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CIME: AN EXPERT SYSTEM FOR LAND USE AND VEGETATION MAPPING BY REMOTE SENSING THE EXAMPLE OF A MOUNTAINOUS AREA (central Himalaya)

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INTRODUCTION

Cartography by remote sensing is a way not only of exposing knowledge but also of *producing* it. The methodologies involved in that process are often very complex (especially in the mountainous areas) as the number of tools utilized is high: radiometry, vegetation and texture indexes, topographical, slope and illumination models. At the same time, in order to speed up the production of maps, to avail of reliable elaboration and control procedures, theses methodologies need to be reproductible and if possible automatized. These reproductibility and automatization cannot be achieved unless the procedures are formalized. Utilizing numerical treatments, these require two types of distinct technical know-how: statistical and computer programming on one hand, thematic knowledge on the other hand. Each of these know-how is refering to distinct spheres of knowledge and implementation methods. If each and every problem encountered by the thematicians require a specific methodology, the procedures of these methodologies are much less numerous: based on the representation and the simultaneous simulation of the two know-hows, CIME System (Intelligent cartography in mountain environment), build on a classical inference motor, was originaly meant for driving and optimizing the sequential activation of numerical treatments in view of mapping vegetation and land-use in Central Nepal, **but this technique is also utilizable by other thematic researches and/or for other areas.** The purpose of this article is to present the methodological set-up, the architecture and the implementation of CIME applied to Landsat and Spot images.

1.- Why an Expert System?

1.-A.- Map, Knowledge and cartography by remote sensing

The knowledge of the environment, the societies and their production systems cannot be conceived without a cartographical representation: the speech does not account for all the interrelations of their components. Graphics and associated modellisations make the description of these systems easier by revealing multi-causal circular relations. Nevertheless, the space of their construction is of no reality. Now the notions of homogeneïty-heterogeneïty, limits, discontinuity, proximity, center and periphery do play an increasing role in geographical analysis and in the study of the state and/or evolution of systems such as landscapes, societies, political units, production systems...: the cartography alone allows to represent not only simultaneous spatial interrelations of the elements of a said system but also the state of these elements. The map cannot say all but is alone to express the knowledge of space.

Cartography cannot be reduced to a mean of communication of acquired information: one can identify two types of maps. One is the *synthetic map* which is a document where information collected on the ground is represented: no new information is produced during the process of the elaboration of the map which is merely a mean of communication. On the contrary, the *analityc map* is prospective and its elaboration requires an analysis of images (aerial photos or satellite images) in order to identify objects, their limits and their states as per the type of map wanted, the technique of analysis and the nature of the more or less extensive ground knowledge which will be amplified and modified by the map. Such a cartography is a mean of *production* not only of *knowledge* but also of *questions* and *directions of investigation* by *the identification and caracterization of the object of the study.*

This type of knowledge production, to which remote sensing does belong, also requires a temporal dimension as no functional natural or human system is fixed and the very notion of equilibrium has to be conceived in terms of capacity of a system to constantly reorganize itself under the differential evolutions of each of its elements and the external disturbances. It becomes then necessary to be able to apprehend the rythm of each component of the system: repetitive mapping allows the comparison of the mapped object with itself. It also allows to put new questions on its nature.

Finally, if a methodology of cartography has to produce a knowledge of the mapped object in time and space (and, if necessary, the conditions of an action on this object), it has also to allow its comparison with other objects of the same order, that is to say their own cartography. In order to meet all these needs at bearable money and time costs, that the taxonomies should be compatible does not suffice: the method itself has to be reproductible. The problems and the methods elaborated to solve them are often so complex that this reproductibility is neither possible nor even thought of: in the majority of the cases, the map is the objective not the methodology of its production. At best, the procedure is explained, a succession of steps that one has to reprogram. The necessity and difficulty of a systematization and a reproduction of the methods and the need of a mass production make then necessary the formalization and the automatization of the production of maps. Thus becomes evident the interest of a procedure like the *Expert System* which separates the methodology and the specificity of each thematic problem, allowing a formalization and the automatization of the construction of thematic maps. Even withstanding the necessary reproductibility, the utilization of an expert system is justified by causes belonging to the process of cartography itself.

1.B.- The procedure

The strategy of CIME simulates the strategy of a human expert who adopts a supervised procedure to elaborate a thematic map, in the present case, the cartography by remote sensing of vegetation and landuse in the Center of Nepal [Blamont & Mering 87]. In other words, the procedure is the partition of a 2-D space (a satellite image) by a succession of numerical treatments on values (the variables) associated to its elementary points (the pixels). Patches of contiguous pixels [*test-plots*] will be identified through a research on the ground, grouped into classes and named after a coherent list, considered as complete, of vegetation units and forms of landuse (forming what is called the landscape of the area) defined *before* the image analysis. They will be the base of the treatments and used for the identification of all the others. The objective of the system is to classify the *pixels* belonging to the *test-plots*, defined by the thematician. To classify them, a common supervised procedure is used: one part of the test plots, called *triaining plots,* is used to define a chain of various segmentations of the numerical variables. The other part, the *control plots*, is used to verify the segmentations. Thanks to the differenciation of internal validation (for example the *Kolmogorov-Smirnov* distance in the case of non parametric discrimation) and external validation by *a posteriori* utilization of control plots, other classification methods can be utilized in the framework of the same general strategy, provided their result is also a segmentation of the variables. The final aim is the identification, the caracterization and the assimilation of the resting unidentified pixels to the landscape units.

At each step, the expert utilizes numerical treatments after having defined their entry variables. The analysis of the results of this first step will tell him whether to interupt the procedure or to select new methods (or other variable of the same method) in order to better the classification. He can also elaborate other chains of treatment; he has then to compare the results of all his chains and choose "the best" to classify the whole mage: the human expert supervises the activation of the treatments, controls the results and chooses the best chains.

1.C.- Why a simulation of the procedure ?

1.C.1.- A complex procedure

1.C.1.a.- Important number of descriptors: The very nature of the studied area is a very complex one and the sources of the complexificaton are of two kinds:

The nature of the landscape units

• **The multiplicity of landscape units**; the altitudinal amplitudes are very important: upto 4,000 to 5,000 m on one single versant. As a result, the gradation of climate goes from subtropical to alpine. The gradations of the vegetation and landuse are further multiplied by the numerous exposures (to sunlight and/or monsoon winds) and situations inside the massif.

• **The size of the landscape units**; as a result of the steepness of the slopes, the gradation of the vegetation is very quick and each grade is very narrow.

• **The margins**: the limits between the different vegetation types are mostly natural ones, that is to say gradual. But they are also fuzzy between *natural* landscape units and the cultivated areas: generally these areas are bordered by grazed areas where the vegetation grows denser with the distance to the fields: they often have to be considered as landscape units as such.

• **The management of the environment**: forests are overexploited and the most accessible slopes are evidently the most vulnerable: big differences in utilization between gentle and near slopes and steep and far away ones add a new factor of differenciation to the natural diversity.

The conditions of image shooting

• **The influence of lighting conditions:** at the time of image shooting (0930), solar elevation is low and the ligthings of the versants stand in very high contrasts. Comparable landscape units have widely different radiometry.

• **Haze effects:** The different lighting conditions do also cause differences in the state of the atmosphere over different versants: haze is more frequent and important over shadowy versants than over lighted versants; thus the radiometry is not of the same kind and the signals cannot be interpreted the same way. This only would justify separate treatments.

The nature of the complexity introduced by all these factors makes necessary the utilization of a high number of variables associated to the pixels. These variables are of three orders:

• Some belong to the image itself: the radiometry.

• others are obtained by calculation from these values: for example, texture indexes caracterizing, in a given spectral band, the variability of the values around a given pixel. They can also be indexes caracterizing more accurately certain categories of components on the ground. In that case they are generally obtained through the combination of spectral bands (for example, green vegetation indexes, combinations of red and infrared bands).

• Others are external to the satellite data: here, the altitude, the slope and the lighting and the time of image shooting.

-1.C.1.b.- Variety of iconic forms: the objects directly treated by the system are pixels belonging to the test plots. Nevertheless, although the pixels are considered individually in the system, the procedures of numerical treatments refer to the plots as wholes, that is to say groups of topologically near pixels. The difference in the modes of representation adopted for numerical treatments and for symbolic treatment corresponds to a difference of status of the procedures operated in these two phases. Furthermore, the notion of classe refers to the geographical limits of a zone, for example "clear oak forest" or dense fir forest". Nevertheless, it is necessary to note that, although the pixel definition (around 80 meters) is comparable to the size of some of the geographical objects studied, the knowledge of these objects has no relation with the knowledge of the pixels.

1.C.1.c. Constant control procedure: Rather than to test all possible chains, at each step contol procedures allow the operator to stop or to go on with a definite chain.

1.C.2.- A changing procedure:

Due to the numerous factors of heterogeneïty and as the congruence between their effects is very high, on one hand, and as no method of signal correction seems reliable enough, on the other hand, the image is divided in sectors in which the influence of the lighting conditions on the radiometry is marginal when compared with the influence of the vegetation and landuse covers. Three sectors have been identified: the versants which face the sun and receive direct lighting (*lighted sectors*), the versants which receive only indirect lighting (*shadowy sectors*) and versants receiving grazing lighting or on which the alternance of lighted and shadowy sectors is at the scale of the pixels (*grazing light sectors*).

As the natures of the landscapes and of the radiometry are different from one type of versant to the other, there is no reason for the relevance of the variables and the order of their utilization to be the same for the three types of sectors: generally the sequences or chains differ, which obliges the operator to work out three different procedures and requires a know-how which generally does not belong to the epistemic domain of the thematician. Thus, the procedure has been rendered independant from the order of introduction of the variables: in other words, the proposed expert system does not require from the thematician any other knowledge than the one of his thematic field.

2.- The system: knowledge and numerical procedures

2.A.- The nature of the knowledge: the knowledge to be introduced into the system is of various domains: one can work out a typology of these domains which will depend on the chosen thematic.

2.A.1.- Thematic and terrain knowledge

The thematic knowledge (taxinomy [:hierarchysed organization of a legend], and the problematic knowledge [elements of organization of a discourse or an interrogation on the taxinomy and establishing relations between its elements others than vicinity or encasing]) are at the origin of each specific mapping project and will determine the elaboration of the legend. The terrain knowledge (the local formalization of the taxinomy) will be collected accordingly to the specific questions raised from the precedent and will be utilized in the elaboration of the test plots.

2.A.2 Knowledge about appearence of geographic entities on satellite images.

This knowledge allows thematicians to delimit significant entities on the image from their iconic attributes such as color, texture and shape. Thematicians may also know about topographic relashions between entities (proximity, adjacency, imbrication), and about the structural relation between entities ("part of whole" relation).
Expert systems in *vision* invoke this kind of knowledge. These systems have been built up in order to analyse natural scene [LEVINE 81] and aerial photographs of suburban areas [NAGAO 80].

At the opposite, our system is not based on simulation of the visual process. As a matter of fact, one has to analyse the remote sensing scene according to a given topic, such as lithology, soils, vegetation, landuse and therefore to elaborate entities which in many cases, are not perceptible on the image from a constant level of observation. On the image of MSS6 band of the Salme scene in Central Nepal (fig 1), one can *see* the main features of a mountainous land such as shadowy valleys, sharp crestlines, versants with various orientations and lightings. But one does not *see* the various types of vegetation such as forests, grass-lands or fields under cultivation. On the resulting thematic map (fig 2) vegetation is represented throuh a given taxonomy, but the relief is no more perceptible: the visual analysis has only a relative part in the analysis process.

The knowledge about iconic expression of landscape units is given to the system through a *prototype data base* composed of test plots. Each pixel of a test- zone is described by attributes such as radiometric values corresponding to the four Mss bands and a textural index[1]. The other attributes of the pixels such as altitude, slope and illumination cannot be considered as pertinent for a visual analysis. In this case, knowledge about expected appearence of the landscape units on MSS data is too much ambiguous and incomplete to be taken into account in the system. With high resolution images such as SPOT, we hope that one can make clear this kind of knowledge in so far as perceptible iconic entities can obviously be interpreted as entities of the landscape under analysis according to their texture and shape.

2.A.3 The activation of numerical treatments

As it does not simulate vision, the system needs to have an explicit knowledge on *how to* elaborate iconic entities corresponding to geographic ones. In this version, the system has a semantic knowledge of the image segmentation techniques. It can therefore activate a technique which is in the conclusion part of a production rule. It also analyze and control the results given by the techique.

The techniques recognized by the system are automatic classification techniques. In this system the interpretation can only be performed through the test plot data base. Therefore we simulate a classical supervised approach of analysis, and we select only supervised classification techniques. In this version we call for a non parametric discrimination method based on the minimization of the bayesian risk [CELEUX 80]. The basic method consist in splitting the set of pixels within two classes . The splitting operation correspond to the thresholding of a the most discriminant quantitative variable according to the bayesian risk criteria in reference to the two theoric classes. the two resulting subsets are called *segments* . When there are more than one descriptive variable, a single iteration will generally not be enough to determine the segments. If one of the two resulting segments satisfies the stop criteria, it becomes a *terminal segment* . If not, the whole procedure is applied to this segment.

The system explicitly invokes the previous method and defines all the formal context of its release (instant of execution, set of data to be processed, calling parameters). Then it processes analysis and control of the numerical results, decides about their acceptance. If accepted as available, the results are integrated to the factual database.
The present system can monitor supervised segmentation methods, each segment being associated to a set of theorical classes.

2.B Knowledge representation

As told in the former paragraphs, the knowledge that has been invoked comes from various domains such as geography, statistics and image analysis. But here, we do not take into account the domain of the knowledge but only the function of it in the resolution process. Therefore we distinguish two kind of knowledge: descriptive knowledge and procedural knowledge.

2.B.1 Descriptive knowledge:

Descriptive knowledge are formalized by assertions containing a set of informations describing the characteristics of the entities under analysis.

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[1] the local standard deviation computed with a sliding window (3x3 pixels) on the MSS 6 image

In our system, we have formalized knowledge about iconic entities, that is the control pixels, as well as knowledge about thematic concepts, such as geographical concepts. For example, the two following assertions :

-"pixel number 12 is associated to the oak forest class "

-"the scene is situated in a mountainous area"

are treated identically by the inference engine "facts" that is as elements of the descriptive database.

Each pixel is described by a set of attributes having either symbolic or numeric values:

- r1,r2,r3,r4 : the four radiometric values corresponding to the four MSS bands
- a : the altitude (evaluated by the MNT)
- p : the slope (evaluated by the MNT)
- e : the illumination at the shooting time (evaluated from MNT and the coordinates of the center of the scene)
- cl : the symbolic name of the class represented by the corresponding test plot.
- cl_afterwards : the list of the symbolic names of the potential classes after a step of analysis

Each pixel is described as an *object* described by all its attributes. The other sort of knowledge, such as the geographical situation of the zone, are considered as attributes describing a single object called *general object.*

The present system can distinguish only two kind of objects : the local ones (ie pixel) and the general one (ie context). In the next version, other kind of objects would be avalaible.

2.B.2 The procedural knowledge

The procedural knowledge defines, how to get an information from already established facts, through a propositional mode. In CIME, this kind of knowledge is represented as individual production rules which have the following declarative form:

If Conditions

Then Conclusions

The content of the Conclusions part can be whether assertions like in the Conditions part, or actions, that is, executions of a given procedure. All the rules are given in bulk. For example the following one is linked to the thematic knowledge about the vegetation altitudinal levels:

rule (1): If
there is an altitudinal level,
altitude < 20,
Then
class_afterwards is not grass-land
class_afterwards is not oak- forest
class_afterwards is not fir-forest
class_afterwards is not rhododendron-forest.

This rule says that, certain types of vegetation cover being absent under a given altitude, one has to eliminate them from the class_afterwards label at the current step.

The following rule enables the execution of the classification numerical method called "dnp":

rule (2): If
the region is a shadow region,
selected classification method is dnp,
Then
execute dnp on the radiometric variables,
step = 1,
state = radiometric analysis,
count resulting segments.

This rule provides the context of the execution of a numerical method, so that the method is applied only to the pixels belonging to a shadow region.

In the conclusion part, input descriptors (here the radiometric ones) of the pixels to be classified are selected, the chain and the step are labeled with respecrtively a symbolic and numeric label, and the resulting segments are computed.

3. The running of the system.

3.A. supervision of numerical treatment by symbolical treatment.

- The pixels under analysis belong to control zones that is to say by already classified zones. To this initial and fixed classes, the system adds the *class afterwards*, that is a subset of the set of a priori classes, thanks to the activation of an external procedure of segmentation.

-Each segment will be considered as a *constraint* that will be applied to the pixels under analysis. We have adopted a general principle according to which the results of a given step of the chain cannot be totally reconsidered by the results of the following step. Such a principle can be applied in the peculiar case where, for every step greater than one, the results concerning *class afterwards* are negative assertions. In the rule (1) this principle is applied.

- The evaluation of the *unreliability* of the current labelling is achieved by the computation of an appropriated numerical coefficient. If this coefficient is not decreasing, the chain has to be interrupted.

-The final aim is to find a sequence of partitions after which each pixel is correctly classified. One can practically find a number of imperfect sequences of partitions the results of which are not equivalent. Therefore one will look after the *best sequence* that is the sequence that give the more relevant classification of pixels according to their initial classes.

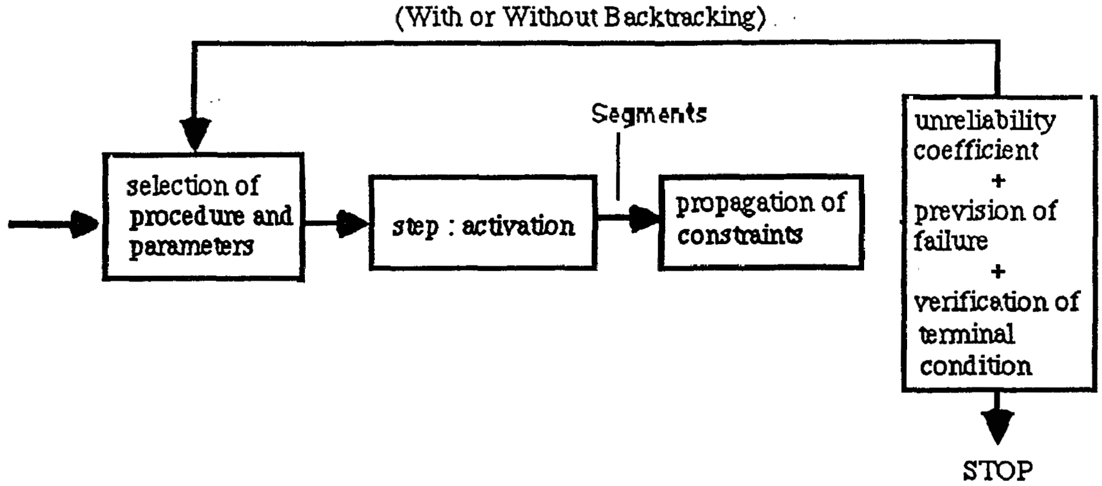
The best sequence found by the system according to the control zones will be at least applied to the whole scene.

-The *inference mecanism* is built according to the constraint propagation principle, with a three phase cycle:

1. The best procedure is chosen according to the general context and to the current state provided by the results of the previous steps.
2. The results of the procedure are propagated.
3. The coefficient of unreliability is computed , the failure is forecast and the terminal condition is evaluated:

If the terminal condition is verified
Then end
If not
Then
If the coefficient of unreliability does not decrease
Then backtrack
If not
Then start a new cycle.

This algorithm can be described by the following scheme:



The interruption can be due whether to the constraints satisfaction or to an irreductible failure. In the last case, the thematicien is asked to reconsider the test plots. Artificial Intelligence techniques have contributed positively to the remotely sensed data interpretation since they can point out a part of the initial information provided to the system, whether it is due a sampling error or to an irrelevant choice of the initial classes.

3.B Control rules and coefficients

The three phases cycle described above has been built up with specific production rules that can be called control rules.
These rules are inependant from the thematic knowledge and could be avalaible for other applications of cartography by remote sensing. For example the following rule describes the likelihood of the result according to the objective and to the selected criterion.

rule (3): If
criterion = well_classified_pixels,
map is ready,
Sum_of_well_classified_well_classified > n,
Then
likelihood = yes.

The following rule leads the user towards the selection of a given numerical procedure:

rule (4): If
prototypes are provided,
prototypes are test plots,
a classification is to be achieved
a segmentation is to be achieved
Then
classification _method = dnp

The following rule allows the control of the current unreliability during the stepwise analysis:

rule (5): If
step = n
initial_class is an element of class_afterwards,
inreliability(n-1) > unreliability (n)
Then
step = n+1.

In CIME, the control is achieved thanks to a couple of numerical coefficients: the unreliability coefficient and the likelihood coefficient. The unreliability coefficient is computed by the system according to the following formula:

unreliability = $\{ \Sigma \{ \Sigma\, \partial_j^{cl\_afterwards(i)} ; j=1,m \}\ i=1,N \}/N$

where :
cl_afterwards(i) est le numerical code of the classes associated afterwards to pixel i;
m is the total number of the initial classes;

N est is the total number of pixels under analysis;

The likelihood coefficient is evaluated by the total amount of accurately classified pixels, according to the following formula:

$$v = 1/N \{ \Sigma \{ \Sigma \{ \Sigma \partial_j^{cl(i)} * (1-\partial_k^{cl\_apres(i)}); k=1,m,k\neq j; \} j=1,m; \} i=1,N \}$$

where :

cl_afterwards(i) is the numerical code of the classes associated afterwards to pixel i;

cl(i) is the numerical code of the initial class of pixel i;

m is the total number of the initial classes;

N est is the total number of pixels under analysis;

4.- First outputs

The system has been originally elaborated in order to map the vegetation and landuse of the Ankhu Khola and upper Trisuli Watersheds. The input data base has been built from test plots on the MSS image of 18th march 1976 and the numerization of the one inch/one mile topo sheet (Indian Survey). Presently the system produces pre-maps for the three identified types of versant (see 1.C.2.). Here the treatment of lighted-versants is presented as an example of the running of the system. The table 3 presents the chain obtained in this particular case.

The interactiveness of the system allows the operator to test easily different hypothesis. For example, the map on figure 6 was produced when the variable *altitude* was threshold by declarative rules summarizing the ground truth knowledge of vegetation grading. At the opposite, the system chooses as the best chain the one which produces the map on figure 7, when it is told through a given rule that the data base is representative of the altitude of the landscape units. In the same simple manner the system will ask the operator which type of versant he wishes to be mapped, and then activate all the relevant rules: for instance the system produced the map on figure 8 after the selection of *grazing light versant* type.

The system strictly and constantly maintaining the coherence between the hypothesis, the treatments and the data, the congruence between the produced maps and the expert's knowledge of the considered area is such that no pixel has been wrongly named and that the operationality of the product is much higher than the one obtained with a map produced previously (see figure 2) where the legend is very precise but the uncertainty of the labels is high.

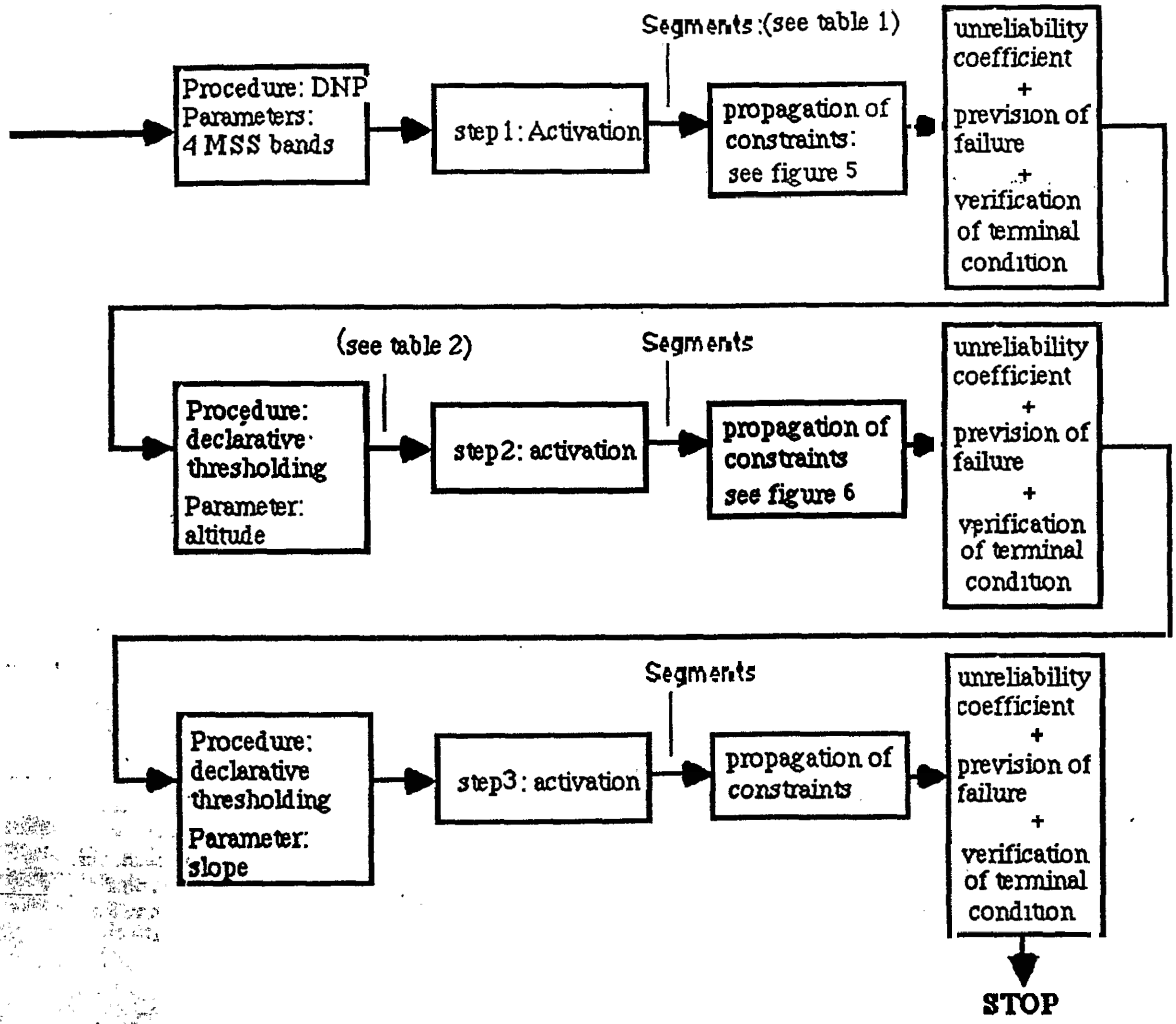
Table 1: Results of the segmentation on radiometric variables
the case of lighted slopes (high Trisuli Watershed)

	MSS4		MSS5		MSS6		MSS7		Associated classes
S1	25	255	0	255	0	255	0	255	**bare soils**
S2	0	16	0	255	0	255	10	255	**oak, firs, cl for, rhod**
S3	0	0	0	255	0	255	0	10	**rhododendrons, firs**
S4	0	16	0	255	0	255	0	10	**firs, oaks, rhod**
S5	17	24	0	24	0	39	0	255	**clear forests, pastures**
S6	17	24	33	255	40	255	0	255	**cl for, cultivation**
S7	17	24	25	255	0	36	0	255	**pastures, cl for**
S8	17	24	25	255	37	39	0	255	**clear for, past, cult**
S9	17	20	0	32	40	255	0	255	**cult, cl for, past**
S10	21	24	0	32	40	255	0	255	**cultivation, cl for**

Table 2: Declarative thresholding of the variable *altitude*
the case of lighted slopes (high Trisuli Watershed)

	Altitude		Associated classes
S1	0	20	**not pasture, not oak, not fir, not rhododdendron**
S2	21	30	**not fir, not rhododendron**
S3	31	35	**not fir, not rhododendron, not clear forest**
S4	36	37	**not rhododendron, not clear forest, not cultivation, not bare soil**
S5	38	40	**not clear forest, not cultivation, not bare soil**
S6	41	50	**not oak, not clear forest, not cultivation, not bare soil**
S7	51	255	**not fir, not rhododendron, not oak, not clear for, not cultivation, not bare soil**

Table 3: the chain worked out by the system for the mapping of lighted versants



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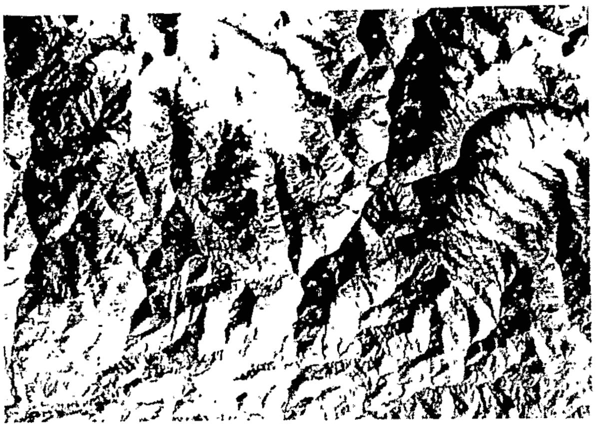

Fig. 1: The whole MSS Scene

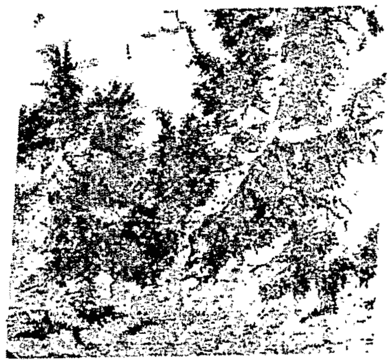

Fig. 2: Map of the vegetation obtained without the introduction of topographical model

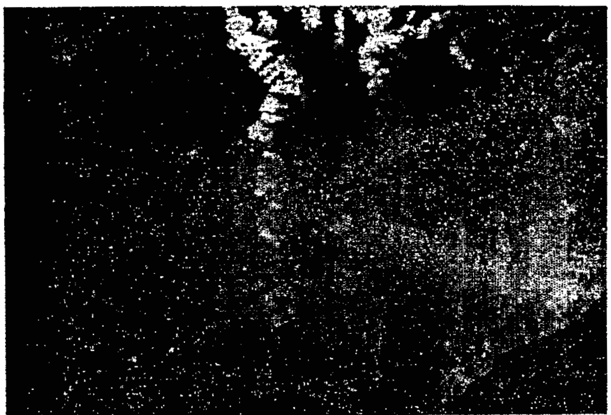

Fig. 3: Lighted versant of MSS 4

Fig. 4: Lighted versant; topographical model

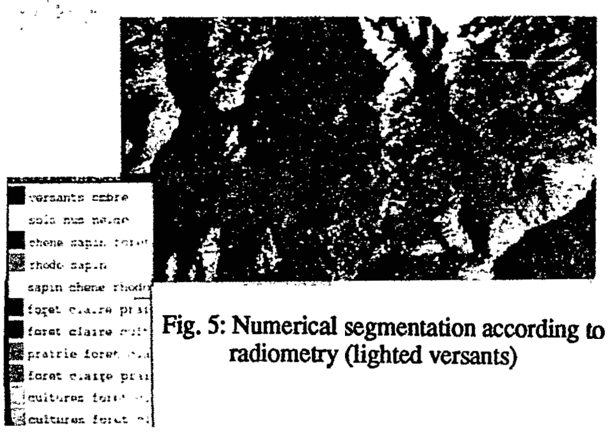

Fig. 5: Numerical segmentation according to radiometry (lighted versants)

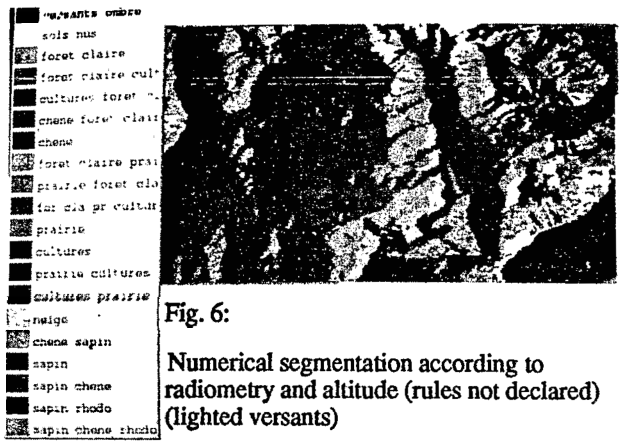

Fig. 6:

Numerical segmentation according to radiometry and altitude (rules not declared) (lighted versants)

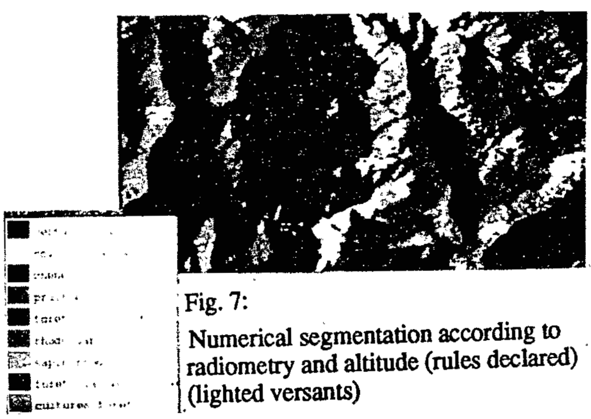

Fig. 7:

Numerical segmentation according to radiometry and altitude (rules declared) (lighted versants)

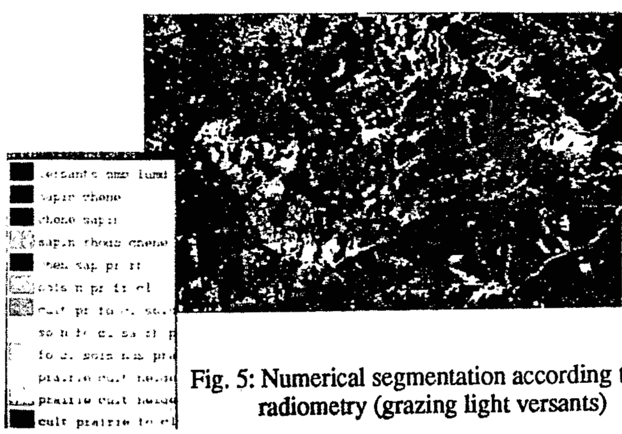

Fig. 5: Numerical segmentation according to radiometry (grazing light versants)