of landscape complexity: the area includes complex hilly topography, smooth rising mountains and almost flat plains;
- the impact of different climatic conditions: the area includes a climatic range from semi-arid (600 mm, 60 days LGP (2)) to humid (> 2000 mm and 365 days LGP );

(1) In this method, the patterns of the isolines are only determined by the relative distances and the values of the stations.

(2) LGP : Length of Growing Period (FAO 1978).
the impact of varying densities of station networks in relation to the complexity of the landscape:

- 1 per 200 to 1 per 1500 km\(^2\) in almost flat regions,
- 1 per 25 to 1 per 1200 km\(^2\) in the complex hilly landscape,
- 1 per 50 to 1 per 200 km\(^2\) on a smooth rising mountain slope.

- the impact of landuse, soil type and geology on landscape and vegetation patterns on imagery.

It is impossible to represent all the relevant ecological conditions in the whole of the developing world on a single scene, but it is expected that the illustration of the improvements obtained under those diverse Kenyan conditions are sufficiently convincing to illustrate the validity of the method for other regions and with other climatic variables as well.

6.1.1 Landsat imagery acquired

A crucial question in the landscape guided method is whether imagery from different seasons and years will result in the same end product.

In order to illustrate the effect of variation of the climatic conditions on the landscape (i.e. mainly on landuse and vegetation), all the available cloudfree imagery of the region was acquired. However, it appeared that the only cloudfree imagery of reasonable quality from July 1972 onwards was 3 scenes from the same period in the year, respectively, 11 February 1976, 22 February 1979 and 17 February 1980.

As can be seen on this imagery, (respectively Images 3, 1 and 2 in the backpocket), the degree of vegetation cover (the red tone) differs considerably.

The scene of 11 February 1976 shows the area in the most advanced stage of dry season conditions with only vigorous vegetation on the top of the mountain and hills. The scene of 17 February 1980 shows less dry conditions with quite some vegetation in most of the plains. The scene of 22 February 1979 appears to have been taken in a period in which the rainy season was still continuing in most of the region, as can be seen from the cloud cover and the intense red tone almost everywhere.

In spite of the fact that the imagery in the above 3 cases is taken at the same period of the year, the agro-climatic conditions are considered varied enough to permit an understanding of the seasonal and temporal fluctuations of the landcover on imagery.
6.2. Description of the area

In order to understand the features on the imagery and to discuss the results obtained, it is necessary to become familiar with some basic topographic and ecological characteristics of the region.

6.2.1 Location and geographical references

The area used for the demonstration is a 120 x 175 km section of Landsat frame 180/61 of 11 February 1976. It is situated around Nairobi in Kenya, just south of the equator.

Map 1 shows the major landsystems that occur in the region and the name by which they are indicated. Also some topographical references are indicated.

Map 1 Orientation map showing major land systems, main towns, rivers, roads. Approx. scale: 1:5 000 000

6.2.2 Ecological conditions

Table 1 gives a summary of the relevant ecological characteristics of the indicated major landsystems in the area.

The climate is determined by the impact of the south eastern trade winds and the movement of the intertropical conversion zone (ITCZ).

This results in a dominantly bimodal rainfall regime. There are two rainfall maxima: one from October to December and one from March to May and two minima around February and July. The April maximum is more important than that around November. The names "long" or "main rains" and "short rains" are commonly given to the two moist periods. Rainfall also varies with altitude. Generally it increases...
### TABLE 1
ECOLOGICAL CHARACTERISTICS OF THE MAJOR LANDSYSTEMS OF THE AREA

<table>
<thead>
<tr>
<th>Major Landsystems</th>
<th>Aberdare Mountain</th>
<th>Machakos Hills</th>
<th>Maasai Plain</th>
<th>Kajiado Plain</th>
<th>Masa Plain</th>
<th>Yatta Plain</th>
<th>Data Source and Definition of Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topography</td>
<td>Radially dissected but smoothly sloping downwards with 2-4% from top to foot</td>
<td>Hilly</td>
<td>Gently undulating</td>
<td>Undulating to rolling</td>
<td>Gently undulating</td>
<td>Undulating</td>
<td>FAO 1967</td>
</tr>
<tr>
<td>Altitude above sea level</td>
<td>1800 - 3000 m</td>
<td>1500 - 2250 m</td>
<td>1500 - 1800 m</td>
<td>1500 - 1800 m</td>
<td>900 - 1500 m</td>
<td>900 - 1200 m</td>
<td>Survey of Kenya 1970</td>
</tr>
<tr>
<td>Average rainfall per year</td>
<td>750 - 2000 mm</td>
<td>750 - 1250 mm</td>
<td>400 - 750 mm</td>
<td>250 - 600 mm</td>
<td>500 - 1000 mm</td>
<td>500 - 750 mm</td>
<td>Mean annual rainfall Map East Africa</td>
</tr>
<tr>
<td>Dominant vegetation</td>
<td>Natural forest, forest plantations and bamboo at higher altitudes perennial crops like tea and coffee below and permanently cultivated land with annual crops on the lower slopes</td>
<td>On hill slopes permanently cultivated land; at the footslopes cultivated land with acacia bush</td>
<td>Dwarf shrub grasslands</td>
<td>Woodland-bushland</td>
<td>Open to medium open acacia shrubland</td>
<td>Bushland to thicket</td>
<td>Pratt (1966) Dwarf shrub: 1-2 m open: &lt;10% crown cover Shrub: 2-5 m medium: 10-40% crown cover Bush: 5-8 m dense: &gt;40% crown cover</td>
</tr>
<tr>
<td>Dominant soil types</td>
<td>From top to bottom: Mollic Andosols, Humic Nitosols and Orthic Ferralsols</td>
<td>From top to bottom: Orthic Ferralsols, Luvisols and Chromic Cambisols</td>
<td>Shallow Pellic Vertisols and Eutric Nitosols (black cotton soils)</td>
<td>Chromic Luvisols and Dystric Cambisols</td>
<td>Chromic Cambisols, Eutric Nitosols</td>
<td>Orthic and Rhodic Ferralsols, Eutric Nitosols and Vertisols</td>
<td>FAO/Unesco Soil Map of the World; Sombroek 1982</td>
</tr>
<tr>
<td>Landuse</td>
<td>From top to bottom: forestry, tea plantations, very intensive small-scale farming with maize, phaseolus beans, coffee, pineapple and irrigated coffee plantations</td>
<td>Intensive small-scale farming of maize, beans and coffee. Extensive grazing of cattle and goats</td>
<td>Large-scale sisal plantations and extensive grazing of cattle</td>
<td>Extensive grazing</td>
<td>Small-scale farming of maize, phaseolus beans, chick peas; large-scale irrigated rice; extensive grazing</td>
<td>Extensive grazing. Small-scale farming of maize, phaseolus beans</td>
<td>Field work</td>
</tr>
<tr>
<td>Population density (person/km²)</td>
<td>300 - 600</td>
<td>&gt;50</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>5 - 30</td>
<td>5 - 30</td>
<td>Norton-Griffiths (1980)</td>
</tr>
</tbody>
</table>
with height up to a certain level and then decreases again. The air
temperature falls off with height at a relatively constant rate of 0.6
degrees centigrade per 100 m. Consequently, the elevation at which
most crops are grown (1500 - 2800 m) enjoys moderate or even cool
temperatures in spite of the tropical situation (After Cocheme 1969).

6.3 Methodological Aspects

The original working scale of the 3 images was 1:500 000. The
scale of display is 1:700 000. The position of the climatic stations
and the contour lines were taken from a 1:500 000 scale map of Kenya
Soil Survey of 1978. The mean annual precipitation data (in mm) was
originally from the Climatic Database of Kenya of the University of
Trier, West Germany (Geatzold 1981). For stations with less than 20
years of records, the number of years have been indicated in brackets
next to the rainfall records. For stations with over 20 years of
records the number of years of records has not been indicated. The
interpolation was carried out within levels of 150 mm or with 300 mm
intervals when the gradient became too steep to be mapped conve-
niently. Dashed lines have been used to indicate when the information
available was insufficient or allowed several interpretations.

i. Straightforward interpolation

On Image 1 of 22/2/79, the results of the straightforward
interpolation have been overprinted. In the straightforward
interpolation, the only criteria that determine the course of
the isolines are the values of the measurements and the
relative distance between the stations.

Thus, the landscape patterns on the underlying image have not
had any influence on the course of the isolines, but just serve
as a general reference for comparison of the three methods.

ii. The interpolation using contourlines as additional reference

Overprinted on Image 2 of 17/2/80 (1) the results have been
indicated that can be expected from the standard interpolation
technique using contourlines as additional references. The
1000 foot interval contourlines were also overprinted. The same
mean annual rainfall data were used as for the straightforward
method. In the interpolation, the effect of the main rain
bringing wind direction (South to Southeast) is accounted for
as is the effect of altitude gradients as far as they can be
inferred from the relationship between stations and
contourlines.

To obtain this result, the image was not used and serves only
for reference purposes.

(1) The black lines on the left part of the image are due to problems
with starting the sensor's scanning lines at that time.
iii. The landscape guided interpolation

The result of the step by step procedure of the landscape guided interpolation as indicated in Annex II is shown on Image 3 of 11/2/76.

For editorial reasons, the major landsystem analysis and topographic analysis have not been indicated on the image. A generalization of the major landsystems discriminated is indicated on map 1, while the description is given in Table 1. In Image 3, the underlying Landsat picture is fully functional as it was the main reference for the interpolation.

6.3.1 Reading of images

In order to follow the text of this section, the 3 Landsat images in the backpocket will have to be consulted at various times. The relevance of the imagery is to obtain a better understanding of landscape/climatic relationships. For this reason, not the isoline patterns, but the trends in the rainfall data in comparison with the trends in the landscape will be discussed. Not all differences can be dealt with. This would become an exhaustive list of increasingly minor aspects. A choice of the most striking examples for each relevant type of improvement or difference has been made. Four types of reference numbers have been used:

- references to climatic data from stations are indicated with large numbers 1-17 from top to bottom in all 3 images, next to the stations;
- encircled numbers relate to remarks concerning interpolation aspects in all 3 images, either doubts 1-3 or interpolation based on landscape features 4-6;
- the abbreviations sc or scl on image 3 relate to soil or landuse aspects as discussed in section 6.4.3;
- capital letters A-C3 (on image 3) relate to landuse aspects (section 6.4.5).

6.4 Evaluation of the Results of the Three Methods

6.4.1 The straightforward interpolation

Although the way in which the straightforward interpolation was carried out has exaggerated the degree of inaccuracy that would be made, in reality it illustrates well the types of mistakes that will be made if there is no clear understanding of landscape/climate relationships.
The following remarks can be made:

- The many dashed lines on Image 1 indicate where several interpretations of the data were possible or where lack of data caused doubts about the course of the isolines (this happened particularly at the edge where no data were available outside the area of interest). These cases have been indicated with reference (1).

- Depending on the relationship between the number of stations and the complexity of the landscape, the fit of the isohyets with the landscape looks reasonable (on smooth rising Aberdare mountains and in the plains) or poor (in the Machacos hilly area).

- The method cannot detect relative importances between the stations (see section 6.5.3 and references 3 and (5) and (6)).

- The method misses gradients if there are no stations available. For example, none of the climatic gradients in the Machacos area is well represented, see reference (6) on Image 3.

- The method fails to detect erroneous conditions as in the case of station 5.

6.4.2 The interpolation using contourline information

Using the contourline information, the result of the interpolation is considerably better, particularly in the complex Machacos region. However, as the ecological and climatic relevance of altitude differences is not clear in many cases, the following doubts and inconsistencies still occur:

- the course of various isohyets can often be interpreted in more than one way from the data (see reference (2) on Image 2);

- gradients without stations are missed (see reference (3) on Image 2 and (6) on Image 3);

- the doubts about the quality of the data of station 5 are stronger, but not yet conclusive.

6.4.3 The landscape guided interpolation

The results of the landscape guided interpolation method will be evaluated by region and in relation with the degree that the density of the station network "catches" the landscape variation.

In the relatively simple landscape of the Aberdare Mountain, with a good representation of stations, no big improvements can be expected. Still, the following improvements are worth noting:

- In the case of station 5, the landscape gradient shows undoubtedly that the value of 945 mm must be an error either in positioning, calculation or even in measurement.
In many cases, the pattern of the landscape gradients permits the measurements of some stations that "do not fit entirely into the line of the general trend" to be seen in true perspective. The deviation of these station data from the general trend is most probably due to minor differences in microclimatic conditions around these stations.

In some examples, the strict course (dashed) and the corrected course (firm) have been drawn and indicated with reference 4.

In the complex Machacos area with insufficient stations to "catch" the landscape variation, the impact of the imagery is greatest.

The beginning, end and steepness of all gradients can be recognized immediately from the vegetation patterns, independent of the fact of whether a station is available or not (if no station is available but a gradient is recognized, it is indicated with reference 5).

Stations numbered 8, 10, 11, 12 and 13 that have rather extreme values for their surroundings appear to represent only a very limited areal extent, which was considerably overestimated with the other methods.

Many hills and their approximate climatic conditions could be detected even though no reference station was available (see reference 6 on image 3).

In particular, the importance of the extremely low value, 598mm of station 14, situated in the rainshadow of a hill that was not represented by a station, appears to be grossly overestimated by the other methods.

The following example is an illustration of how sensitive the landscape guided method can be in detecting errors and deviations. By comparing the trends indicated by the landscape and those indicated by the stations on the Aberdare Mountain, many stations seem to be out of line with the general landscape trend.

There are two possible explanations for these deviations: a statistical variation in the data, or differences in microclimatic conditions around the stations.

Most probably both causes play a role, but the most important one seems to be the impact of microclimatic conditions: whereas the general trend of the major landscape gradient is very smooth, its slope is entrenched by many steep valleys. In such a landscape, it is very difficult to choose a consistent position for all stations.

Some examples of strict interpolation are indicated with dashed lines on Image 3, while the corrected course based on the landscape trends is drawn firm. The corrections are indicated with reference no. 4.
In the almost flat, semi-arid plains with only a few stations available, the areal impact of a badly situated station can be considerable:

- The value for station 8 of 630 mm, superficially seems to be a correct transition from station 7 and 9 (respectively 557 and 569 mm) to station 6 (of 660 mm). However, the landscape features show that station 8 is situated on a tiny hill with slightly moister conditions. The conditions for which stations 7 and 9 are representative also continue beyond the hill.

- One of the bigger changes in areal extent was the result of a closer study of the situation around station 3. Again, superficially, the 637 mm of this station seems to be a correct transition from stations 1 and 2 with 830 mm, to station 4 with 620 mm. However, the vegetation greenness and the land use around 3 is not much different from that around 1 and 2. Furthermore, station 3 is situated at the dam site of an artificial lake. The combination of these two factors makes it very probable that station 3 represents a micro-climatic condition for the narrow valley around the dam only and that the climatic gradient from 830 to 750 mm is much less steep than foreseen by other methods.

6.5 The information content of landscape features on imagery

In this section will be discussed the indicative value of landscape features on imagery for landscape guided climatic inventory using Image 1, 2 and 3 as references. The most important matter is if the information on topography, vegetation and landuse patterns on the imagery is consistent under different ecoclimatic conditions. This determines if one image suffices or more images are required to carry out a landscape guided climatic inventory.

6.5.1 The quality of the imagery available

The most striking feature of Image 1 of 22/2/79 is its cloud cover obscuring + 25% of the area of interest. Comparing the cloud-free part to that of the other images, it shows that on the (generally dry) Northern Mwea Plain, the landuse conditions can be much better distinguished under these humid conditions. Roads, fields, rivers and artificial lakes show up very clearly, whereas they are not visible at all on Image 3.

The landuse patterns on the Aberdare Mountain are easily distinguishable on the 3 images, but not the individual agricultural plots, as they are smaller than the resolution of the sensor.

The ecological gradients in the Machacos (hilly) area are very distinct on the two drier images (2 & 3) due to the high contrast in vegetation greenness between hilltops and valley bottoms.
Although the total vegetation cover is overall much greater on Image 1, the relative differences between the top and bottom of each gradient enable all land gradients still to be easily recognized.

6.5.2 The information on topographic and vegetation patterns

An impression of the topographic variation on the imagery is obtained from differences in vegetation cover. However, the impression from the vegetation must be confirmed by drainage patterns or other evidence (according to the principle of converging evidence). The reader can check his own impression by comparing it with the contourline patterns which are overprinted on Image 2.

As vegetation and topographic patterns are so tightly interwoven, they will be discussed together here.

The last remark in the previous section on the consistency of relative vegetation cover differences over landscape gradients indicates the main clue for the use of the imagery. Some clarifying remarks can still be made:

By comparing the 3 images, it is clear that Image 1 is not optimal for landscape analysis because of the clouds and the reduced contrast in vegetation patterns.

Also, Image 3 is not the best. On the plains, vegetation has dried out completely, which reduces the information content.

It is the intermediate state of drying out, represented by Image 2, that contains most information.

As an illustration of differences in information content between the 3 images, the conditions in the area around stations 15, 16 and 17 will be discussed:

On Image 3, the drainage pattern and the change from green to yellow colour indicate that there is a sudden change in soil type and topography from North to South. Both landscape types look equally arid and void of vegetation.

The vegetation shown on Image 2 gives quite a different impression of the Southern part. The image shows a vegetated horseshoe shaped feature with a very distinct drainage system, which suggests a considerable slope difference. Also, the two hills over 6000 feet West of this area show up far more pronouncedly on Image 2.

The crucial question for our inventory is whether these differences indicate variations in climatic conditions or soil differences only. The answer can be found by using the principle of converging evidence.

The relevant information available is:
i. Three climatic stations are present:

No. 15 indicates 511 mm and is situated in the "greenish" zone just behind the horseshoe-shaped area of interest;

No. 16 indicates 552 mm and is situated in the horseshoe-shaped zone itself;

No. 17 indicates 593 mm and is situated at the beginning of the major landscape gradient near the main drainage channel.

ii. The soil types in the area are Luvisols (yellowish) in the horseshoe-shaped area and Vertisol (greenish) in the plain north of it.

iii. The slope of the area is exactly exposed to the rain bringing wind.

iv. The two hills have a similar height difference that led to well documented rainfall gradients in the nearby Machacos area.

v. In at least one of the images (no. 2) the vegetation indicates that there is considerably more moisture available in the horseshoe-shaped area than in its surroundings.

This information suggests that the two hills most probably receive over 600 mm of rain, whilst the horseshoe-shaped area itself receives a little less than 600 mm.

In conclusion: if only Image 3 would have been available, the hills would not have been detected as places with higher rainfall conditions.

6.5.3 The effect of landuse on the usefulness of the imagery

It is often feared that man's impact on the landscape, and particularly on the vegetation, can be so vast that any trace of information on the climatic impact is removed. In how far this fear is relevant can only be ascertained by testing the method on a large scale. It can be expected that in flat or almost flat areas, landuse patterns like soil changes can become more dominant than the climatic impact. The interpreter's skills can become an important factor in these cases. In the scope of the demonstration image, the following illustrations of complicated and supportive landuse patterns can be given. As a reference, the capital letters A to C3 are given on Image 3.

Possibly confusing landuse patterns:

A.(1) Forest reserves

The edge of the red top of the Aberdare Mountain is very abrupt and shows artificial straight sections. This indicates a man-made boundary between a forest reserve and the cultivated zone.

(1) references on Image 3
below. This boundary thus does not mean much in terms of climatic gradient. That this is indeed the case is clearly shown on the isohyet pattern which is reliably based on sufficient reference stations in this area.

B.1(1) Irrigation

The dark red speckled zone between the 750 mm and 1050 mm isohyet on the Aberdare Mountain does not mean a locally higher rainfall, but a band of irrigated coffee fields. The manmade influence can be recognized also here from the artificially straight boundaries of the patches.

B.2(1) The irrigation plot B2, if not recognized as such could easily be taken for a twin small hill of the one situated just north of it. The absence of a drainage pattern and the square shapes are the clues for recognition.

B.3(1) Irrigated pineapple fields

Supportive landuse patterns

Despite the very intense landuse on the Aberdare slopes, the landscape gradient is visible just as clearly as if there were only natural vegetation.

C1: C1 indicates a zone with large scale rangelands and sisal plantations on black vertisols in low rainfall areas.

B1: B1 indicates the previously mentioned large-scale irrigated coffee plantations on the lower slope of the Aberdare Mountain.

C2: C2 indicates a dark zone above the irrigated coffee plantation. This dark zone is an area in which mainly annual rainfed crops are grown by smallholders. The dark colour originates from the fact that the image is from the dry season. The annual crops have been harvested and the soils exposed.

C3: C3 indicates an area that has a pinkish colour on the image. This is due to the fact that in this area sufficient moisture is available also in the dry season to enable small farmers to grow rainfed perennial crops like coffee, pineapple, tea, sugarcane, etc., and hardly any soil is exposed.

6.5.4 Temporal differences in indicative value of landuse patterns

Burning patterns: If only the 1976 scene (no. 3) is consulted, the black patterns in the Mwea plain give the impression of being burning patterns in the semi-arid rangeland environment. However, by consulting the other imagery, especially the one of 1979, it becomes clear that the patterns are constant and can bear vegetation, and should be considered as soil patterns. This was confirmed by field checks.

(1) references on Image 3
On the 1976 imagery, hardly any agricultural landuse can be distinguished in the Mwea plain between stations 2 and 3. On the 1979 image (no. 2) there is some indication of agricultural landuse. However, on the 1980 imagery (no. 1), the landuse is almost clear enough to be used as a guideline for a census.

6.5.5 The effect of soil type changes

In the evaluation of vegetation greenness gradients to determine climatic gradients, the effect of changes of soil characteristics has to be taken into account.

Becoming aware of the differences between soil and geological conditions is the main reason for carrying out the "major landsystem analysis" (see Annex II).

It can be expected that vegetation greenness patterns no longer correspond to climatic gradients at the edges of major landsystems. On Image 3 some examples have been indicated where vegetation patterns do not correspond to climatic patterns due to soil type changes (indicated with s.c on the image) or due to soil and landuse changes (indicated with slc on the image).

6.5.6 The number of images required

In landscape guided climatic inventory, climatic stations supply the climatic reference data, while imagery is the reference for the variation in local conditions and serves to judge the degree to which a station represents its surroundings.

Comparison of the 3 images, which were taken under considerably different ecoclimatic conditions, proves that each of them shows the landscape variation well (provided cloudfree conditions exist).

This is due to the fact that the ecoclimatic differences affect mostly the absolute amount of vegetation cover. The relative differences in vegetation cover that indicate the beginning, end, length and direction of landscape gradients, remain constant and recognizable, and this is what is required for the assessment.

Particularly the vegetation conditions in the area South of station 4 and East of station 12 are very different on the 3 images. However, each of them permits the assessment of the ecological homogeneity of the area and the direction and steepness of the landscape gradients, required to judge the position of the stations and the climatic gradients.

It is concluded that any cloudfree image of good quality permits the achievement of the majority of the improvements that can be attained with the landscape guided approach.

The case described in section 6.5.2 shows that the use of more than one image can lead to further refinements. Whether one or more images are required, depends on the degree of accuracy that one wishes to achieve.
7. WHEN TO PREFER THE LANDSCAPE GUIDED APPROACH TO CONVENTIONAL METHODS

As indicated in section I, the landscape guided approach is a new version of the isohyetal method (Shaw 1983, Annex I).

When it is appropriate to use this approach depends on a large number of factors. In this chapter these factors are discussed. Although most of them are interrelated they are discussed separately here for editorial reasons. In the judgement of the usefulness of the landscape guided approach in a certain situation, all factors have to be considered in their context.

The factors fall into two groups:

i. Technical considerations that determine under which conditions the results of the landscape guided method will be better than those of conventional methods.

ii. Administrative and policy considerations that determine when the effort and cost are worthwhile.

Fifteen major factors, that will have to be considered in most circumstances, have been indicated in Figure 1.

Figure 1  FACTORS TO BE CONSIDERED IN THE DECISION OF WHEN TO PREFER THE LANDSCAPE GUIDED APPROACH TO CONVENTIONAL METHODS

<table>
<thead>
<tr>
<th>TECHNICAL CONSIDERATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. The climatic parameter</strong></td>
</tr>
<tr>
<td>Type: Moisture related</td>
</tr>
<tr>
<td>Evaluation: Very useful</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>2. The relationship of the station density and landscape complexity</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio: Insufficient cover</td>
</tr>
<tr>
<td>Evaluation: Very useful</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>3. The timeframe of the study</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: Long-term inventory</td>
</tr>
</tbody>
</table>
Evaluation: Very useful at large reconnaissance scale, using Landsat, aerial photography

Evaluation: Very useful at small scale using NOAA imagery

Evaluation: Could be useful at large reconnaissance scale using Landsat and aerial photography

<table>
<thead>
<tr>
<th>No. of years of records</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Less useful</td>
</tr>
<tr>
<td>1-30</td>
<td>Very useful, both for reliability checks of data and filling datagaps</td>
</tr>
<tr>
<td>30-over 200</td>
<td>Useful for filling datagaps and evaluation of station positions</td>
</tr>
</tbody>
</table>

5. The degree to which the siting of stations is representative

<table>
<thead>
<tr>
<th>Siting:</th>
<th>Evaluation:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad</td>
<td>Very useful</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Useful</td>
</tr>
<tr>
<td>Good</td>
<td>Less useful</td>
</tr>
</tbody>
</table>

6. The scale of the study

<table>
<thead>
<tr>
<th>Scale:</th>
<th>Evaluation:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:10 000-1:100 000</td>
<td>(False colour) Landsat very useful</td>
</tr>
<tr>
<td>1:125 000-1:2 000 000</td>
<td>NOAA/AVHRR imagery very useful</td>
</tr>
<tr>
<td>1:2 000 000-1:25 000 000</td>
<td></td>
</tr>
</tbody>
</table>

7. The quality of the imagery available

<table>
<thead>
<tr>
<th>Quality:</th>
<th>Evaluation:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Very useful</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Less useful</td>
</tr>
<tr>
<td>Bad (30-90% cloud) (i.e. haze)</td>
<td>Not useful</td>
</tr>
</tbody>
</table>

8. The dominant climate (over large areas)

<table>
<thead>
<tr>
<th>Type:</th>
<th>Evaluation:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid (LGP 0-75 days)</td>
<td>Vegetation patterns difficult to interpret, less useful</td>
</tr>
<tr>
<td>Semiarid-humid (LGP 75-300 days)</td>
<td>Very useful</td>
</tr>
<tr>
<td>Very humid (LGP 300-365 days)</td>
<td>Often no suitable imagery available, less useful</td>
</tr>
</tbody>
</table>

9. **The degree of human dominance in the landscape**

<table>
<thead>
<tr>
<th>Type</th>
<th>Degree</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-scale agric.</td>
<td>slight</td>
<td>very useful</td>
</tr>
<tr>
<td>Large-scale agric.</td>
<td>complete</td>
<td>v. useful</td>
</tr>
<tr>
<td>Rangeland</td>
<td></td>
<td>less useful</td>
</tr>
</tbody>
</table>

10. **The experience of the interpreter**

<table>
<thead>
<tr>
<th>Degree</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great</td>
<td>Very useful</td>
</tr>
<tr>
<td>Some</td>
<td>Useful</td>
</tr>
<tr>
<td>No</td>
<td>Useful</td>
</tr>
</tbody>
</table>

11. **The reliability of the plotting of the reference stations**

<table>
<thead>
<tr>
<th>Degree</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Very useful</td>
</tr>
<tr>
<td>Slight</td>
<td>Doubtful</td>
</tr>
<tr>
<td>No</td>
<td>Not useful</td>
</tr>
</tbody>
</table>

**ADMINISTRATIVE AND POLICY CONSIDERATIONS**

12. **The benefits expected**

<table>
<thead>
<tr>
<th>Size</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>Very useful</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Useful</td>
</tr>
<tr>
<td>Small</td>
<td>Less useful</td>
</tr>
</tbody>
</table>

13. **Efficiency requirements**

<table>
<thead>
<tr>
<th>Type</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Too open network</td>
<td>Very useful to fill gaps</td>
</tr>
<tr>
<td>Appropriate density</td>
<td>Useful to fill gaps</td>
</tr>
<tr>
<td>Very dense network</td>
<td>Very useful to reduce number of stations</td>
</tr>
</tbody>
</table>

14. **The availability of imagery**

<table>
<thead>
<tr>
<th>Type</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover already available</td>
<td>Highly cost effective</td>
</tr>
<tr>
<td>No cover available</td>
<td>Less cost effective</td>
</tr>
</tbody>
</table>

15. **The need for integration of data (e.g. for land resources data base in G.I.S.)**

<table>
<thead>
<tr>
<th>Need</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great</td>
<td>Very useful</td>
</tr>
<tr>
<td>Small</td>
<td>Useful</td>
</tr>
<tr>
<td>No</td>
<td>Less useful</td>
</tr>
</tbody>
</table>

7.1 Technical considerations

Some evaluative remarks will be made on Figure 1 in the following sections, following the 15 considerations in the sequence they are mentioned.

7.1.1 The climatic parameter

The value of the landscape guided approach is twofold:

i. Imagery always gives some idea of the conditions at and between the stations which permits extrapolation and gapfilling between point data. This can always improve the mapping of any parameter for which only point data are available.

ii. The information on the imagery has a closer relationship with some parameters than with others. For example the vegetation patterns obviously have a closer relationship to moisture (or moisture balance) than to the wind direction or strength. Temperature related parameters take in an intermediate position, as they have a strong relationship with altitude (topography) and also with the moisture balance. As temperature patterns have a more straightforward relationship with contourline patterns than rainfall patterns, the additional value of imagery over topographic maps is less great in such cases.

7.1.2 The density of the climatic station network in relation to the landscape complexity

Without reference stations, a landscape guided approach cannot produce any satisfactory results. The number of reference points required, depends on the landscape complexity. The Guide to hydro-meteorological practices (WMO 1965) recommends the following densities for precipitation measurements.

Table 2 ADvised station densities for precipitation measurements under various conditions

<table>
<thead>
<tr>
<th>Region</th>
<th>Minimum density range (km²/gauge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperate, Mediterranean and tropical zones</td>
<td></td>
</tr>
<tr>
<td>Flat areas</td>
<td>600 - 900</td>
</tr>
<tr>
<td>Mountainous areas</td>
<td>100 - 250</td>
</tr>
<tr>
<td>Small mountainous islands (&lt; 20 000 km²)</td>
<td>25</td>
</tr>
<tr>
<td>Arid and polar zones</td>
<td>1500 - 10 000</td>
</tr>
</tbody>
</table>
This report does not analyse optimum densities and siting of stations, although imagery could be used for this. Most appropriate would be to indicate the station density against a continuous scale of topographic complexity. This, however, could not be achieved within the time frame of this study. To allow the reader to obtain some feeling about the conditions where a landscape guided approach is preferable over other methods, Figure 2 has been designed following the indications of Table 2. The figure is based on the experience of the author only and not on research, and thus should not be taken as authoritative.

The width of the bars indicates how much extra information is expected from the landscape guided approach. The circled numbers 1-6 refer to those on Figure 2. The general trend as indicated by each bar is:

1. In a very dense network in relation to the landscape complexity all climatic variation is "caught" and no additional information is gained using landscape information.

2. At a certain point (and this depends on the complexity of the topography), the decreasing density of stations starts missing local variation. This happens generally before the optimum station density is reached. With the landscape approach this variation can easily be recognized and integrated in the inventory.

3. With a lower than optimum density of the network, the amount of information missed increases quickly, while the few stations available still form enough reference to interpret the landscape patterns and thus sharply increase the usefulness of the imagery.

4. The full width of the bar does not mean that the outcome of the landscape guided approach is perfect. It means that the imagery is most useful where the number of stations is far too low to catch the landscape complexity.

5. At a certain point, the limits of a satisfactory understanding of the situation with the landscape guided approach are stretched too much and areas have to be left blank.

6. Some indication of climatic variability can always be obtained.

7.1.3 The timeframe of a study

Various timeframes can be relevant for different climatic inventories:

i. Long-term analysis (e.g. average rainfall, etc)

ii. Seasonal trends (particularly for agricultural purposes, e.g. determination of the length of the growing season)

iii. Short-term analysis (e.g. single rainstorm analysis for hydrological engineering purposes).
Figure 2 GRAPHICAL ILLUSTRATION OF ESTIMATED USEFULNESS OF LANDSCAPE GUIDED MAPPING IN RELATION TO STATION DENSITY AND LANDSCAPE COMPLEXITY

Recommended density of stations for precipitation mapping (table 2)
Estimated result using imagery (width is indicative)
See notes in text.

Aerial photography Landsat Landsat imagery NOAA imagery
Landsat imagery imagery NOAA imagery + Landsat images

The graph is based on the experience of the author only and meant for illustration of the general trend. The data should not be taken as authoritative.
In all cases, where point data are the basic working material, the imagery can assist in determination of the spatial interactions.

Specific time related aspects are:

i. Long-term analysis

For long-term analysis the additional value of imagery depends on the number of years of records (see 7.1.4)

ii. Seasonal trends

Studies following seasonal trends have always been hampered by data supply. Aerial photography and radar imagery are too expensive in most cases. Landsat imagery brought some improvement, but the 16-18 days interval (sometimes 9 if two satellites were in orbit) was too long for agricultural purposes. This was particularly so because in the important (rainy) season, clouds hamper the view at crucial moments. With the technique of compositing daily NOAA AVHRR NVI imagery, this cloud problem is almost solved, at least for scales smaller than 1:2,000,000.

iii. Short-term analysis

The only advantage of the use of imagery in this case is that the overview of the topographic variation makes it possible to understand the variations of a certain pattern with only a limited number of reference points available; e.g. if the movement of a rainstorm and the rainfall at certain points is known, the complete picture can be composed.

7.1.4 The number of years of record

For long-term analysis, records of at least 20-30 years are required statistically for trend and other verification analyses. However, particularly in developing countries, it very often happens that stations with 5 or 6, or even 2 or 3 years of data are the only ones with information available. In these cases the imagery has additional value, because the comparison of the vegetation patterns (that can be considered as a long term record of the climatic conditions) with those indicated by the stations, can lead to a better judgement of the situation.

7.1.5 The representative value of the sitting of stations

It is clear from the case study results (section 6.4) that correct sitting of stations is highly relevant and that wrong sitting can lead to very large areal mistakes. It is not the first time that this is recognized (see e.g. Shaw 1983), but it seems that landscape information, as proposed in this report, is an ideal tool for assessing the best position for a station. The greater the expectation that station sites are not representative, or the greater the need for a reduction in the number of stations, the more useful imagery can be.
7.1.6 The scale of the study

For an inventory at any scale, a suitable type of image exists. The only limitation is the practical availability of detailed imagery (aerial photographs, radar images) which are generally owned by the State or a private company. For studies at scales of 1:250 000 and smaller, a virtual 100% (land) cover is offered by the commercial freely available Landsat and NOAA products.

7.1.7 The quality of the imagery available

Part of the outcome of the inventory is determined by the quality of the imagery that is used. The quality is determined generally by cloud cover, haze or dust effects and by the ecological conditions. Some rules of thumb to obtain the best imagery are:

- Near desert areas: Dust prevents a clear view most of the year, and vegetation patterns, if present, are hardly visible. The best images are obtained on a cloudless day in the wet season.

- In semi-arid and subhumid areas vegetation patterns can be less well discriminated in the wet season due to a high chance of haze (moisture in the air) and clouds. The clearest picture (dry air, no dust, good discrimination of ecological conditions) is obtained from the beginning to the middle of the dry season. The vegetation on soils with a good waterholding capacity, or that receive rain longer, is still lush. On poor soils, the vegetation has already dried out. At the end of the dry season, burning patterns and dust obscure the picture.

- In very humid areas, haze and clouds obscure the picture most of the year. The best imagery is obtained in the driest period in the year.

The most accurate method for determining these periods for each area, if no climatic data are available, is by using NOAA NVI imagery over a whole year cycle. The author used 12 monthly NOAA NVI images of Africa produced by NASA/GSFC for FAO to determine the best moment for acquisition of Landsat imagery for the whole continent.

7.1.8 The dominant climate

In section 6.4.2, the effect of different major climatic conditions on landscape features is indicated. It is particularly the landuse and vegetation patterns that are affected. The information content and the easiness of extracting information from the imagery is particularly affected in flat, arid to semi-arid areas. An additional drawback in the very humid areas is the scarcity of good quality imagery.
7.1.9 The degree of human disturbance

Whether imagery will be useful or very useful will be partly determined by the degree of human disturbance in the area of interest. Some landuse types have indicative values equal to the natural vegetation or even enhance the patterns. This is true particularly for small-scale agriculture, which is largely ecologically integrated in the landscape.

The dominance of human activity is an important aspect to consider. No matter how devastating the landuse is, if it only covers minor parts within the area of overview of the imagery, it does not influence the judgement negatively. However, large scale human activity such as partly irrigated agriculture in Europe or extensive grazing in the Sahel could mean that the indicative value is negatively affected. Such situations, however, require further study as the author has no experience in them.

7.1.10 The experience of the interpreter

As Shaw (1983) mentions, the isohyetal method is subjective, because the results depend on the skills of the person who judges the information from the stations in relation to the contourline patterns. This subjectiveness also applies to the landscape guided method. Although imagery is easier to interpret in some aspects, the method requires some additional knowledge of remote sensing and interpretation of ecological interactions between climate, vegetation, landuse, soils and geology.

7.1.11 The reliability of the location of the reference stations

It is important that the position of the stations on the imagery can be precisely located. If a precise localization is not possible, a large part of the information from such a station is lost.

7.2 Policy and Administrative Considerations

7.2.1 The benefits expected

Although all technical considerations influence the usefulness of the method, generally factor 2 (the density of the stations in relation to the landscape complexity) will be the most important and will make imagery worth using.

7.2.2 Efficiency requirements

In many cases, there is a need to evaluate the efficiency of the network. Either the cost of data acquisition or data manipulations becomes too high, requiring a reduction in the number of stations, or (as illustrated in Chapter 6) the siting of the stations could be optimized. In both cases imagery is a useful tool.
7.2.3 The availability of imagery

If imagery is already available for other purposes (landuse planning, land inventory), interpretation experience is already available. Thus, less effort and cost are involved in carrying out climatic inventory on the landscape guided approach as well.

7.2.4 The need for integration of data

With graphic computers becoming more readily available, there is an increasing tendency to bring landuse planning data bases together in the so-called geographic information systems (GIS). In FAO this process is already in an advanced stage. The author has indicated in previous papers (Van der Laan 1985 and 1985b) how important the geographical and thematic integration of the different data layers is. As climate is one of the most important factors for land resources planning and management, a good integration of climatic data with the other data is of utmost importance.

As imagery is the only product that supplies a holistic overview over the landscape, it is the best tool to carry out such an integration (AIC, 1982). In case of the need for data integration of several themes, the use of the landscape guided method is particularly appropriate.

8. THE SELECTION OF SUITABLE IMAGERY FOR DIFFERENT APPLICATIONS

In the last 10-15 years, an increasing flood of information on the surface of the Earth, both from space and from the air, has become available. Still more is to become available shortly. It is the objective of this section to provide an overview of the most common and/or useful sensors and to assess their present or potential usefulness for landscape analysis for climatic inventories.

The range of application of the landscape guided approach for climatic studies covers all inventories where point data are involved. Particular examples are:

By Field

- Land resource inventories at any scale

- Hydrological studies (short-term: rain storm analysis (long-term: water resources inventories)

- Soil conservation

etc.
By Theme

- Rainfall related inventories
- Water balance
- Temperature

One self-imposed limitation, at least for this report, is the distinction between inventories (static) and monitoring (dynamic). Only inventories requiring one or a limited number of images will be discussed in this report, which can be considered as an introduction to a subsequent paper on the, in many aspects, more complex matter of monitoring climate using vegetation patterns.

8.1 Criteria for suitability

The objective of using imagery is to use the landscape patterns to complement the data from scattered point references on climatic networks. As climatic analyses and inventories are carried out at any scale between 1:25 000 to 1:25 000 000, the scale is the first criteria that determines the suitability. Other criteria are the capacity to depict relevant details of topographic, vegetation, and landuse features.

8.1.1 Scale

The relevant detail required depends on the working scale. Thus, "relevant" topographic patterns on scale 1:50 000 can be ignored at scale 1:5 000 000.

Imagery that permits a stereoscopic view (aerial photography, Metric, camera, SPOT) has an advantage over the other imagery for topographic analysis in detailed studies. In large reconnaissance studies, the volume of data and detail makes stereoscopic work too tedious.

At scales over 1:2 000 000 and a spatial resolution of over 100 m, so much detail of topographic patterns is lost that vegetation patterns become the major reference for topographic differences. In studies at scales smaller than 1:2 000 000, topographic information from another source (topo maps, Landsat) will have to be used for reference purposes.

8.1.2 Resolution

The analysis of landuse requires a better spatial resolution than for topographic analysis. This is due to the fact that manmade structures and particularly agricultural fields need to be recognizable. The utmost limit for any recognition in most cases is a resolution ± 50-60 m at a scale of ± 1:500 000. With a greater scale and resolution, more detail becomes visible.
8.1.3 Spectral resolution

The requirement for discrimination of vegetation is less in spatial resolution than in spectral resolution. It is even convenient for analysis of vegetation patterns not to see (distracting) details, but to have an overview large trends.

To discriminate vegetation from other features (mainly soil, rock, soil humidity, water, settlements, etc.), the sensor must be receptive for at least two different wavelengths. These wavelengths are $\pm 0.6$ to $\pm 0.7 \mu$ (red visible light) where healthy green vegetation has a lower reflection than almost any other feature, and $\pm 0.8$ to $\pm 1.1 \mu$ (near infrared radiation) where vegetation has generally a higher reflection than other features. The combination of high and low reflection for vegetation in these bands is very specific.

These bands are the functional ones in so-called false colour imagery, where vegetation shows up in red.

In any imagery which is printed in one colour (generally black and white), the subtle differences between vegetation cover gradients and soil brightness gradients cannot be discriminated any more. Thus, such products are almost useless, considering the great importance of vegetation for the analysis.

Also, sensors that are not sensitive in these vegetation discriminating wavelengths deliver products that cannot be used for this method (e.g. Meteosat imagery).

8.1.4 Availability of imagery

Both the availability in time and in space can be relevant depending on the application. For most climatic inventories, at least one cloudfree, high quality false colour cover of a convenient scale is sufficient (see section 6.5.6).

The fact that the products exist does not mean that they are readily available. Fortunately, many satellite products, especially those with a resolution of more than 30 m, are commercially obtainable without restrictions.

The products showing more details are mostly government-owned and require special agreements.

8.2 Evaluation of the most relevant imagery

In Table 3 the most relevant sensors, the characteristics of their products and their suitability for a landscape guided approach are indicated.

Some evaluating remarks will be made in a sequence from the coarsest resolution and the smallest scale to the most detailed resolution and the largest scale.
<table>
<thead>
<tr>
<th>Imagery</th>
<th>Scale</th>
<th>Resolution</th>
<th>Discrimination</th>
<th>Availability of repetitive cover</th>
<th>Suitable scale of application, data volume and easiness of handling</th>
<th>Remarks/Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imagery from geostationary</td>
<td>1:20 000 000 -</td>
<td>2.5-7 km</td>
<td>Not possible</td>
<td>48 images per day of whole world.</td>
<td>- very large bulk of data; no vegetation discrimination, too coarse resolution.</td>
<td>Not suitable:</td>
</tr>
<tr>
<td>satellites</td>
<td>1:40 000 000</td>
<td></td>
<td></td>
<td>Commercial, easily available.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOAA/AVHRR</td>
<td>1:5 000 000 -</td>
<td>1, 4, 8 and</td>
<td>Good</td>
<td>4 daily, whole world, cloudfree composites; orientaion difficult;</td>
<td>- optimum scale 1:20M-1:25M; potentialy suitable for various applications on exploratory scale and monitoring vegetation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1:25 000 000</td>
<td>20 km</td>
<td></td>
<td>can be made for any area and any period. Commercial, easily available</td>
<td>- no standard cloudfree false colour composite product yet available;</td>
<td></td>
</tr>
<tr>
<td>Nimbus-CZCS</td>
<td>1:4 000 000 -</td>
<td>825 m</td>
<td>Good</td>
<td>1 per day from 1978-1986 covering coastal zones. Commercial, easily available</td>
<td>- small data volume.</td>
<td>Not suitable due to large radioinstant and geometric variation of imagery</td>
</tr>
<tr>
<td></td>
<td>1:25 000 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat MSS</td>
<td>1:250 000 -</td>
<td>58 X 79 m</td>
<td>Good</td>
<td>Of most of world except humid tropics at least one or two cloudfree covers are available. Commercial, easily available</td>
<td>- suitable for regional and national scale; convenient resolution; convenient data volume.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1:1 000 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat TM</td>
<td>1:100 000 -</td>
<td>± 30 m</td>
<td>Good</td>
<td>Similar cover as for Landsat MSS is being acquired as from Nov. 82 onwards. Commercial, easily available</td>
<td>- as for MSS</td>
<td>Highly suitable (as MSS) when first world cover has been completed</td>
</tr>
<tr>
<td></td>
<td>1:1 000 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat RBV</td>
<td>1:100 000 -</td>
<td>± 30 m</td>
<td>Poor</td>
<td>Very scattered cover of areas in developing world. Commercial, easily available</td>
<td>- as for MSS</td>
<td>Not useful due to poor availability and poor separation of vegetation</td>
</tr>
<tr>
<td></td>
<td>1:1 000 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPOT</td>
<td>1:50 000 -</td>
<td>10-20 m</td>
<td>Good</td>
<td>Satellite still to be launched. Possibly restricted to regional scale and stereoscopic view.</td>
<td>- for regional and national scale; due to higher precision and stereoscopic view, data volume will be larger than MSS</td>
<td>Potentially highly suitable once world cover complete (1987-1990)</td>
</tr>
<tr>
<td></td>
<td>1:1 000 000</td>
<td>stereoscopic view</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metric Camera</td>
<td>1:50 000 -</td>
<td>10-20 m</td>
<td>Good</td>
<td>The metric camera is still in research phase. Many years before coverage is complete. Available for research only</td>
<td>- as for SPOT</td>
<td>Potentially highly suitable once operational (not yet foreseen)</td>
</tr>
<tr>
<td></td>
<td>1:1 000 000</td>
<td>stereoscopic view</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sidelonging Airborne Radar (SLAR)</td>
<td>1:50 000 -</td>
<td>± 25 m</td>
<td>Only black and white imagery can be made. This has superior qualities for topographic &amp; landuse analysis, but is poor for soil/vegetation discrimination</td>
<td>Available for some developing countries in humid tropics, and for many developed countries. Owned by national institutes</td>
<td>- data volume large; interpretation requires special training</td>
<td>In humid conditions superior to other types of imagery due to cloud penetration capacity. In other conditions, Landsat is superior</td>
</tr>
<tr>
<td></td>
<td>1:400 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic Aperture Radar (SAR)</td>
<td>1:250 000</td>
<td>± 25 m</td>
<td>Idem SLAR</td>
<td>Available for parts of Northern Hemisphere only, Commercially available</td>
<td>- as for SLAR</td>
<td>Idem SLAR</td>
</tr>
<tr>
<td>Medium-High Aerial photography</td>
<td>1:50 000 -</td>
<td>± 10 m</td>
<td>Good</td>
<td>Available for relatively few countries in the developing world. Owned by national institutes</td>
<td>- for regional studies; due to stereoscopy, still larger data volume than SPOT</td>
<td>Useful for small studies. In large studies Landsat is preferable</td>
</tr>
<tr>
<td>(false colour)</td>
<td>1:120 000</td>
<td>Stereoscopic view</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Pair-</td>
<td>1:40 000 -</td>
<td>± 5 m</td>
<td>The photos are black and white which do not allow soil/vegetation discrimination</td>
<td>Available for most countries in the world. Owned by national institutes</td>
<td>- very large data volume</td>
<td>Poor vegetation discrimination. Very large data volume and little overview make aerial photography less suitable</td>
</tr>
<tr>
<td>chromatic</td>
<td>1:150 000</td>
<td>Stereoscopic view</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8.2.1 Geostationary satellites

The fact that these satellites cannot discriminate vegetation from soil makes them unsuitable for our purpose. Additionally, the spatial resolution is too coarse. For further information, see e.g. Cornillon 1980.

8.2.2 NOAA/AVHRR (Advanced High Resolution Radiometer)

This sensor, which is present on two NOAA satellites, scans the whole world four times daily (twice during daytime, twice at night) with a resolution of ± 4 km.

High resolution images can be obtained at 1.1 km. However, for most of the developing world this can only be achieved infrequently. The wavelengths which are recorded permit the production of false colour composite imagery. Cloudfree composites can be made by selecting cloudfree portions of a series of subsequent daytime recordings (C.J. Tucker, personal communication). These could be used for exploratory analysis. A Landsat based reference showing landuse and topographic patterns is additionally required at this scale.

The most revolutionary application of this imagery is, however, that production of cloudfree 7-10 day or monthly composite vegetation index imagery is possible. This permits constant monitoring of vegetation conditions anywhere in the world since 1979, and is on the fringe of becoming operational. For further information see Tucker 1983; Tucker 1985; Hielkema 1985.

8.2.3 Nimbus Coastal Zone Colour Scanner (CZCS)

Although this sensor has produced a wealth of information and it can discriminate vegetation, no suitable standard product has been developed. For further information see Needham 1984; and Nykjaer 1984.

8.2.4 Landsat

Five different Landsat satellites have been in orbit almost continuously since spring 1972 covering every point on Earth every 16-18 days. The three most relevant sensors on board have been the Multispectral Scanner (MSS), the Radio Beam Vidicon (RBV) and recently (since November 1982) the Thematic Mapper (TM).

**MSS sensor**

With this sensor imagery has been acquired almost uninterruptedly since 1972, which means that for receiving stations within reach imagery has been obtained every 16-18 days since then. Outside this range, it can be assumed that at least 1-2 reasonable or good pictures were acquired of every landmass on earth, except for some areas in the most humid tropics. The resolution, scale price and availability for the whole world
makes it the most ideal tool for any reconnaissance scale landscape analysis (+ 1:125 000-1:2 000 000) anywhere in the world. Topography, landuse and vegetation can be well studied. For further information see e.g. NASA/GSFC (1972).

**Thematic Mapper**

With its increased spatial and spectral resolution, the TM is superior to the MSS imagery. However, the increased detail is not always required, but always has to be paid for. A complete world coverage has not yet been acquired and could still take several years. In scale and projection, TM imagery can be used complementarily to MSS imagery. For further information, see e.g. ESA (1984).

**Radio Beam Vidicon**

Very little imagery was acquired before acquisition due to lack of interest. The initial advantage of higher spatial resolution than with the MSS has been superseded by the TM.

8.2.5 **SPOT (Système Probatoire d'Observation de la Terre)**

In November 1985, the first French polar orbiting satellite will be launched. The main sensor will be the HRV (High Visible Resolution) which will be able to produce pictures with 10-20 m resolution that permit stereoscopic analysis. The spectral characteristics will permit vegetation discrimination. The products to be delivered have promise for 1:50 000 - 1:1 000 000 scale landscape analysis. In practice, the correct functioning of the sensor and satellite will have to be awaited and also (considering the high resolution) the regulations on free commercialization. For further information see CNES (1983).

8.2.6 **Metric Camera**

The metric camera experiment on Spacelab and Spaceshuttle missions produces black and white as well as colour pictures with the same qualities as aerial photographs, but with scales between 1:250 000 and 1:1 000 000 and for certain applications up to 1:50 000. The pictures are very suitable for the landscape guided method. It is not known at present whether a full world cover will be made. For further information see DFVLR (1983).

8.2.7 **Side Looking Airborne Radar (SLAR)**

Radar imagery is very different to all other imagery, both in the way of acquisition and in its properties. Its major advantage is that it can be produced independently of weather (and clouds) and can thus be produced from normally cloud-covered areas. As it is the only reliable data source from such areas, it is thus the best in spite of its limitations in vegetation discrimination. The imagery is always the property of a government institute and not freely available. For further information, see McCoy (1967), Savigear (1973) and Morain (1970).
8.2.8 Synthetic Aperture Radar (SAR)

SAR imagery is a technically advanced version of the SLAR with, amongst other things, a higher resolution. It can be made airborne and there has been one Seasat satellite mission, which only covered the developed world in the Northern hemisphere. The characteristics of SAR imagery are very similar to those of SLAR. For further information see NOAA (1982).

8.2.9 High Altitude Aerial Photography

All false colour aerial photography is suitable for use in the landscape guided approach. This type is generally used for medium to high altitude flights due to its relative insensitivity to haze. However, the photography is only made for a limited number of countries or areas and is not readily available.

8.2.10 Standard panchromatic aerial photography

This type of photography is at present available for most of the inhabited land surface on earth, as it forms the basis for topographic mapping at scales of 1:50 000 - 1:100 000. With the technology developed around it, it forms the most precise source of data on topography. Its wide availability invites its use for the landscape guided approach. However, the analysis of trends in vegetation cover is difficult to impossible on black and white pictures. Additionally, the handling of the data is very tedious, unless the area of study is limited, and the detail of individual trees that are visible is often more confusing than helpful in the analysis.

9. CONCLUSIONS

1) Many types of imagery supply useful information on topography, which has a casual relationship with climatic variation and on vegetation and landuse patterns, which are, to a large extent, determined by climatic variation.

2) The study of landscape features on imagery can be as useful for climatic inventory as it is for soil, vegetation and geological inventories for which it is already widely used. For climatic inventory, imagery can be used as a continuous reference matrix that permits the determination of the area for which each station is representative.

3) The image feature with most information on climatic variation is vegetation cover. Although the absolute amount of vegetation cover varies greatly in space and time, the relative differences that indicate the beginning, end, steepness and direction of ecological gradients remain visible on any imagery.
Landscape patterns on imagery contain direct or indirect information on all major climatic parameters, i.e. temperature, rainfall, wind, moisture balance, major climatic conditions, etc.

By plotting the measurements of any parameter on the imagery, an understanding of the relationship between climatic gradients and landscape gradients can be achieved.

It is the converging evidence from the trends indicated by topographic, vegetation and landuse patterns on imagery, data on altitude from contourlines, and the calibration with climatic data from climatic stations, that leads to the most accurate results in climate inventory.

A final true and perfect climatic inventory cannot be made because of the variable and changing nature of climate. What can be done is to improve the approximations.

Under many circumstances, the landscape guided method can produce better results than conventional techniques; particularly if the climatic data are scarce and of doubtful quality.

With one good quality image of any date, the majority of the improvements possible with the landscape guided method can be achieved. With more imagery available, further refinements can be obtained.

The two following major improvements can be achieved generally in comparison with conventional methods:

a. Relative improvements of the spatial and geographical accuracy as a consequence of a better understanding of landscape - climatic relationships. This understanding permits the scientist to extrapolate trends thus fill data gaps and to judge better the siting of stations and the area for which they are representative.

b. Absolute improvement of the results. The critical comparison between the trends indicated by the station data and the landscape trends permits detection of data of doubtful quality and human errors (data computation, typing and plotting) that otherwise would remain unnoticed. The greater the deviation, the easier the detection.

The use of imagery can always improve an inventory, but several factors determine whether the effort is worthwhile. The most important are:

- the poorer the fit of the station density with the landscape complexity, the more useful the method;
the greater the topographic differences, the more dominant the climatic impacts are in comparison to other ecological factors (soil differences, rooting depth, landuse, etc);

Other factors are discussed in chapter 7, they are:
- the climatic parameter
- the time frame of the study
- the number of years of record
- the siting of the stations
- the scale of the study
- the quality of the imagery available
- the dominant climatic condition
- the degree of human disturbance
- the experience of the interpreter
- the efficiency requirements

11) Using imagery has a special advantage if the climatic inventory is to become part of an integrated automated geographical data base. The holistic overview of the landscape on imagery is the best tool available to integrate different types of data (soils, vegetation, geology, climatic maps, etc).

12) Imagery from satellite and airborne sensors has become so widely available that it can be obtained for almost any part of the world at any scale. The following image requirements are relevant for the landscape guided method:
- spectral discrimination of vegetation from soil brightness gradients;
- false colour imagery to display soil and vegetation patterns;
- a resolution that permits recognition of drainage patterns and landuse;
- a broad overview over the relevant landscape gradient at the scale of interest:
  - for detailed studies (<1:100 000) false colour aerial photography is most convenient;
  - for reconnaissance studies (1:100 000 - 1:2 000 000) Landsat (MSS or TM) is optimal with SPOT and Metric Camera possibly in the future;
  - for exploratory scale studies (>1:2 000 000) NOAA false colour composites of band 1 + 2 are most useful, but require support of topographic maps or Landsat mosaics.
9.1 **Recommendations**

1) Since imagery at any scale has become so widely available, the use of it also for climatic inventory is recommended.

2) It is recommended that the method sketched in this report and in Van der Laan 1985, be applied more widely to test its usefulness, both for other climatic parameters and under different conditions in other parts of the world. Reports of experience and results will be welcomed by the FAO Remote Sensing Centre.
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Many methods have been developed to obtain acceptable quantitative estimates or areal impact starting from point data. Particularly on the estimation of total or average rainfall, e.g. for a certain catchment area or for the determination of agricultural production, a lot of research has been done.

Shaw (1983) mentions the following most customary areal rainfall estimation techniques:

i. With many uniformly spaced raingauges in an area of no marked surface diversity the calculation of the arithmetic mean is a good approximation.

ii. In the Thiessen polygon method, the measurements of the stations are weighed by the fraction they represent in the area. This requires a network of representative stations.

iii. The Isohyetal method is considered the most accurate method, but is subjective as it depends on skilled analysts. Isolines, connecting points of equal conditions are drawn between stations over a contour map, taking into account exposure and orientation of the stations. The method requires long homogeneous records for large numbers of stations.

iv. The Hypsometric and Multiquadratic methods take topography into account. These methods are recommended for small to medium size areas, where detailed experimental studies are required. They require the establishment of detailed correlations between topography and rainfall.

The conditions specified indicate that none of the conventional methods for areal rainfall determination is optimal under the conditions found in many developing countries, where low density networks occur and data can be unreliable.
THE LANDSCAPE GUIDED INTERPOLATION METHOD STEP BY STEP

The main usefulness of Landsat imagery for the improvement of the accuracy of climatic inventories is that it leads to an improved understanding of the relationship between topography and climate. This relationship is not always immediately obvious and will usually have to be inferred from different features such as drainage patterns, vegetation zonations and landuse patterns. This requires some experience in image interpretation and/or familiarity with the local conditions. In order to prevent misinterpretation, the following step by step methodology is recommended as a first experience.

II.1 PRELIMINARY INTERPRETATION OF THE IMAGERY

This stage has two main objectives:

1) to determine the altitude gradients;

2) to understand the landscape features as visible on Landsat in relation to the climatic factor to be mapped.

II.1.1 TOPOGRAPHIC GRADIENTS

An understanding of the topography can be obtained in two ways:

Step 1: a) The hard way: by copying the drainage pattern on a transparent overlay. A perfectly suitable but relative overview of all altitude gradients, their length and their direction can be obtained.

b) The easy way: it is simpler if topographic maps of a suitable scale are available and contour lines can be copied and overlaid over the imagery. In this case an absolute idea about the altitude gradients is obtained.

II.1.2 ANALYSIS OF LANDSCAPE FEATURES ON THEIR INFORMATION CONTENT FOR CLIMATIC GRADIENTS

Step 2: Separate the difference in vegetation greenness or land use patterns due to climatic influences from those due to other factors. A convenient method is to subdivide roughly the area of interest into "major land systems" on geological and geomorphological criteria on a separate overlay (no. 2).
Step 3: This process makes you aware of unrepresentative vegetation and landuse patterns which are due to soil differences, run-off, run-on (marshlands) etc.

Step 4: Assess the effect of human interference, i.e. forest reserves, over-grazing, burning patterns, irrigation schemes, deforestation etc., in order to recognize them as artifacts at a later stage.

Step 5: Differentiate between regions with moist and stable humid conditions and those with arid and semi-arid conditions, where rainfall tends to be erratic and thus vegetation patterns can be misleading on a single data image.

Step 6: From literature or the patterns of the vegetation around elevations, assess the direction of the rain bringing winds. Verify if this direction varies at other times of the year apart from the period when the imagery is available.

II.2 ANALYSIS OF LANDSCAPE FEATURES IN RELATION TO CLIMATIC DATA

Step 7: If sufficient understanding of the landscape features on the image has been obtained, the climatic point data can be plotted.

Step 8: If situated correctly, the trends in the point data and the trends in the landscape gradients should support each other, as well as the artifacts specified in point 3.6.

Step 9: The point data form the quantitative references, while the landscape features give an indication of the area for which each station is representative as well as the direction and extent of the gradients. As both types of inputs are independent sources of information on climatic patterns, they form an excellent tool for critical comparison.

This will often lead to discoveries of new artifacts in the features of the Landsat image. However, it is not infrequent at this stage that the data from the stations requires checking and re-evaluation.

II.3 DATA CHECK FROM METEOROLOGICAL STATIONS

Step 10: Several types of mistakes can occur in climate reference data. (see also section 4 and 6.4.3).

- Check if the measurement of a station represents a general tendency or a specific micro-climatic condition. A station can be, for example, in front of or behind a hill that is almost too small to be noticeable.
Check if all stations are plotted in their right positions. The greater the deviation from the value of the trend shown by the landscape feature, the easier the detection of a misplaced station.

If the data of a station still does not fit into the confirmed landscape gradients, check the number of years of records and the reliability of the original data and even the computation.

II.4 THE LANDSCAPE INTERPOLATION ITSELF

Step 11: After the relationship between the climatic data and the landscape gradients has been ascertained and explained, the actual interpolation can be effected.

The interpreter is now fully familiar with the region and can best judge how representative each station is for its surroundings. By comparing the landscape features around and between the various stations in each gradient, the characteristic landscape features for certain climatic conditions can be determined.

The relative priorities between the stations, supplemented by the additional landscape characteristics where necessary, determine the best course for the isolines.
MEAN ANNUAL RAINFALL ISOHYETS RESULTING FROM THE STRAIGHTFORWARD INTERPOLATION METHOD

ISOHYETS AT 150 OR 300 MM INTERVAL

ISOHYETS, WHERE SEVERAL INTERPRETATIONS OF THE DATA ARE POSSIBLE

POSITION OF RAINGUAGES

825 (3) — NUMBER OF YEARS OF RECORDS, IF LESS THAN 20 YEARS

MEAN ANNUAL RAINFALL

1-17, 1 — REFERENCE NUMBERS FOR DISCUSSION IN SECTION 8.4.1 AND 8.4.3

N.B.: THE LANDSAT IMAGE 180/61 HAS BEEN DISPLAYED FOR REFERENCE PURPOSES ONLY

SCALE APPROX. 1:1000000
MEAN ANNUAL RAINFALL ISOHYETS RESULTING FROM CONTOURLINE ASSISTED INTERPOLATION

Contour lines, 1000 feet interval

Isohyets at 150 or 300 mm interval

Isohyets if several interpretations of the data are possible

Position of raingauges

557 (9) — Number of years of records, if less than 20 years

Mean annual rainfall

1-17 2-1 Reference numbers for discussion in section 8.4.2 and 8.4.3

N.B.: The Landsat image 180/61 has been displayed for reference purposes only

SCALE APPROX. 1:1000000
Isohyets at 150 or 300 mm interval
Isohyets, where several interpretations of the data are possible
Position of raingauges
766 (3) Number of years of records, if less than 20 years
Mean annual rainfall
1-17 Reference numbers for discussion in section 8.4.3
A-C Reference numbers for discussion landuse in section 8.4.4
5/6/L Reference numbers for discussion soil change aspects in section 8.4.4.2
N.B.: Landsat image 180/61 as shown, has been fully functional in the determination of the course of the isohyets.