PN-ABI-668
72629

FINAL REPORT
Covering Period: August 1, 1988 to March 30, 1991

Submitted to the Office of Science Advisor
U. S. Agency for International Development

ECOGEOGRAPHICAL ANALYSIS OF DECLINING TRADITIONAL CROPS USING SATELLITE REMOTE SENSING AND GIS

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Project Number: 936-5542
Grant Number: DPE-5542-G-SS-8060-00

A.I.D. Grant Project Officer: Dr. Raymond E. Meyer

Project Duration: August 1, 1988 to March 30, 1991

EXECUTIVE SUMMARY

Substitution of traditional crops by "modern" agricultural crops has caused loss of biodiversity and unforseen economic consequences in developing countries. Traditional crops represent a valuable source of genetic diversity whose preservation is absolutely indispensable to humanity. These crops are often nutritionally superior to "modern" crops, are well adapted to local micro-environments, have high economic potential, and represent a rich source of genetic diversity.

The general purpose was to explore whether earth observing technology represents a cost effective and efficient methodology for locating and identifyind traditional crops in Peru. The goal of the present study was to investigate the prospects for developing a new methodology to ecogeographically characterize six traditional inca crops of the Peruvian highlands using satellite remotely sensed data in a geographic information system environment. The traditional crops on which the present study was focused were kiwicha, quinoa, oca, olluco, añu and tarwi.

The overall aim of this study was to assess whether earth observing technology represents a cost-effective and efficient methodology to be used in support of critical germplasm collection and in situ conservation efforts involving traditional crop varieties in the Developing World, and to eventually extend cropping areas of these crops.

The specific objectives were: (1) to determine how effectively the cultivated areas of the selected traditional crops could be identified through analysis of moderate spectral and spatial resolution satellite imagery; and, (2) to determine how well their distinctive ecological niches can be characterized through computer analysis of satellite data and digitized cartographic and tabular information.

The study took place in an area of the Department of Cusco, Peru, of approximately 2,300 square kilometers, roughly bounded to the north by the Vilcanota river and to the south by the city of Cusco. To characterize the crops within this area, moderate and spectral resolution satellite systems (SPOT 20- and 10-meter spatial resolution, and Landsat Thematic Mapper (TM) seven spectral channels) were used. The field and satellite data obtained were input to a computer system and analyzed. The cartographic data collected were sorted out and the layers of the GIS created.

The original estimate of 12 months was extended from July 1989 to March 1991 due to adverse circumstances, mostly security concerns in the field, lack of suitable satellite data, poor weather conditions in the Cusco region, and difficulty obtaining satellite, cartographic and photographic data.

Three field visits to the study area and one visit by the Co-Principal Investigator to TAC facilities resulted in: a) slides of crops and field conditions; b) radiometric readings and observations; c) unpublished tables and descriptions of the selected

crops; d) aerial photographs and maps; e) books and publications; and, f) a Peruvian cadre of field trained technicians. Office activities yielded: a) bibliographic citations; b) photocopied technical articles; c) digital satellite tapes; d) photographic satellite prints; e) maps; f) pre-processing and digital analysis of 1988 and 1990 satellite data; g) input of all radiometric readings; h) creation of several layers of a GIS; i) several map and satellite classified print-outs and photographs; and, j) spectral curves for the selected crops. Two technical articles were presented at international symposia in Mexico and the USA, and three more will be presented at an international symposium in Peru at the end of 1991.

A total of five digital satellite images were acquired: four SPOT images and one Landsat Thematic Mapper (TM). Only SPOT data were available for the 1988 season. All available ancillary data were used to create a knowledge base from which a digital classification could be executed. The digital data were radiometrically and atmospherically corrected to remove unwanted noise created by the sensor system itself, and by the distortions caused by atmospheric diffraction, absorption, and scattering. After these corrections were performed, the images were geometrically corrected using the available topographic maps. SPOT Multispectral and Panchromatic, and TM data were merged to produce a map base. This map base contained 20-meter and the 10-meter resolution pixels, as well as the 28.5-meter pixels from TM, which had been resampled to 10 and 20 meters. The result of this data merge was an updated map of the study area.

Once the pre-processing corrections were completed, the data were digitally classified using the unsupervised classification approach, in which only the statistical variability is given. The smaller this statistical variability, the greater the number of expected spectral classes. Since the variability of land use of the study area was thought to be high, the classification process was started with a statistical variability value such that a manageable number of spectral classes, around 50 classes, was obtained. In this sense the classification process is "controlled" but statistically the procedure is considered to be unsupervised.

Interactive analysis and display of preliminary results produced a classification containing 55 and 46 spectral classes for the SPOT 1988 data. These spectral classes were displayed using a two-channel plot of red/infrared ratios and aggregated into 13 and 10 land use/cover classes. The results from these classifications indicated the presence of three main crop groups: 1) kiwicha/quinoa, 2) tarwi and 3) oca/olluco/añu. It was thought at this point that greater spectral resolution was needed to test whether it was possible to detect and classify kiwicha from quinoa, and differentiate between oca, olluco and añu. The sixth crop, tarwi, appeared at this stage to be distinguishable using SPOT.

Data from SPOT and Landsat TM were acquired on 2 and 3 May 1990 and a second classification of 1990 SPOT and Landsat TM was performed. Both images were radiometrically and atmospherically corrected and then geocorrected. The unsupervised classification of the 1990 SPOT data resulted in 49 spectral classes, which were aggregated into 17 crop and land use/cover classes. This accumulated

experience was then applied to the controlled unsupervised classification of 1990 TM multispectral data. A total of 59 spectral classes resulted from the unsupervised classification, which were then clustered into 15 land use/cover classes.

The two 1990 controlled unsupervised classifications were plotted in the two-channel red/infra-red ratios form showing the clustered data and compared to each other. SPOT's data clustering indicated a clear differentiation between river and lake water, and between gypsum and bare/dry soils and clouds. Also, the resulting distance between cluster quinoa and cluster kiwicha was quite sufficient to indicate spectral differentiation. It was not possible to separate the oca/olluco/añu cluster from other agricultural and fallow areas. It appeared that the oca/olluco/añu cluster and potato cluster was mixed with the fallow fields, shrubs/agriculture and other agriculture areas.

TM's clustering indicated a good spectral differentiation between cluster quinoa and kiwicha, and a clear separation of cluster tarwi from quinoa. The closeness of tarwi to oca/olluco/añu and potatoes was of concern; oca, olluco, añu and potatoes are inter-cropped to such an extent that it will probably be very difficult to separate them spectrally and spatially. Further, most of the "other agriculture" found during the 1990 season was failed crops (identified in SPOT as fallow or recently harvested areas) and these crops could possibly be clustered with oca/olluco/añu to form a single class. The known gypsum areas were mixed with urban/bare and dry soils.

The final classification indicated that tarwi, quinoa and kiwicha covered between three to five percent of the study area in 1990, or between 4,400 to 6,200 hectares. All agricultural classes covered about 88,400 hectares in the SPOT classification and 90,000 in the TM classification. The TM water cluster covered about 800 hectares, while the two water clusters of SPOT covered just under 1,000 hectares. When putting together water and shadows, two classes having similar spectral signatures, the areas were 5,700 (3.5 percent of total area) and 5,800 hectares (3.4 percent of total area) for TM and SPOT respectively. Urban areas/bare soils and bare/dry soils clusters are also spectrally similar and accounted for 8,100 and 9,200 hectares in SPOT and TM (6.0 and 6.5 percent of total area respectively).

The creation of the GIS was hindered by the general absence of reliable cartographic data and incompatibility of scale/projection of available data. A topographic layer was created using the 1/25,000 maps. The same 1/25,000 data set was merged with 1/100,000 scale maps and to create toponomy and drainage layers. No soil data were available, and the geologic maps did not match each other, precluding their use for the GIS. The resulting GIS was output to 1/100,000 scale and overlaid on the SPOT False Color image obtained for June 1988.

The following general results can be reported: 1) it is possible to detect and locate agricultural plots as small as 700 square meters using high spatial resolution SPOT imagery; 2) the detection and classification of tarwi, quinoa and kiwicha appear possible using the available civilian satellite systems spectral resolution TM data; 3) digital analysis of these two data sets produced a land use/cover classification of the

study area; 4) merging of SPOT Panchromatic and Multispectral data resulted in an efficient way to map the study area, and merging of multi-date SPOT and TM data was possible; 5) the eco-characterization originally proposed was a limited success because the cartographic data obtained was not sufficient for the purpose of creating an all-encompassing GIS; 6) contemporaneous field data gathering with satellite data acquisition was accomplished, and sufficient radiometric measurements were obtained to determine spectral curves of the crops studied; 7) weather conditions were extremely determinant when acquiring satellite data, which still are not as accessible as purported by their distributors, presenting problems of delays that will not offer "real-time" data analysis; and 8) a sufficiently large satellite data set has been collected, as well as a large bibliographic one.

The present study set the basis for a wider effort of biological diversity protection by examining the usefulness of satellite data in the detection and classification of traditional Inca agricultural crops. Mapping these crops could serve the purpose of extension and dissemination programs for quinoa, tarwi and kiwicha that may be undertaken by the Government of Peru or concerned international agencies. In situ conservation efforts could benefit from a mapping tool such as the one developed in this project.

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1. INTRODUCTION

Biological diversity and international conservation concerns were brought to national attention by the National Forum on BioDiversity convened in Washington, DC in 1986. While there were several reasons and accumulated information that brought this awareness, we can say that two particular reasons were paramount in realizing the impact of these concerns on agricultural systems: (1) the close connection between the preservation of biodiversity and agricultural economic development; and, (2) the success of "modern" agricultural crops[1] which threatened the existence of traditional crops, original source of the "modern" crops genetic stock (Dasmann et al., 1973; Brush et al., 1981; Barney, 1982; Interagency Task Force, 1985; and Wilson, 1988).

Substitution of traditional crops by "modern" agricultural crops has caused loss of biodiversity and unforseen economic consequences in developing countries. Rapid population growth in developing countries, as well as misguided agricultural policies, have been determinant in the removal of native plants; and have caused loss of productivity in traditional ecosystems. These events have brought some negative economic consequences: soil degradation due to loss of vegetative cover; increased costs of soil restoration; and, public health concerns from dust and contaminated waters.

The case of the Andean region and the Inca civilization that, at the time of the Spaniard's arrival, cultivated as many as 80 food crop species, more species than the farmers of Europe cultivated at the time (Vietmeyer, 1986; NRC, 1989), is an example of loss of biodiversity due to their replacement by European crops. At the onset of Spaniard occupation, traditional crops were forcibly substituted by European crops; notably wheat, barley, carrots, and broad beans. Of the several root crops available to the Incas, the Spaniards only used the potato ignoring time-honored maca, mauka, arracacha, oca, olluco and añu. They also ignored the beans tarwi and nuñas. The main cereals used by the Incas, kiwicha, quinoa and kañihua, were all but forgotten.

This decline of traditional Inca crops has continued to this day. The alarming rate at which these "modern" crops are supplanting traditional crops (through loss of natural habitat) has brought about a loss of genetic material of the many species cultivated by the ancestors of today's peasants. This genetic material is necessary for the preservation of the very "modern" crops that replaced traditional species; their own success is now threatening them. Traditional crops represent a valuable source of genetic diversity whose preservation is absolutely indispensable to humanity. They are often nutritionally superior to "modern" crops, are well adapted

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[1] "Modern" crops are those on which today's human population bases most of its food sources. These include wheat, corn, rice, potatoes, barley, sweet potato and cassava.

to local micro-environments, have high economic potential, and represent a rich source of genetic diversity.

The purpose of the present study was to explore the development of a new methodology to characterize the ecogeography of six traditional Inca crops in the Peruvian highlands using satellite remotely sensed data and to do this in a geographic information system context. The traditional crops on which the present study was focused were kiwicha, quinoa, oca, olluco, añu and tarwi. An area within the Department of Cusco in the highlands of Peru was the selected study area (See Figure 1).

This project is part of on-going work by other scientists and agencies intent on conserving biological diversity. The Congress of the United States mandated the U. S. Agency for International Development (USAID) in November of 1983 to develop a coordinated strategy for conserving biological diversity in developing countries. This mandate was reiterated in November, 1989 and May, 1990. Current funding by USAID is substantial in the biological diversity area, including major support of the International Board for Plant Genetic Resources (IBPGR); establishing specific biodiversity groups within USAID; and direct support to over 300 projects worldwide with distinct biological diversity components. This work is tied to that being done by the Nature Conservancy, the National Academy of Science, the National Research Council, and the United Nations Food and Agriculture Organization, among others (US Department of State/USAID, 1978; ITFTF, 1980; IBPGR, 1984; Interagency Task Force, 1985; Wilson, 1988; and NRC, 1989).

1.1 Objectives

The general purpose of the study was to explore whether Earth observing technology represents a cost-effective and efficient methodology for locating and identifying areas of declining traditional crops in Peru. A specific product of Earth observing technology, satellite imagery, was applied to answer the question of whether biodiversity preservation can be advanced by using high spectral and spatial resolution images to classify traditional crops in Peru.

The overall aim was to assess whether earth obserting technology represents a cost-effective and efficient methodology to be used in support of critical germplasm collection and in situ conservation efforts involving traditional crop varieties in the Developing World.

The use of modern technologies such as satellite remote sensing and geographic information systems (GIS) were identified by an IBPGR Task Force as technologies with significant new potential for conducting ecogeographical surveys and expediting implementation of in situ conservation projects. These technologies had not previously been used for these tasks. The major questions to be adressed focused ultimately on whether current commercial satellite systems have sufficient

spectral and spatial resolution to satisfy the objectives of the research; and whether adequate cartographic and tabular data exist to permit the creation of a GIS.

The project's aim were to 1) classify imagery into spectrally different classes and match them to field samples of known traditional crops; 2) determine if these crops could be spectrally segregated; and, 3) to determine if GIS could be applied to improve classification.

The specific objectives were:

(1) to determine how effectively the cultivated areas of the selected traditional crops could be identified through analysis of high spectral and spatial resolution satellite imagery; and,

(2) to determine how well their distinctive ecological niches could be characterized through computer analysis of satellite data and digitized cartographic and tabular information.

1.2 Study Area

All the selected crops grow under the relatively harsh climatic conditions of the Andean highlands: (1) little precipitation (less than 300 mm per year); (2) cold and frost conditions during the latter part of their phenological life (-6° to 2° C from September to March); (3) high and diverse altitudes (ranging from near-sea level to 5,000 meters); (4) relatively unique microclimates (soil humidity conditions, slope and exposure) in which genetically diverse variants of the traditional crops have evolved and been selected for cultivation; and, (5) difficult terrain accessibility, making remote sensing particularly relevant. The selected area of study presented most of these conditions: it is an area between 2,900 and almost 5,000 meters of altitude; it receives little precipitation and it is subjected to frost conditions toward the end of the growing season (February to April); there are a multitude of microclimates, exposures and slopes; and the peasants of the area still cultivate the land in relatively unchanged conditions since the Incas ruled the area.

The study area covered approximately 2,300 square kilometers, bounded to the north by the Vilcanota river and to the south by the city of Cusco (Figure 1). It goes from a maximum altitude of 4,900 meters north of Calca, and along the Vilcanota to Urubamba; to a large plain or mesa-like area, Pampa de Anta (3,400 meters) in the west; to lake Huaypo, Chincheros and the Piuray and Qoricocha lakes to the east at an altitude of 4,100 meters. It then slopes to Cusco (3,250 meters) to the south, and winds up and down along the road from Cusco to Pisaq in the north-east corner, where it reaches an altitude of around 2,950 meters. The valley of the Vilcanota, commonly referred to as the Sacred Valley of the Incas because of its excellent soil fertility, slopes slowly from east of Pisaq to Urubamba in the north-west

corner from about 3,000 to 2,900 meters. From Urubamba, at 2,900 meters, a road climbs rapidly to the south and to Chincheros (3,700 meters).

1.3 Methodology

The technical work plan and collaborative approach proposed had four main phases and was to extend over a 12-month period: (1) a preparatory phase; (2) a field radiometry research phase; (3) an analytical phase involving image processing and GIS activities; and (4) a final phase involving field checking and report development. The actual work combined and changed these phases somewhat to accommodate the particular conditions of internal security in Peru, the unpredictable weather conditions of the Cusco region, and the uncertainty of data acquisition in Peru, as well as in the USA.

The study area was selected by the Principal and Co-Principal investigators, and having the K'ayra Experimental Station at the Universidad Nacional San Antonio Abad de Cusco (UNSAAC) as base of field operations. It is at K'ayra where the National Research Center for Andean Crops is located, and whose director was the Co-Principal Investigator.

The Peruvian counterpart determined the location of the selected Inca crops and followed the preparation and planting of the fields by the peasants of the area. All available cartographic and aerial photography data were located and, when possible, purchased or duplicated. The phenological characteristics of the crops were recorded, and then field data were collected. The collection of the field data consisted of radiometric measurements using a hand-held radiometer, plant height, plant spacing, soil characteristics, slope and exposure measurements. Field data collection coincided with the end of the cropping season (at the end of April and early May) and before harvesting. The plants were then mature and easily distinguishable from each other, and the cloudy conditions were expected to be minimal so satellite data collection was possible.

Since the objective of the study was to determine whether and how well crops could be characterized using available commercial satellite systems, the high spatial SPOT satellite system (20- and 10-meter resolution) and the equally moderate spectral resolution of a Landsat Thematic Mapper (TM) satellite system (seven spectral channels) were used. The companies responsible for the two satellite systems were asked to obtain imagery at the same time the field data were being collected, from early April to end of May. They were further asked to obtain imagery with a maximum of 20 percent cloud coverage.

Once the field data and the satellite imagery were obtained, they were digitized and analyzed, respectively. The cartographic data were sorted, the layers for a GIS were selected and the process of digitizing began. Image processing, aerial photographic interpretation, map analysis and field data reduction were done at TAC. The satellite data were radiometrically and atmospherically corrected, and then

geometrically corrected using the cartographic data obtained previously. It was at this point that actual digital classification of data began. The approach was one of unsupervised controlled classification, under which the unsupervised spectral classes generated are "controlled" or clustered into meaningful classes 'a posteriori' to the classification. Parallel to these tasks, several layers of GIS data representing available biophysical factors were digitized to overlay on the classified satellite data. The merging of these kinds of data could later be used to characterize the ecogeography of the studied crops.

2. DECLINING TRADITIONAL CROPS

2.1 Generalities and Background of Inca Crops

Present "modern" agricultural crops depend on the survival of their ancestors, and most of these ancestors are found in areas such as highland Peru. The rugged terrain, harsh climate, the vast differences of altitude within rather short distances, the isolation of peasant communities, and the numerous distinct micro-climates in which agriculture has been practiced since the time of the Incas, have all led to a remarkably diverse environment for crop evolution.

After the conquest by Spain, much of the Incan agricultural system fell into disrepair. The net impact of the Spanish occupation on traditional agriculture was that many of the ancient crops disappeared, and most suffered substantial declines in their cultivated area (Ochoa, 1975; Brush et al., 1981). This decline has been accelerated during the past couple of decades. The Government of Peru reported only 15 hectares of kiwicha in 1979, 3,500 hectares of tarwi in 1980, and a decline of 80 percent in quinoa production between 1951 to 1975 (Salis, 1985).

The agricultural system devised by the Incas on the highlands of Peru was based on the rational and judicious use of soil and water, and on the development of a "cornucopia of crop varieties" (NRC, 1989). Terraces were built to collect and retain scarce soil along steep slopes of the Andes; irrigation canals were built to bring water from highland lakes to all terraces; and, seeds and roots from all corners of the Tahuantinsuyu were brought and adapted to their environment through years of painstaking research. Out of this came a variety of roots (achira, ajipa, añu, arracacha, maca, mauka, oca, olluco, chuno potato, frog potato, table potatoes, weed potaoes and yacon), cereals (kiwicha, quinoa and kañihua), beans (nuñas and tarwi), and fruits (cape gooseberry, chirimoya, naranjilla, passion fruit, pepino and tree tomato). This agricultural legacy is in need of study and protection, and remote sensing and GIS techniques can obtain information on the location and classification of agricultural areas.

2.2 Description of Crops Studied

From this cornucopia of crop varieties, we selected six species of declining traditional crops for the present study:

(1) Kiwicha (**Amaranthus caudatus** L.), is also known as quihuicha, amaranto, amaranthus and grain amaranth. It is a very pleasant and appealing plant, of between 80 cm to 2.5 m in height, depending on the strain and soil on which it is growing. Its multi-colored leaves, ranging from deep green to yellow and red, and its also multi-colored flowers, ranging from green to gold to orange and red, create an incredible mosaic of colors along the mountain slopes and river valleys of the Andes. The seedheads are impressive, reaching lengths of up to 90 cms. They contain thousands of the tiny kiwicha seeds, 1.0-1.5 mm in diameter.

Grown by the Maya, Aztec and Inca civilizations prior to the arrival of the Spaniards, it almost disappeared during the period of Spanish domination. Kiwicha, as it is known in Peru, Bolivia, Ecuador and Mexico, is a broad-leaved non-grass grain crop. It can grow from sea level to about 3,500 meters. We found it in the study area between 3,300 and 3,500 meters. It adapts itself to diverse environmental conditions; and it tolerates most adverse conditions of weather. It can tolerate drought conditions better than most crops, and can tolerate frost once pollination has occurred. It grows on soils subject to salinization and on soils where most other crops will not grow. It withstands most of the common pests, except one called green bug in the Cusco region. Mice do not apparently like kiwicha seeds. Kiwicha's environmental adaptability is apparently due to its use of an especially efficient type of photosynthesis known as the C4 carbon-fixation pathway. This process is particularly efficient at high temperatures, in bright sunlight,and under dry conditions where plants tend to require less water than those that use the more common C3 process (Sumar Kalinoswki, 1988; NCR, 1989).

The most important characteristic of kiwicha from an agricultural point of view is its exceptionally high protein content and the content, in a human digestible form, of the amino acid lysine. Kiwicha's mineral contents make it a balanced meal all by itself (NRC, 1984; Salis, 1985; Rodriguez, 1986; Sumar Kalinowski and Jara, 1987). Its leaves are also rich in protein, vitamins, large amounts of calcium and minerals, and are used in salads and soups. Early cuttings (at about the third month of growth) can be used as fodder, and the plant will regenerate and carry to maturity. Table 1 shows kiwicha's phenology from soil preparation to emergence and harvesting.

(2) Quinoa (**Chenopodium quinoa** Willd.), also known as quinua or kinoa, is also an appealing and pleasant plant, of between 70 cm to 2.0 m in height. The color of its leaves range from light to deep green to light yellow, with flowers of deep red and orange, many times confused with those of kiwicha. Quinoa's flowers are not as impressive as kiwicha's, but the mosaic of colors they create is just as spectacular. Its seedheads are shorter and rounder than those of kiwicha, and its seeds are smaller

than kiwicha. The color of the seeds varies from red to yellow, pink and white, depending on the strain.

Quinoa is a broadleaved non-grass grain crop, growing at altitudes from sea level to almost 4,000 meters, and under quite unfavorable conditions, at high elevations, on poorly drained soils, in cold regions, and under drought conditions. Quinoa was one of the few crops that withstood the recent 1989-90 drought in the region.

Its protein content is slightly higher than kiwicha's when fresh but loses some when dry. It has comparable lysine content. It was considered the "mother grain" by the Incas, a food so vital it was sacred (NRC, 1989). The only drawback is that its seeds contain saponines that must be removed before consumption by washing or scarifying the seeds. It is during the removal of saponines that some of the protein content is lost (FAO/UNESCO/OMM, 1975; CORDE-Cuzco, 1987; Salis, 1985; Rodriguez, 1986; NRC, 1989).

Its leaves are consumed by humans in salads and soups, and are used as forage for animals. Table 2 shows quinoa's phenology.

(3) Oca (**Oxalis tuberosa** Mol.) is also known as okka, cuiba, sorrel and kao. It is a small plant, 30-40 cm in height, of fleshy and soft stems. Its leaves are light green to yellowish on the upper part and violet on the underside. It presents yellow and abundant flowers that may produce fruits and seeds.

Oca is a potato-like crop, whose roots vary in size, shape and color. Roots are cylindrical to spherical, from 3 to 20 cms long, and yellow to reddish to white to violet in color. Oca has an extremely high leaf area given is small height, which provides it with an efficient photosynthesis factory. Oca was reportedly domesticated as a crop at about the same time or before the potato; in fact, it appears oca was a very important food to the pre-Inca people before corn became pre-eminent in their diet (FAO/UNESCO/OMM, 1975). It is, after the potato, the most widely cultivated crop in the Andes.

Oca grows at altitudes where most plants do not prosper. It was found in this study at 3,800 meters and has been reported at 4,000 meters and higher (FAO/UNESCO/OMM, 1975; NRC, 1989), where frost is a major threat. It is usually inter-planted with potaoes and olluco, although its planting occurs a few weeks earlier than potatoes (Sumar Kalinowski, 1988). Table 3 shows oca's phenology.

Oca is a good source of carbohydrates, calcium and iron. It is freeze-dried into "chuño" (water content when dried is 13 percent, when in the ground is 80-84 percent), in which state it can last for years. It is eaten raw, cooked in soups or salads and as "chuño".

(4) Olluco (**Ullucus tuberosus** Caldas) is a typical Andean crop also known as ulluco, melloco, olloco, hubas and micuchi. Together with the common potato and

the oca, olluco is the most important root crop in the Andean region. It is one of the few traditional crops whose demand has been reported to be on the increase in the Andes (NRC, 1989). However, the total area planted in Peru in 1970 was reported to be over 19,000 hectares, while in 1983, when its demand was reported to be on the increase, was 15,000 hectares (FAO/UNESCO/OMM, 1975; NRC, 1989).

Olluco is a small plant of about 20 to 30 cm in height, being compact and bush-like, with deep green to green-yellow fleshy leaves, and green-yellow to reddish small flowers. It is very similar to oca and some potatoes. Its stems are succulent and shiny. No seeds are reported in the wild, although laboratory grown plants are known to have flowered (NRC, 1989).

Olluco grows mostly at high altitudes and has been reported at 4,100 meters in the area (FAO/UNESCO/OMM, 1975). It was found at 3,800 meters during our study, and reported to be quite resistant to frost (even more than oca and potatoes, with which it is commonly inter-cropped). Most of the olluco grown in this region is affected by viruses which tend to reduce its yield.

The edible root has a rainbow of colors: pink, purple, yellow, reddish, white and green; it is mostly round to elongated, but it can be long and twisted. Root sizes range from small (3-5 cms) to long (5-10 cms). Water content is very high for olluco roots (about 85 percent), and they are a good source of carbohydrates and vitamin C. Table 4 shows olluco's phenology.

(5) Añu (**Tropaeolum tuberosum** Ruiz & Pavon), also known as mashua, isañu, anu, navo and apilla, is a most visually appealing plant, especially when flowering. Its flowers, red-yellowish in a sea of light green leaves, are small and elongated, and sometimes used as an ornamental. A sprawling plant, it is also a climber of weeds, 10 to 20 cms high.

Inter-cropped with oca, olluco and potatoes because of its pest control properties, añu is a high yielding crop rich in carbohydrates. Its tubers are rather small when compared to oca and olluco. Tubers have all kinds of colors: black, white, red, yellow and spotted. It is not widely commercialized but nonetheless is widely consumed, but not in great quantities. Añu is reported to have anti-aphrodisiac properties (Incan armies were given añu while on campaign) and to cause goiter if consumed in great quantities under an iodine-free diet (Sumar Kalinowski, 1988; NRC, 1989). These two items may partly explain the low commercialization of añu and the fact that its cultivation tends to disappear faster than the other studied traditional crops (Gade, 1975).

Añu tolerates frost but not as well as potatoes, oca or olluco, and is extremely resistant to pests, insects and diseases, although several viruses decrease its yield. It does not withstand drought very well, which became apparent during the drought of 1989-1990. No añu fields were found during our last visit to the area in 1990. In fact, only two fields were recorded during three seasons of data gathering.

Añu grows between 2,300 to above 4,000 meters. Its phenology is presented in Table 5.

(6) Tarwi (**Lupinus mutabilis** Sweet), also known as tauri, chocho, lupin, and ullus, is a bean. The most visually striking of the crops studied, tarwi has blue-violet flowers, large deep green leaves, is about 1 to 1.5 meters tall, and grows luxuriously on good soils. Its hairy pods, 8 to 12 cms long, contain bitter seeds high in protein; in fact, tarwi's seeds have the highest protein content of all Andean legumes. Its protein content (reported as high as 50 percent of dry weight) is higher than soybean; and its oil content as high as soybean (Schoeneberger, et. al., 1982; Sathe et al., 1982; CORDE-Cusco, 1987a). Legumes are also known for their nitrogen-fixing capabilities and tarwi helps loosen and enrich soils.

It is the only seed bearing legume growing above 3,000 meters. It was found at 3,900 meters near Hullqui, during our field work but has been reported at 4,000 meters (Schoeneberger et al., 1981). It is quite resistant to frost once it has flowered but its pods can be damaged and its growth stunted, as was found to be the case in the 1989-1990 season, which was characterized by early frost and drought conditions (Rodriguez-Bejarano, 1991). **L. mutabilis** is believed to have originated in the Peruvian Andes; several wild relatives, all small in size, were found in rich copper-bearing areas and were reported to us (FAO/UNESCO/OMM, 1975; Sumar Kalinowski, 1988). Because of its bitter taste, tarwi is used as a green fence against cattle (FAO/UNESCO/OMM, 1975; Sumar Kalinowski, 1988).

Tarwi's seeds need to be cooked and washed to remove their bitterness, actions which have hindered its spread. Several geneticists have already produced a "sweet" variety with minimum bitterness (NRC, 1989).

Tarwi's phenology is presented in Table 6.

3. REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM TECHNOLOGIES

3.1 Background

Preservation of biological diversity of traditional Inca crops requires the detection, classification and location of those crops. The information obtained by satellite remote sensing when placed in a GIS context fulfills this requirement for the most part. The particular characteristics of Peruvian highlands - difficult accessibility, rugged terrain, multitude of micro-environments - make satellite remote sensing and GIS the appropriate technologies to detect, classify and map the traditional crops and/or the most likely habitats where they may grow. This information should help in formulating an organized strategy for germplasm collection and in situ conservation.

Two characteristics of traditional agriculture are its heterogeneity and the size of agricultural plots. Heterogeneity refers to the cornucopia of crops grown as

well as the different planting times and cropping systems observed in the area. Agricultural plots are normally small (a few hundred square meters for the most part) and are difficult to detect and locate on aerial photography or satellite imagery. Thus, remotely sensed imagery must be able to discriminate between different spectral classes and to detect small agricultural plots; high spectral and spatial resolutions will likely be required, but at present the science community only has access to moderate resolution systems operated by EOSAT Corporation and SPOT Image Corporation.

Once the remotely sensed data have been processed to detect and classify the crops in question, the data must be geo-referenced to a larger scale for easier map use. Peruvian maps for the study area are scarce and of old edition; the scales are sufficiently large, though, for the purpose of in situ conservation. The major problem encountered was that not all the study area had large scale (1/50,000 or larger) coverage. Even at 1/100,000 scale there was incomplete coverage of the study area.

3.2 Remotely Sensed Data

3.2.1 Satellite Data

The satellite data used for this project were provided by Landsat and SPOT systems in a digital format. Landsat's Thernatic Mapper (TM) data were used. TM has a spectral resolution of seven channels, from the visible to the near and medium infra-red and thermal parts of the spectrum. It also has a spatial resolution of 28.5 meters. SPOT's system has two modes: a Panchromatic mode with a continuous spectral band from visible green to red, and a spatial resolution of 10 meters; and, a Multispectral mode with three spectral bands from the visible green to the near infra-red, and a spatial resolution of 20 meters.

3.2.2 Aerial Photography

The aerial photography used in this project was that provided by the Servicio Aerofotografico Nacional of Peru over several portions of the studied area. This black and white photography was at a scale of 1/25,000 and acquired in July 1970 over various places of the study area; and at 1/10,000 scale acquired in July 1984 over the city of Cusco.

3.3 Geographic Information System (GIS)

Thematic and topographic cartographic data of diverse scales were collected for the Department of Cusco. These data were studied to determine which themes to introduce into a geographic information system. These themes were then digitized into ARC/INFO, which allows the user to manipulate vector (ARC) and attribute (INFO) data for the purpose of creating new information.

3.4 Interfacing Remote Sensing and GIS

Once the two types of information generated from the satellite data and from the cartographic/aerial photographic data were housed in our system, they were interfaced by merging one type with the other. The problems in this particular case were the different scales, lack of map coverage in certain areas, and the raster quality of the satellite data versus the vector characteristics of the ARC/INFO GIS.

4. ECOGEOGRAPHIC CHARACTERIZATION OF AGRICULTURAL CROPS

An agro-ecological characterization involves the understanding of those biophysical factors and anthropogenic activities necessary to either modify micro-environmental components or successfully modify the genetic characteristics of the crop being grown. The Incas were very good managers of soil and water and quintessential agronomists. Their terraces along very steep slopes and their irrigation works are witness to the former; the fact that several of their agricultural crops were adapted to ecologically different places, ranging from sea level and tropical jungles to oxygen-poor Andean regions, and later transported to other latitudes, are witness to the latter. The Incas adapted crops from fertile, warm, and moisture plentiful regions to rainfall-starved, frost-prone and high altitude regions, and attained self-sufficiency in food to an extent seldom seen today.

Our present state of agricultural development is characterized by large extensions of high-yield crops, sustained by large amounts of fertilizers, herbicides, pesticides and insecticides. Further, this agricultural state is based on a few "modern" crops grown in large homogeneous masses. Most of these "modern" crops are descendants of the traditional crops that Incas, and other ancient civilizations, used to cultivate. These conditions make "modern" crops highly vulnerable to catastrophes such as that befallen on the potato varieties of mid-nineteenth century Europe. It is because of this that their genetic sources need to be preserved; the protection of the biological diversity of traditional Inca crops will accomplish this.

To ecogeographically characterize ancient Inca crops one must locate them in the field where they are presently being cultivated, and one must try to identify the micro-components of the ecological niches where they are being grown. This means looking into biophysical factors such as soil parent material, and soil type; topography, aspect and slope; precipitation amount and distribution; solar radiation (given altitude above sea level); average temperature and range (altitude, soil color and type); soil relative humidity (soil type, season); and other factors. It also means determining human activities such as kinds of crops being grown, cropping patterns, terracing, vegetation cover, irrigation and road networks, and other related factors.

Several of these biophysical factors and human activities, necessary for eco-characterization, can be obtained from satellite sensor data, from existing

cartographic data and from field gathered data. It is this information gathering approach that is presented in this chapter.

4.1 Satellite Data Analysis

Given the particular characteristics of small field size and heterogeneous make-up of the crops, the satellite sensors need to have a moderate spatial resolution for the field size detection and a moderate spectral resolution for the crop signature classification. The best commercially available moderate spatial resolution system is the SPOT satellite: 10-meter in the Panchromatic mode and 20-meter in the Multispectral mode. SPOT's Panchromatic mode covers one spectral channel, similar to Black and White panchromatic film, from 0.51 to 0.73 μm; the Multispectral mode covers three spectral channels, channel 1 from 0.50 to 0.59 μm, channel 2 from 0.61 to 0.68 μm and channel 3 from 0.79 to 0.89 μm.

The best commercially available moderate spectral resolution system is the Landsat's Thematic Mapper (TM). This system consists of seven spectral channels: channel 1 from 0.45 to 0.52 μm, channel 2 from 0.52 to 0.60 μm, channel 3 from 0.63 to 0.69 μm, channel 4 from 0.76 to 0.90 μm, channel 5 from 1.55 to 1.75 μm, channel 6 from 10.4 to 12.5 μm, and channel 7 from 2.08 to 2.35 μm. The spatial resolution of this system is 28.5 meters.

Radiometric, atmospheric and geometric corrections were applied to the raw satellite data. Then, an unsupervised classification was run, and the results "controlled" using field observations and available ancillary data. This "control" is similar to supervising the classification, the difference being that in the controlled unsupervised classification the different classes are grouped after the classification has been obtained, while in the supervised classification the class patterns are given before the classification is performed. The grouping or aggregation of classes was done in an interactive mode, the analyst using all base knowledge available and a two-channel plot of the classified data. This two-channel plot shows the use/cover patterns based on ratios of the red and infrared reflectance values of the satellite system used. Figure 2 shows the these patterns in a schematic way.

4.1.1 Landsat TM Data

Landsat data for the area and dates needed for the study were consistently dominated by high cloud cover. A preliminary search of all Landsat data up to 1988 showed no useable data for the area and date required. So, we were not unduly surprised when in 1988 Landsat failed to acquire a TM cloud free (less than 20 percent cloud cover) image over the study area, although SPOT did manage to obtain one, most likely because of its pointing capability (see below).

We were disappointed when Landsat again failed to acquire a cloud-free image (less than 20 percent cloud cover) in the 1989 season, a year particularly

cloudy. The three TM acquisitions, on 14 and 30 April and 16 May 1989, over the study area showed 60, 80 and 90 percent cloud cover respectively.

The 1990 season in the region was punctuated by a moderate drought. This situation caused up to 23 percent decrease of vegetative cover between the 1988 season (an average precipitation season) and 1990, when drought and frost conditions prevailed in some regions of the Department of Cusco (Rodriguez-Bejarano, 1991a). This potentially disastrous situation proved to be, in a twisted way, a benefit to the project. The area was clear of clouds for the most part, allowing Landsat to obtain TM data on 3 May, with only 40 percent cloud cover overall (See Table 7 for information). Most of the study area was cloud free on that particular overpass in 1990.

4.1.2 SPOT Data

The SPOT satellite system obtained images for 1988, 1989 and 1990, more data than the Landsat system. This is possible because of SPOT's pointing capacity; the system is capable of tilting and directing its mirror to "look" or point at a specified place when the satellite is not directly overhead. This pointing capability proved determinant in obtaining data in May 1988, while Landsat could not.

The 1988 data served the purpose of ground reference and for an initial analysis through an unsupervised controlled classification. An image taken on 12 May 1988, with about 25 percent cloud cover, was obtained and analyzed for crop information (unsupervised controlled classification). For 1988 we were also able to acquire images taken on 6 June with nearly zero percent cloud cover; computer compatible tapes (CCTs) for these images were obtained containing the Multispectral as well as Panchromatic data, which were used to initially test the analysis methodology. These data were used for ground referencing by merging the high, 10 m resolution of the panchromatic with the multispectral 20 m resolution data. (Table 7 shows information about these data).

Data for 1989, obtained on 25 April and 16 May, contained cloud cover of more than 60 percent and the study area fell in two different satellite passes. The high cloud cover, especially over the study area, prevented us from using these data.

The 1990 data were obtained on 2 May 1990 with a cloud cover of about 10 percent. For these data we obtained a CCT containing the Multispectral data only. This Multispectral image was used to classify the study area, and it was merged with the panchromatic 1988 image to produce a new, updated map.

4.2 Cartographic Data and GIS Creation

The topographic maps at 1/25,000 and 1/100,000 scales covered only part of the study area. The general area of interest was defined as that between 12° 30′ to 14° 00′ N and 71° 30′ to 73° 00′ W. The study area was that shown in

Figure 1. The 1/25,000 maps contained contour intervals of 25 meters, while the 1/100,000 had 50 meter contour intervals. A topographic layer with 50 meter contour interval was created based on the two scales. Table 8 presents the maps and aerial photography acquired for the project.

The thematic maps, at scales ranging from 1/50,000 to 1/1,000,000, contained information about roads, surface hydrology, political boundaries, geology, soil potentiality, and life zones. These maps had been produced by different organizations at different scales, using different data sources (aerial photography, Landsat images, ground control) and some had different map projections, or had no defined projection (See Table 8 for a description of the cartographic data). These different attributes made their use and comparison difficult. Several of the obtained maps were photocopies of photocopies and had severe distortion problems, which limited their use in the GIS. Thus, from the available maps, layers containing drainage, communication networks and toponomy (city and place names) were created.

The selected layers - topography, drainage, communication networks and toponomy - were then input into our GIS. First, the required maps were reproduced to a stable medium to minimize further distortion, and the information layer highlighted. Then, this information was digitized using a digitizing table and cursor into ARC/INFO. Once in the system, we output all layers or selected ones at 1/50,000 and 1/100,000 scales and covering sections of the study area to help as ancillary data on the image classification process. We concentrated our initial analysis on four sections: Chincheros, Cusco/K'ayra, Ccorao and Pisaq. These preliminary findings were then used to classify the entire 2,300 square kilometer study area.

4.3 Radiometric Field Data

Forty seven crop fields were located and radiometric data were obtained during three visits to the study area. All the visits coincided with satellite overpasses, and with the dates when satellite data were actually obtained and used in the project (See Tables 9 and 10 for details). At each plot the following data were collected: crop type, field measurements, average slope, general exposure, distance between rows/plants, crop height, crop general health, presence of pests/diseases, time of day, date, weather outlook, locality of crop, and a series of measurements with a hand-held radiometer. This information was recorded on a Radiometric Data Sheet (Appendix 4).

At least ten radiometric measurements were made at each of the 47 sites, each measurement consisting of four spectral band readings, replicated at each measurement (the four spectral bands being similar to the first four spectral bands of the TM system). Several fields (in fact, the great majority) had more than ten (replicated) measurements with the hand-held radiometer. These measurements were distributed in a systematic way throughout the site: first, a line along the longest side of the field was followed on which measurements were taken, and then on a parallel

line to the inital one and perpendicular to the shortest side of the field. Ten measurements were the minimum sought for a small field, but more measurements were obtained for larger fields (See Table 10 for details of field sizes).

These radiometric measurements were later manipulated using Lotus 1-2-3 to obtain averages per crop per season, and were graphically displayed using Freelance. The series of spectral curves per crop per season obtained are presented in Appendix 5.

5. RESULTS

Of the four proposed project research phases, three were fully completed and the fourth was partially completed. The estimated 12-month period was extended from July 1989 to March 1991 due to adverse circumstances, mostly security concerns in the field, lack of suitable satellite data, poor weather conditions in the Cusco region, and difficulty obtaining satellite, cartographic and photographic data. Several of these adverse circumstances were known and are, in fact, part of the challenge of this kind of project.

Three field visits to the study area and one visit by the Co-Principal Investigator to TAC facilities, produced over 300 photographic slides, more than 500 radiometric readings and observations, six unpublished tables and descriptions of the selected crops, over 250 aerial photographs and maps, several books and publications, and a Peruvian cadre of four trained technicians. It also allowed TAC personnel to contact scientists at nine Peruvian government agencies and universities, and knowledgeable USAID personnel (See Appendices 1 to 4).

Office activities in Albuquerque yielded hundreds of bibliographic citations, tens of photocopied technical articles, five digital satellite scenes, one photographic satellite print, several maps, pre-processing and digital analysis of 1988 and 1990 satellite data, input of all radiometric readings using two software packages, creation of several layers of a GIS, several map and satellite classified print-outs and photographs, and spectral curves for the selected crops using field data. Two technical articles were presented at international symposia in Mexico and the USA, and three more will be presented at an international symposium in Peru at the end of 1991.

5.1 Satellite Data Classification

5.1.1 SPOT Data Analysis

A total of five digital satellite images were acquired by the project: four SPOT images and one Landsat TM (Table 7). Only SPOT data were available for the 1988 season. The best SPOT image in terms of cloud cover and radiometry was that obtained on 6 June 1988 and so we decided to use it to test the classification

procedure. In terms of agricultural crop detection, June was not the best month because most of the crops would have been harvested by this time. Also, field data had been obtained in April-May, thus a contemporaneous spectral analysis would have required a May image. The classification procedure determined using the June 1988 data was later applied to the May 1988 data.

All available ancillary data (maps, photos, field notes, and field radiometric data) were used to create a knowledge base from which a digital classification could occur. Thus, the analyst, prior to performing the classification, studied the maps of the area; photo-interpreted the photos of the different locations where field data had been collected; became familiar with the environmental indicators of the selected crops; visited the particular locations; and visually interpreted the SPOT photographic print acquired over the area.

The June 1988 SPOT digital data were radiometrically and atmospherically corrected to remove unwanted data noises created by the sensor system itself, and by the distortions caused by atmospheric diffraction/absorption/scattering of the spectral radiation as it travels back and forth through the atmosphere. After these corrections were performed, the image was geometrically corrected using as cartographic base the 1/100,000 topographic maps (the 1/25,000 maps did not cover all the study area). This was all done using TAC's in-house ELAS digital analysis package and the LOWTRAN atmospheric correction model (Rodriguez-Bejarano and Campos-Marquetti, 1988; Rodriguez-Bejarano, 1991; Rodriguez-Bejarano, et. al., 1991).

SPOT Multispectral and Panchromatic data for the 6 June 1988 date were then merged to produce a map base and test the methodology. The city of Cusco was selected as a test case because it presented ideal conditions for the location of control points (clear and well defined road intersections, large building structures), whose number were restricted given the quality of the maps available. This map base contained the 20-meter and the 10-meter resolution pixels, which had been resampled to 10 meters. The resulting image showed degradation of detail at the edges, highlighting the problem of poor ground control from the 1/100,000 maps, but still good enough as an update map of Cusco. This exercise served the purpose of streamlining the methodology to merge different resolution data, a methodology that would later be used with the 1990 data.

Once the three pre-processing corrections were completed, the data were digitally classified. The approach was one of unsupervised classification in which only the statistical variability was given. Under this condition, the software will calculate mean, standard deviation of the mean, and the total number of spectral classes. The smaller this statistical variability (called "scaled distance" by ELAS and "minimum-distance to means" by others), the greater the number of possible spectral classes. Since the variability of the study area was high (the question of agricultural systems heterogeneity), it was decided to start the classification process (statistics gathering) with a statistical variability value such that a manageable number of spectral classes, around 50 classes, be obtained.

After a few tries, interactive analysis and display of these preliminary results, a classification containing 55 spectral classes was obtained. These spectral classes were displayed using the two-channel plot red/infrared ratios (SPOT channels 2 and 3) and aggregated into 18 land use/cover classes. These classes were the result of all accumulated knowledge base obtained up to this point in time, and allowed us to conclude: (1) spatial resolution of SPOT data is sufficient to detect and locate small traditional crops; (2) it is possible to detect and classify several agricultural and density vegetation classes; (3) SPOT's spectral resolution is sufficient to detect the heterogeneity of traditional Inca crops; and (4) the merging of the different spatial resolution modes of SPOT is good enough to produce a base map of Cusco using the 1/100,000 scale map series (Rodriguez-Bejarano and Campos-Marquetti, 1988). The results of this classification are presented in Figures 3 and 4, and Table 11.

This first classification approach of the June 1988 SPOT data was then tried on the 12 May 1988 data. The resulting number of spectral classes, 46, was clustered into 10 crops and land use/cover classes. The results from this second classification indicated the presence of three main crop groups: kiwicha/quinoa, tarwi and oca/olluco/añu. Even though the high infra-red reflectance agriculture associated with kiwicha/quinoa appeared to be unique, its areal extension was large compared to what we knew existed in the field, and its correct detection was thought to be suspect. Figures 5 and 6 show the spectral classes and the clustering obtained using May 1988 SPOT data, while Table 12 presents the resulting crop and land use/cover classes. It was thought at this point that higher spectral resolution would be needed to detect and segregate kiwicha from quinoa, and to differentiate between oca, olluco and añu. The sixth crop, tarwi, appeared at this point to be distinguishable using SPOT.

As it has been mentioned, the 1989 year was a poor one, weather-wise. No useable data, less than 20 percent cloud cover, were obtained by either Landsat or SPOT. Field data were, however, collected during the April-May crop maturity season. In fact, two radiometers were brought to the field and the Peruvian counterpart had an opportunity to use the skills developed the previous year. The data collected proved quite useful in producing a series of spectral signatures for the crops studied (Appendix 5). The fact that no satellite data had been collected during the 1989 season, and especially because of the lack of multi-spectral TM data, prompted a request for an extension to the deadline, which was granted by PSTC in November 1989.

The 1990 season brought clear skies and drought conditions to the area (Rodriguez-Bejarano, 1991a), making it possible to obtain nearly cloud-free images. Data from SPOT and Landsat TM were acquired on 2 and 3 May 1990, respectively (See Table 7), and a second classification of 1990 SPOT and Landsat TM was performed. We were not able to obtain the data before July 1990 due to late data delivery. A second extension was thus necessary and requested, and was granted in October 1990.

Both images were radiometrically and atmospherically corrected and then geocorrected using the 1/25,000 scale maps and the 1/10,000 aerial photography of the city of Cusco. During the geocorrection, the TM image was resampled to 20 meters to have it coincide with the 20 meter resolution of the SPOT data. The selected study area sub-frames from the two images were then rotated to superimpose on each other. The resulting superimposed image had in fact 10 channels, seven from TM and three from SPOT. From this superimposed image it was then possible to produce a map of the study area that could be projected to any scale. These corrected and rotated data were then classified using ELAS.

The unsupervised classification of the 1990 SPOT data resulted in 49 spectral classes, which were aggregated into 17 crops and land use/cover classes. This new controlled unsupervised classification contained clusters of spectral classes of patterns associated with kiwicha and quinoa, and a cluster associated with tarwi/peas/barley and other legumes. Most of oca, olluco, añu and potatoes fell in recently harvested areas and other agricultural fields. Figures 7 and 8 show the spectral and clustered classes of the 1990 SPOT data classification, and Table 13 presents the classes of land use/cover obtained. This classification appeared to differentiate well between bare wet soils (wettest and less wet soils), and between fallow and recently fallowed fields. The interactive approach to controlled unsupervised classification told us that the resulting classification of Table 13 had certain problems of spectral signature, confusion that could possibly be answered using the TM and field radiometric data (Rodriguez-Bejarano, 1991a; Rodriguez-Bejarano, et. al., 1991). These problems centered around a cluster of high infra-red and low red reflectivity, indicative of high density vegetation (Figure 2). We had found kiwicha, quinoa and tarwi within this general cluster, and the distance from the centers of possible clusters (Figure 8) appeared too close.

5.1.2 TM Data Analysis

This accumulated experience was then applied to the controlled unsupervised classification of 1990 TM multispectral data. A total of 59 spectral classes resulted from the unsupervised classification (Figure 9), which were then clustered into 15 land use/cover classes (Figure 10, Table 14). This classification made apparent the difference in spectral signature between kiwicha and quinoa, and the apparent differentiation of tarwi from other legumes. The distinction between oca, olluco, añu and potatoes was still undefined. The problem with this classification was the cluster obtained for other agricultural areas (19 spectral classes grouped together), and the fact that there was no clear differentiation of gypsum areas, which were obtained with the SPOT data. The six-channel classification of the TM data did not clearly differentiate between fallow, recently fallowed or other low density vegetation characteristic of the agricultural areas during the 1990 season (Rodriguez-Bejarano, 1991a).

The two resulting 1990 classifications, SPOT's and TM's, were plotted in the two-channel red/infra-red ratios form showing the clustered data, and compared (Figures 11 and 12). SPOT's clustering indicated a clear differentiation between river and lake water, and between gypsum and bare/dry soils and clouds. Also, the

resulting distance between the quinoa cluster and the kiwicha cluster was quite sufficient to indicate differentiation. The only problem was the nearness of the tarwi cluster to that of quinoa. The differentiation between the two bare wet soils in SPOT was evident when looking at the classified area along the Vilcanota river; a closer look at the TM data indicated that it was possible to make the same soil wetness separation along the river. It was not possible to separate oca/olluco/añu from other agricultural and fallow areas. It appeared that the oca/olluco/añu and potatoes cluster was mixed with the fallow fields, shrubs/agriculture and other agriculture areas resulting from the SPOT classification.

TM's clustering indicated a good differentiation between the quinoa cluster and kiwicha, and a clear separation of the tarwi cluster from that of quinoa. However, the closeness of tarwi to oca/olluco/añu and potatoes calls for caution. As mentioned previously, oca, olluco, añu and potatoes are inter-cropped to such an extent that it may be very difficult to separate them spectrally or spatially. Further, most of the "other agriculture" found during the 1990 season consisted of failed crops (identified in SPOT as fallow or recently harvested areas) and these crops could possibly be clustered with oca/olluco/añu to form a single class. An interesting result of the TM classification was the corn cluster, which had been observed in the June 1988 SPOT classification. The gypsum known areas (near the upper left corner of the study area, north of Maras) were mixed with urban/bare and dry soils.

The SPOT and TM images were obtained within 24 hours of each other but the cloud cover and shadow areas were rather different between the two dates. Shadows are due both to the cloud cover and to the terrain relief, which is great in the Vilcanota river area (the fact that the SPOT image was obtained on a "side-looking" mode, i.e. not perpendicular to the terrain, increased shadows due to the terrain relief but not as significantly as we had thought). Shadows covered under four percent of total area on both images, or under 5,000 hectares. Since TM had more clouds, and thus more shadows, the same shadow area in the SPOT image indicated the effect of relief in SPOT. Clouds and their shadows obscure ground features and decrease the accuracy of classification since we do not know what classes clouds and shadows cover. Clouds within the study area covered about two percent in the TM image, and less than 0.1 percent in the SPOT image (See Tables 15 and 16). These cloud and shadow classes were determined for both classifications and tended to make these classifications not directly comparable. Another difficulty in comparing them is the fact of the two different sensing systems of SPOT and TM; even the similar channels - green, red and near infra-red - obtain spectral information in slightly different places, making spectral classes from the unsupervised classifications slightly different.

What Tables 15 and 16 did tell us was that tarwi, quinoa and kiwicha covered between 3 to 5 percent of the study area in 1990, or between 4,400 to 6,200 hectares. All agricultural classes covered about 88,400 hectares in the SPOT classification and 90,000 in the TM classification. The TM water cluster covered about 800 hectares, while the two water clusters of SPOT covered just under 1,000 hectares, the difference being the identified river water in the latter image. When

putting together water and shadows, two classes having similar spectral signatures, the areas were 5,700 (3.5 percent of total area) and 5,800 hectares (3.4 percent of total area) for TM and SPOT respectively. Urban areas/bare soils and bare/dry soils clusters are also similar and accounted for 8,100 and 9,200 hectares in SPOT and TM (6.0 and 6.5 percent of total area, respectively).

(The total area presented in Tables 15 and 16, 141,896 hectares, represents the common area of the SPOT and TM images after geometric correction and rotation. It differs from the total area of the study area, 230,000 hectares, because of the rotation applied to the data to make the two images coincide; some of the classified areas fall outside this common area).

5.2 Study Area GIS

The creation of the study area's GIS encountered the problem of limited cartographic data and incompatibility of scale/projection of available data. A topographic layer was created using the 1/25,000 and 1/100,000 maps, although it did not cover the whole study area. From the same series and from the 1/100,000 scale maps a toponomy, communications network, and limited drainage layers were created. No soil data were available and the geologic maps obtained did not match each other, precluding their use for the GIS.

The visual analysis and the discussions held with the Co-Principal Investigator suggested that altitude and field exposure are determinant on the selection of agricultural fields by farmers in the area. Precipitation is another parameter which will enter into an ecogeographic characterization. These data, however, do not exist at present. Slope and exposure information can be derived from topography but an intermediate product, a digital elevation model (DEM), has to be created first. This DEM requires the original topographic data used in the creation of the topographic maps 1/25,000 of Peru, and that data were not available to the project.

The resulting GIS was output to 1/100,000 scale and overlaid on the SPOT False Color image obtained for June 1988. This image approximates a map at 1/100,000 scale and its comparison to the 1/100,000 GIS output showed that it was necessary to geocorrect the satellite data to have complete coincidence.

6. CONCLUSIONS

1) It is possible to detect and locate agricultural plots as small 700 square meters using current spatial resolution SPOT imagery.
2) The detection and classification of tarwi, quinoa and kiwicha appear to be possible using the current spectral resolution TM data.

3) Digital analysis of the SPOT and TM data sets produced a land use/cover classification, leading to the production of a map of the study area.
4) Merging SPOT Panchromatic and Multispectral data resulted in an efficient way to map the City of Cusco. Merging of multi-date SPOT and TM data was possible using the Peruvian cartographic data as control, and produced a map of the study area.
5) The cartographic data obtained was sufficient to create an initial operating GIS, but insufficient to permit eco-characterization of traditional crops.
6) Contemporaneous field data gathering with satellite data acquisition was accomplished. Sufficient radiometric measurements were obtained to determine spectral curves of the crops studied, albeit not as complete as may be spectrally desired.
7) Weather conditions were extremely determinant when acquiring satellite data. These data still are not as deliverable as the needs of the science community dictate, presenting problems of delays that will not offer a "real-time" data analysis.
8) A sufficiently large satellite data set has been collected, as well as a large bibliographic one. A sufficiently large cartographic data set still has to be collected.

The present study set the basis for a wider effort of biological diversity protection by determining the usefulness of satellite data in the detection and classification of traditional Inca agricultural crops. Mapping of these crops will serve the purpose of extension and dissemination programs for quinoa, tarwi and kiwicha. In situ conservation efforts will benefit from a mapping tool such as the one developed in this project.

Satellite data can be obtained, weather permitting, during April-May by the pointing capability of the SPOT satellite system. The delivery of these data can take up to two months, at which time a classification can be done. To field verify this classification it will be necessary to obtain several ground truth samples at the same time satellite data are being acquired.

Once this classification exists, it can be overlaid on a GIS containing altitude, slope, exposure, precipitation and soils characteristics. This resulting map will be the begining of the eco-characterization of the studied crops.

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TABLES

Table 1: Chronogram and Phenology of Kiwicha
Centro de Investigaciones de Cultivos Andinos
Cusco, Peru

	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
1. Soil Preparation		XXXXX									
2. Watering			XXX								
3. Planting			XX	XXX							
4. Germination			XX	XXXXX							
5. 1st Weeding					XXXXX						
6. Fertilizer					XXXXX	XX					
7. Soil Bed Raising					XXXXX	XXX					
8. Beginning of Flowering					XX	XXXX					
9. Full Flowering						XXXXX	XXX				
10. 2nd Weeding							XXXXX				
11. "Milky" Seed							XXX	XXXXX			
12. Physiological Maturity								XXXXX	XX		
13. Commercial Maturity									XXXXX		
14. Harvest									XX	XXX	
15. Drying										XXXX	
16. Threshing										XXX	XXXXX

Table 2: Chronogram and Phenology of Quinoa
Centro de Investigaciones de Cultivos Andinos
Cusco, Peru

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
1. Soil Preparation						XXX	XXX				
2. Planting		XXXX									
3. Germination			XXXX								
4. 1st Weeding				XXXXX							
5. Fertilizer				XXXXX							
6. Soil Bed Raising				XXXXX							
7. Beginning of Flowering				XX	XXX						
8. Full Flowering					XXXX	XXX					
9. 2nd Weeding					XXXX	XXX					
10. "Milky" Seed						XXXX					
11. Physiological Maturity						XXX	XXX				
12. Commercial Maturity							XXXXX	XXXX			
13. Harvesting								XXX	XXX		
14. Drying								XXX	XXXX		
15. Threshing									XXXX		

Table 3: Chronogram and Phenology of Oca
Centro de Investigaciones de Cultivos Andinos
Cusco, Peru

	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
1. Soil Preparation	X							X	X		
2. Planting	X	X	X								
3. Germination				X	X						
4. 1st Weeding						X					
5. Soil Bed Raising						X	X				
6. Beginning of Flowering						X	X				
7. Full Flowering							X	X			
8. 2nd Weeding								X			
9. Tuber Formation						X	X				
10. Full Tuber							X	X			
11. Maturity									X		
12. Harvesting										X	X

Table 4: Chronogram and Phenology of Olluco
Centro de Investigaciones de Cultivos Andinos
Cusco, Peru

	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
1. Soil Preparation											
2. Planting			XXX	XXX							
3. Germination				XXX	XXX						
4. 1st Weeding						XXX					
5. Soil Bed Raising						XXX					
6. Beginning of Flowering						XXX					
7. Full Flowering							XXX				
8. 2nd Weeding							XXX				
9. Tuber Formation						XXX					
10. Full Tuber							XXX				
11. Maturity								XXX	XXX		
12. Harvesting										XXX	XXX

Table 5: Chronogram and Phenology of Añu
Centro de Investigaciones de Cultivos Andinos
Cusco, Peru

	APR	NOV	DEC	JAN	FEB	MAR	APR	MAY			
1. Soil Preparation	XXXX										
2. Planting		XXXXX									
3. Germination		X	XXXXX								
4. Soil Bed Raising				XXXXX							
5. Beginning of Flowering					XXXXX						
6. Tuber Formation					XXXXX						
7. Maturity							XXXXX				
8. Harvesting								XXXXX			

Table 6: Chronogram and Phenology of Tarwi
Centro de Investigaciones de Cultivos Andinos
Cusco, Peru

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	
1. Soil Preparation	XXXXX	X									
2. Planting	XXXXX	X									
3. Germination	X	XXX									
4. Soil Bed Raising			XX	XX							
5. Beginning of Flowering					XXXXX						
6. Full Flowering					XX	XX					
7. "Milky" Seed						XX	XX				
8. Physiological Maturity							XX	XX			
9. Commercial Maturity								XXXX			
10. Harvesting									XXXX		
11. Drying									XXXX	X	
12. Threshing									X	XXX	

Table 7: Satellite Data Acquisition

Tape Number	Image ID Number	Path/Row	Date	Cloud Cover %	Remarks
H007-SPOT	16593778805121459531X	659/377	12 May 88	25	Multispectral
H012-SPOT	16593778806061519261X	659/377	6 June 88	10	Multispectral
H013-SPOT	16593778806061519241P	659/377	6 June 88	10	Panchromatic
H014-SPOT	26593779005021504491X	659/377	2 May 90	10	Multispectral
C074-TM	Y42848-14234	4/69	3 May 90	40	Multispectral

Table 8: Map and Aerial Photography

Map/Photo	Date	Scale	Projection	Remarks
Tanca, Ollantaytambo, Moras, Urubamba, Calca, Paraparo, Rio Colorado, Zurite, Anta, Pukicara, Coya, Pisac, Cuzco, Oropesa, Caycay	1972	1/25,000	Transverse Mercartor	Topography, toponomy, rivers and lakes, roads, contour intervals at 25 meters. 1962-63 photography. Produced by National Directorate of Agrarian Reform.
Diagrama Vial del Departmento de Cusco	April 1988	1/500,000	Unknown	Road and communication network. Produced by CORDE-Cusco
Calca, Tambobamba, Cuzco, Ocongate	1970	1/100,000	Transverse Mercartor	National map of Peru series with. topography, toponomy, main rivers and lakes, roads, contour intervals at 50 meters. 1962-63 photography. Produced by IGN (National Geographic Institute).
Anta, Cuzco, Sheet 27-S	1973-1974	1/100,000	Unknown	Geologic Interpretation with schematic geology based on radar imagery. Incomplete data.
Anta, Cuzco, Sheet 27-S	1973-1974	1/100,000	Unknown	Planimetry Series with schematic information. Incomplete data.
Anta, Cuzco, Sheet 27-S	1973-1974	1/100,000	Unknown	Radar controlled mosaic of radar images with little detail. Incomplete data. Produced by SBM (Geological and Mineral Service Institute).
Carta de la Region Norte del Cusco	1955-1959	1/200,000	Unknown	1/200,000 national series. Produced by IGN.
Departamento de Cuzco	1986	1/747,000	Unknown	Political boundaries and topography each 1,000 meters. Produced by IGN.
Mapa de Capacidad de Uso Mayor de las Tierras del Peru	1981	1/1,000,000	Transverse Mercator	Complete coverage of Peru, maps produced by ONERN (National Office for the Study of Natural Resources).
Mapa de Imágenes de Satelite	1975-1983	1/250,000	Transverse Mercator	Complete coverage of high quality satellite imagery prints, produced by ONERN in 1988.
Fotos Aereas de Cusco	15 July 1984	1/10,000	Central	Black & white infrared photos covering Cusco and environs, 87 photos. Obtained by Servicio Aerofotografico Nacional (SAN).
Fotos Aereas	15 July 1970	1/25,000	Central	Black & white photos of several places where crop fields were taken, 19 photos. Obtained by SAN.

Table 9: Crop Fields Locality and Altitude

	1988		1989		1990	
	Locality	Altitude (m)	Locality	Altitude (m)	Locality	Altitude (m)
Kiwicha	Tancauparta K'ayra	2,960 3,300	K'ayra K'ayra San Salvador Huayocori Paullo/Taray	3,500 3,220 3,000 2,900 2,950	K'ayra Pisaq Pisaq	3,300 2,975 2,950
Quinoa	Ccorao Ccorao Calca Campanachayoc	3,400 3,400 2,920 2,930	K'ayra Campanochayoc Huayocori Ollantaitambo Paullo/Taray Ccorao Tambo Real	3,500 2,850 2,920 3,000 2,950 3,400 3,500	Huila-Huila Huila-Huila Ccorao	3,700 3,700 3,450
Oca	Chincheros	3,800	Fierro Ccata	3,800	Huila-Huila	3,700
Olluco	Corimarca	3,750	K'ayra Sta. Corimarca Chincheros Cachimayo	3,800 3,600 3,700 3,700	Tamboray	3,650
Añu	Chincheros	3,700	Fierro Ccata	3,800		
Tarwi	Huaillarco San Salvador	3,650 3,000	K'ayra Sta. K'ayra Chincheros Ccorao Hullqui Huila Huila	3,650 3,500 3,750 3,450 3,900 3,800	Tamboray Huila-Huila Yuncaypata	3,650 3,700 3,600

Table 10: Crop Field Sizes

SITE	CROP	DATE	AREA (m2)	SLOPE %	ROW ORIENT.
1	Olluco	22 Apr 88	4,216	10	EW
2	Quinoa	25 Apr 88	2,618	10	NS
3	Quinoa	25 Apr 88	2,275	10	NS
4	Kiwicha	26 Apr 88	8,430	1	EW
5	Tarwi	26 Apr 88	3,684	15	SE
6	Kiwicha	26 Apr 88	12,802	22	NS
7	Oca	27 Apr 88	1,064	3	EW
8	Quinoa	29 Apr 88	4,312	1-3	NS
9	Quinoa	30 Apr 88	7,980	1	EW
10	Añu	30 Apr 88	697	15-20	NS
11	Tarwi	02 May 88	5,600	30	NN
12	Olluco	03 May 88	5,292	5	EW&NS
1-1	Kiwicha	30 Apr 89	30,000	1	EW
1-2	Quinoa	30 Apr 89	45,000	1	NS
1-5	Quinoa	04 May 89	9,700	2	EW
1-6	Tarwi	04 May 89	6,960	2	NE
1-7	Tarwi	05 May 89	28,168	25	EW&SW
1-8	Quinoa	05 May 89	15,394	2	NS
2-1	Tarwi	03 May 89	4,551	25	NS
2-2	Añu	03 May 89	154	30	EW
2-3	Oca	03 May 89	1,004	30	EW
2-4	Olluco	03 May 89	1,323	30	EW
2-5	Kiwicha	04 May 89	10,823	10	NE
2-6	Tarwi	04 May 89	6,875	15	EW&SE
2-7	Quinoa	04 May 89	5,549	8	EW
2-8	Kiwicha	04 May 89	8,792	3	SE&EW
2-10	Tarwi	05 May 89	1,400	15-20	NS
2-13	Kañihua	07 May 89	2,040	10	NS
2-14	Kiwicha	09 May 89	60,000	2	NS
2-15	Quinoa	09 May 89	6,500	1	NS
2-16	Kiwicha	10 May 89	32,819	2	NS
2-17	Quinoa	10 May 89	NA	15	EW

2-18	Quinoa	12 May 89	14,985	13	NE
1	Olluco	02 May 90	6,975	NA	SE
2	Tarwi	02 May 90	5,565	NA	SE
3	Quinoa	02 May 90	1,665	NA	EW
4	Tarwi	03 May 90	4,576	NA	NS&EW
5	Oca	03 May 90	630	NA	SW
6	Quinoa	03 May 90	1,509	NA	EW
7	Quinoa	03 May 90	20,151	NA	EW
8	Tarwi	04 May 90	24,811	NA	SW
9	Kiwicha	05 May 90	12,380	NA	NS
10	Kiwicha	06 May 90	2,503	NA	SE
11	Kiwicha	06 May 90	1,710	NA	EW

Table 11: SPOT June 1988 Land Use/Cover Controlled Unsupervised Classification

No.	Land Use/Cover Class	Spectral Class No.	Color Table Code
1	Low Density Agriculture (Alfalfa)	46	Green, bright 0/255/0
2	High Density Vegetation, Tree-Like	23	Green, dark 0/100/0
3	Fallow Agricultural Fields with Sandy Soils	41, 40	Green, light 0/185/0
4	Fallow Agricultural Fields with Wet Soils	10	Cyan, light 0/255/255
5	Low Density Vegetation with Bright Soils	38	Cyan, bright
6	Agricultural Areas with Bare Soils	53	Yellow, bright 255/255/0
7	Irrigated Agricultural Areas	13	Yellow, light 185/185/0
8	Agricultural Areas Partially Harvested (Corn)	15	Yellow, dark 100/100/0
9	Low Density Vegetation	2, 7	Red, bright 255/0/0
10	Low/Medium Density Vegetation	1, 3	Red, light 185/0/0
11	Low/Medium Shrub Vegetation	8, 14, 4, 24, 5 27, 29, 43, 6, 25 35, 9	Red, dark 100/0/0
12	Medium/High Tree-Life Vegetation (Eucalyptus Plantations)	20, 17, 52, 33 26, 36, 48, 22, 21	Magenta, bright 255/0/255
13	Medium/High Agricultural Vegetation (Barley)	51, 45, 50, 49 12, 32	Magenta, light 185/0/185
14	Small Agricultural Areas with Medium Density Cover	16, 42, 34, 47	Magenta, dark 100/0/100
15	Terrace Fields with Medium Density Cover	18, 19, 11	Purplish Blue 65/0/255
16	Low Density Agricultural Areas	39, 30, 31	Gray 200/200/200

Table 12: SPOT May 1988 Land Use/Cover Controlled Unsupervised Classification

No.	Land Use/Cover Class	Spectral Class No.	Color Table Code
1	Water and Shadows	24	Blue 0/0/255
2	Shadows and Areas under Shadows	31, 25, 43	Black 0/0/0
3	Clouds	22, 19, 35, 42, 46	White 255/255/255
4	Urban Areas/Bare Soils	30, 32	Yellow 255/255/255
5	High Infrared Reflectance Agriculture (Kiwicha/Quinoa)	34	Magenta 255/0/255
6	Medium/High Density Agriculture (Presence of Oca/Olluco/Añu and Potatoes)	6, 9, 10, 11, 12, 13 20, 26, 27, 36, 37 38, 40	Green 0/255/0
7	High Density, Tree-like Vegetation	2, 8, 14, 18, 23 33, 39, 44	Green, dark 0/165/0
8	Medium Density Agriculture (Presence of Tarwi)	28, 41	Magenta, dark 165/0/165
9	Medium/Low Density Vegetation	1, 3, 4, 15, 16 17, 21	Red 255/0/0
10	Low Density Agriculture	5, 7, 29, 45	Red, dark 165/0/0

Table 13. SPOT May 1990 Land Use/Cover Controlled Unsupervised Classification

No.	Land Use/Cover Class	Spectral Class No.	Color Table Code
1	Water (lakes)	12	Dark Blue 0/0/650
2	Water (rivers)	29, 33, 41	Light Blue 0/0/255
3	Shadows	1, 2, 8, 23	Black 0/0/20
4	Clouds	25, 28, 36, 38	White 255/255/255
5	Urban Areas/Bare Soils	7, 20, 33, 45	Cyan, bright 0/255/255
6	Bare/Dry Soils	18, 22, 24, 39, 48	Cyan 0/125/125
7	Tree-Like/ Shrub Vegetation	3, 4, 5, 6	Green, dark 0/100/0
8	Shrub Vegetation with Agricultural Fields (Fallow)	9, 11, 49	Green/light 0/125/0
9	Fallow Agricultural Fields Recently Harvested	13, 34, 37	Green, bright 0/255/0
10	Other Agricultural Areas, Including Potato/Oca/Olluco/Añu Fields	14, 15, 16, 17, 26	Yellow 225/225/0
11	Irrigated Fields, Grasses & Vegetable Crops	21, 30, 35	Magenta 255/0/255
12	Tarwi, Peas, Barley	10, 42	Magenta 125/0/125
13	Quinoa	43	Red, bright 255/0/0
14	Kiwicha	32	Red, dark 100/0/0
15	Gypsum	31, 40	Purplish Blue 65/0/255
16	Wet Alluvial Soils (Wettest)	19	Dark Gray 65/65/65
17	Wet Alluvial Soils (Driest)	Wet 27 Driest 41	Light Gray 125/125/125

Table 14: TM May 1990 Land Use/Cover Controlled Unsupervised Classification

No.	Land Use/Cover Class	Spectral Class No.	Color Table Code
1	Water	44, 3	Black 0/0/0
2	Shadows	9, 11	Gray 100/100/100
3	Clouds	37, 23	White 255/255/255
4	Bare/Dry Soils	35, 47, 27, 38	Red 255/0/0
5	Mostly Bare/Dry Soils and Urban Areas	34, 24, 31, 41	Red Orange 255/64/0
6	Bare, Wet Soils	36, 7, 48	Orange 255/128/0
7	Shrubs	39, 6, 58	Green 0/255/0
8	Tree-Like Vegetation	32, 57, 1, 2, 45, 14	Dark Green 0/128/0
9	Agricultural Areas (Wheat, Alfalfa, Barley, Vegetables)	26	Yellow Green 128/255/0
10	Corn	22	Yellow 255/255/0
11	Tarwi	55, 25	Magenta 255/0/255
12	Oca, Olluco, Añu, Potatoes	5, 4, 13, 16, 49, 51	Purple Red 255/0/128
13	Quinoa	53, 56	Blue 0/0/255
14	Kiwicha	54, 50	Purple Blue 128/0/255
15	Other Agricultural Fields	28, 17, 33, 30, 15, 8, 42, 21, 29, 46, 12, 59, 18, 10, 52, 20, 43, 19, 40	Cyan 0/255/255

Table 15: Area Results from SPOT 1990 Classification

No.	Cluster	Ha.	%
1	Water (Lakes)	758	0.5
2	Water (rivers	224	0.2
3	Shadows	4,871	3.4
4	Clouds	79	0.1
5	Urban Areas/Bare Soils	1,619	1.1
6	Bare/Dry Soils	6,459	4.6
7	Tree-like/Shrub Vegetation	38,873	27.4
8	Shrubs/Fallow Agricultural Fields	46,800	33.0
9	Fallow Agricultural Fields	9,725	6.8
10	Other Agriculture	25,150	17.7
11	Irrigated Agriculture	2,351	1.7
12	Tarwi	3,833	2.7
13	Quinoa	411	0.3
14	Kiwicha	126	0.1
15	Gypsum	84	0.1
16	Very Wet Soils	202	0.1
17	Wet Soils	331	0.2
TOTAL		141,896	100.0

Table 16: Area Results from TM 1990 Classification

No.	Cluster	Ha.	%
1	Water	766	0.5
2	Shadows	4,971	3.5
3	Clouds	2,518	1.8
4	Bare/Dry Soils	2,800	2.0
5	Urban Areas/Bare Soils	6,425	4.5
6	Wet Soils	231	0.2
7	Shrubs	6,827	4.8
8	Tree-like Vegetation	27,340	19.3
9	Agricultural Areas (mostly wheat, alfalfa, barley & vegetables)	2,674	1.9
10	Corn	6,579	4.6
11	Tarwi	5,001	3.5
12	Oca/Olluco/Añu & Potatoes	28,700	20.2
13	Quinoa	2,232	1.6
14	Kiwicha	940	0.7
15	Other Agriculture	43,892	30.9
TOTAL		141,896	100.0

FIGURES

Figure 1: Study Area

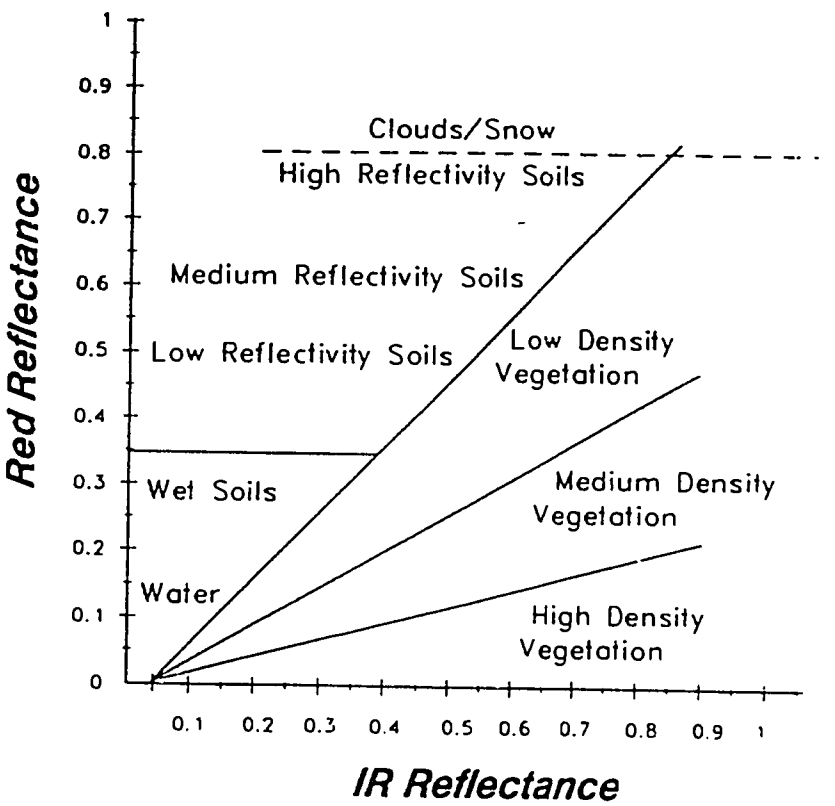


Figure 2. Spectral Class Definitions on Two-Channel Plot

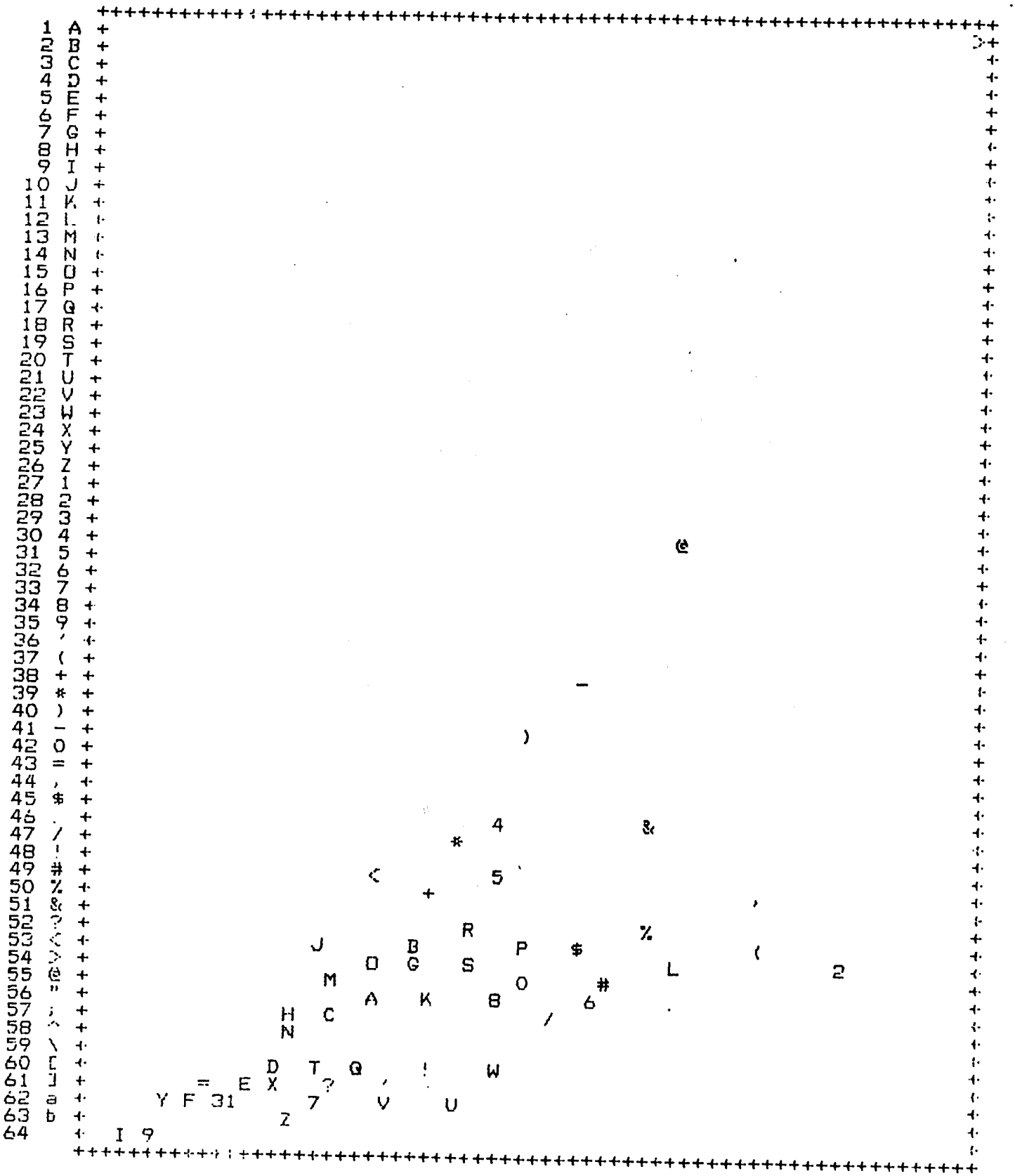


Figure 3: SPOT June 1988 Spectral Classes

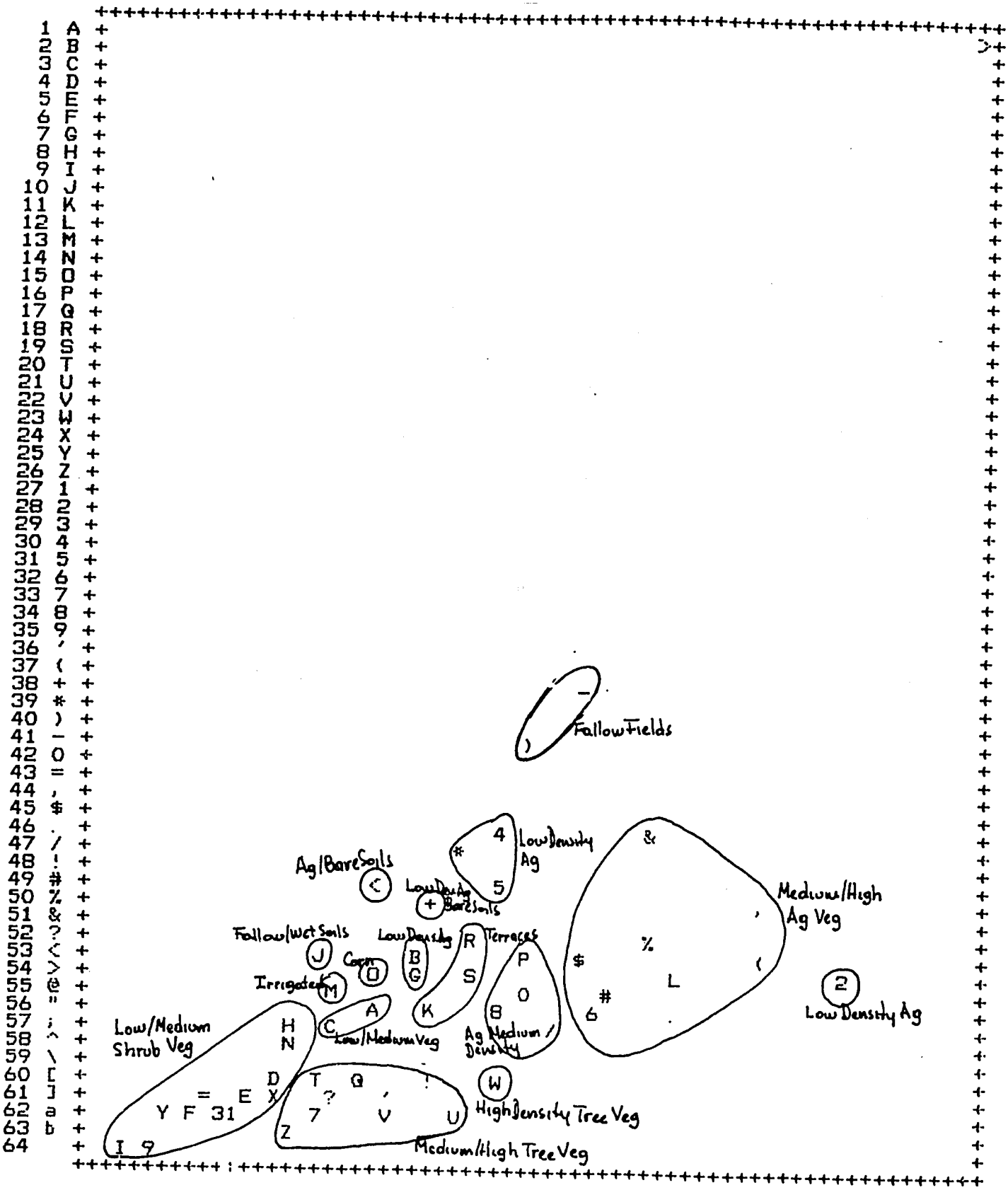


Figure 4: SPOT June 1988 Controlled Unsupervised Classification

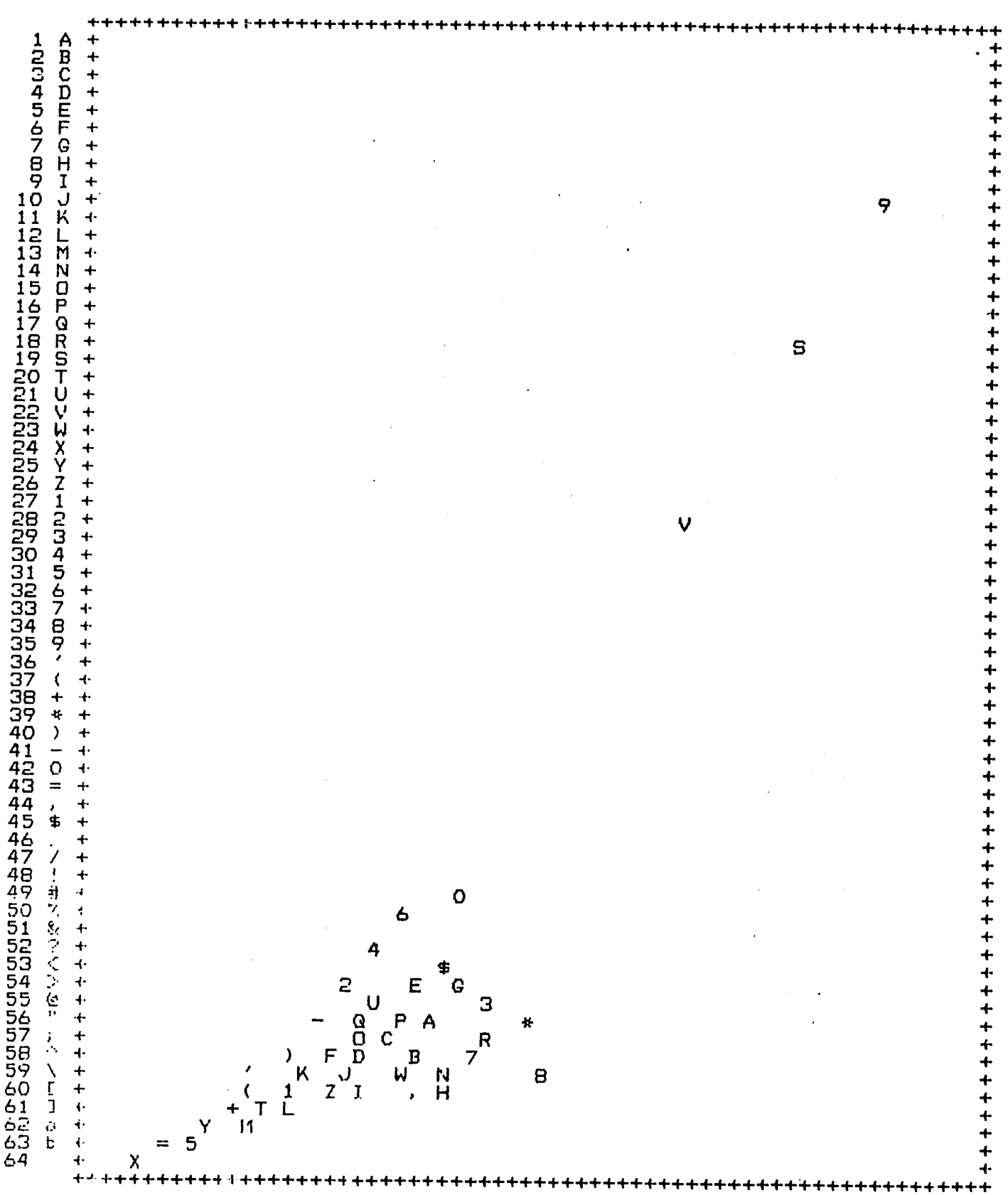


Figure 5: SPOT May 1988 Spectral Classes

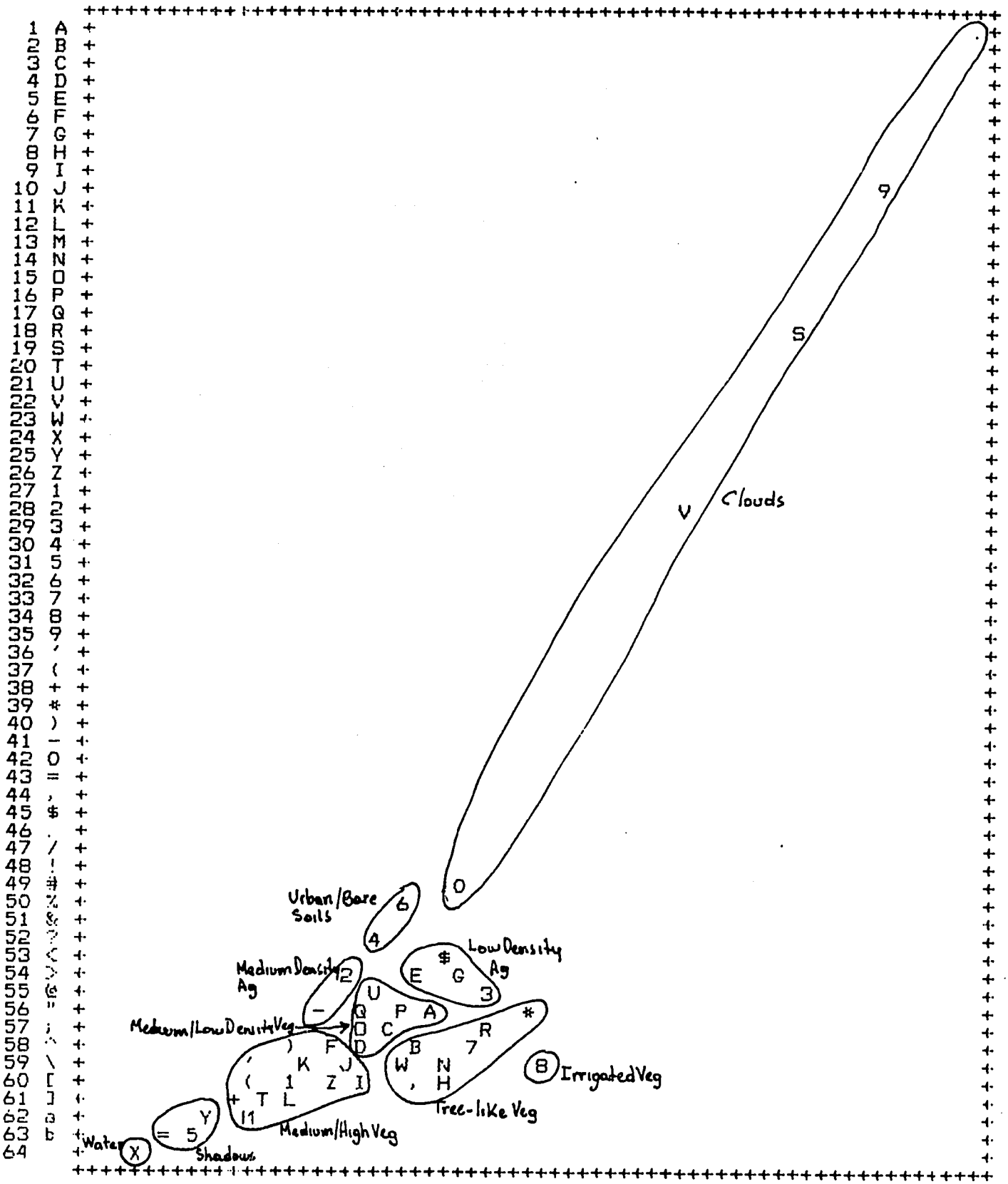


Figure 6: SPOT May 1988 Controlled Unsupervised Classification

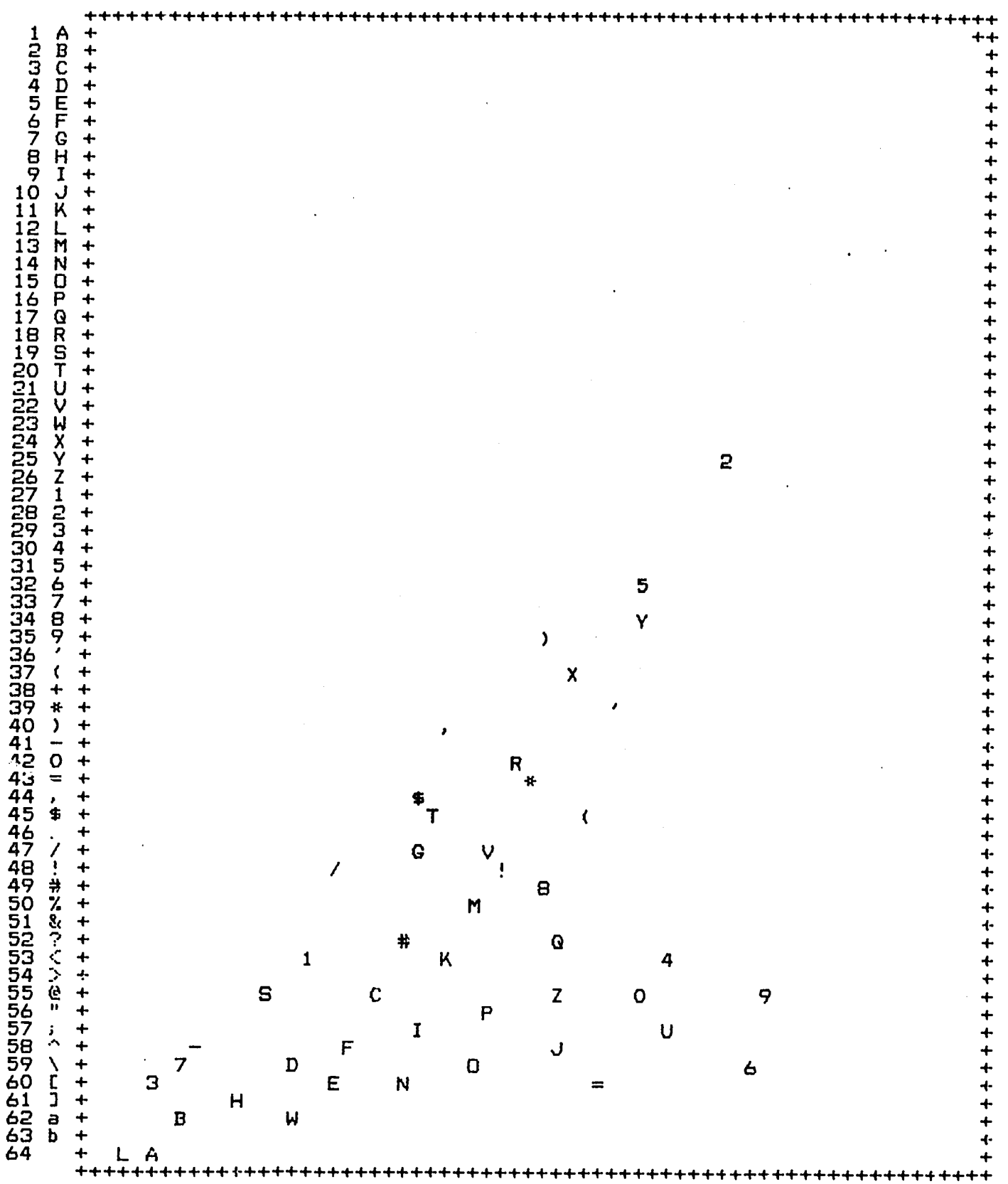


Figure 7: SPOT May 1990 Spectral Classes

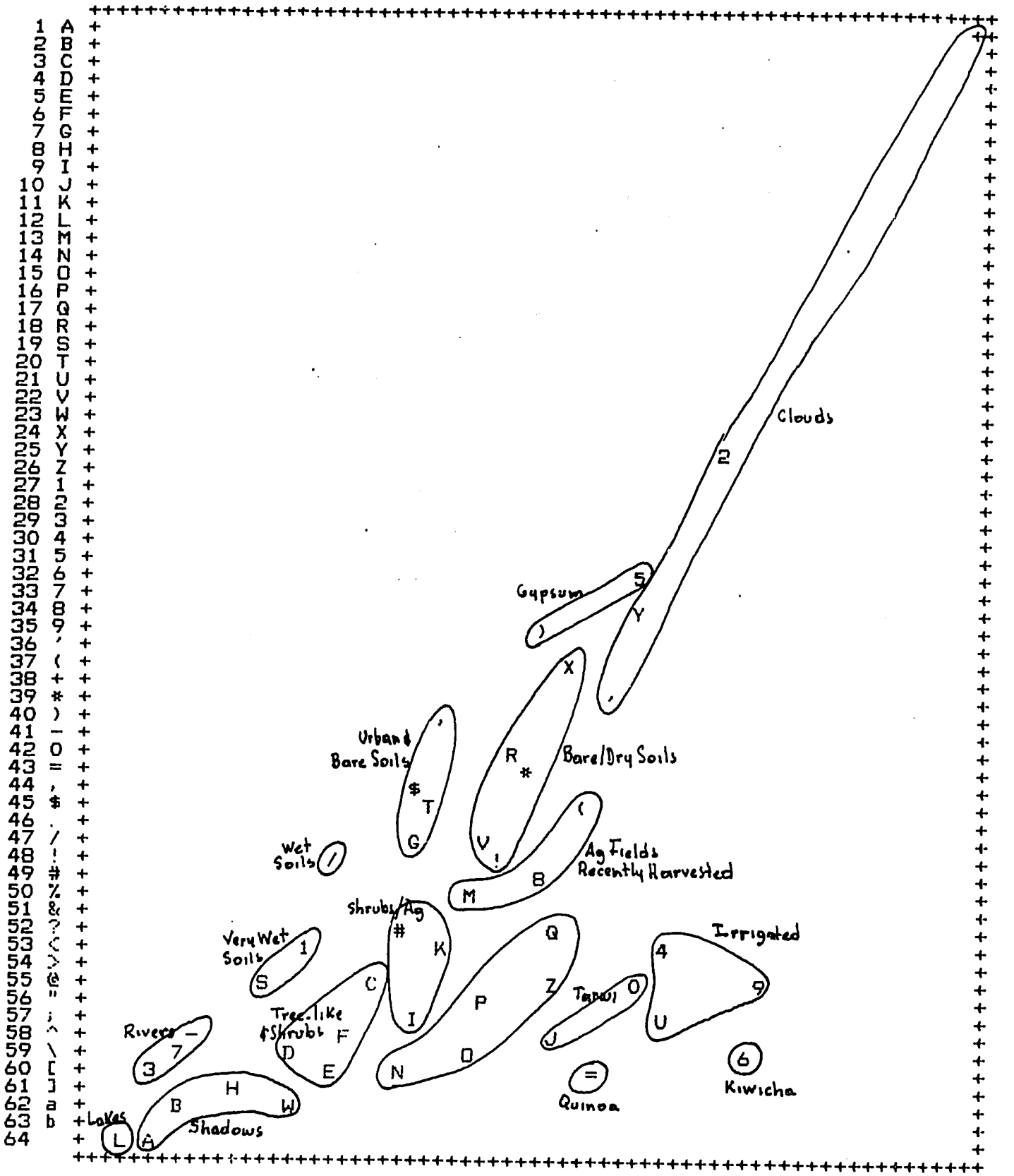


Figure 8: SPOT May 1990 Controlled Unsupervised Classification

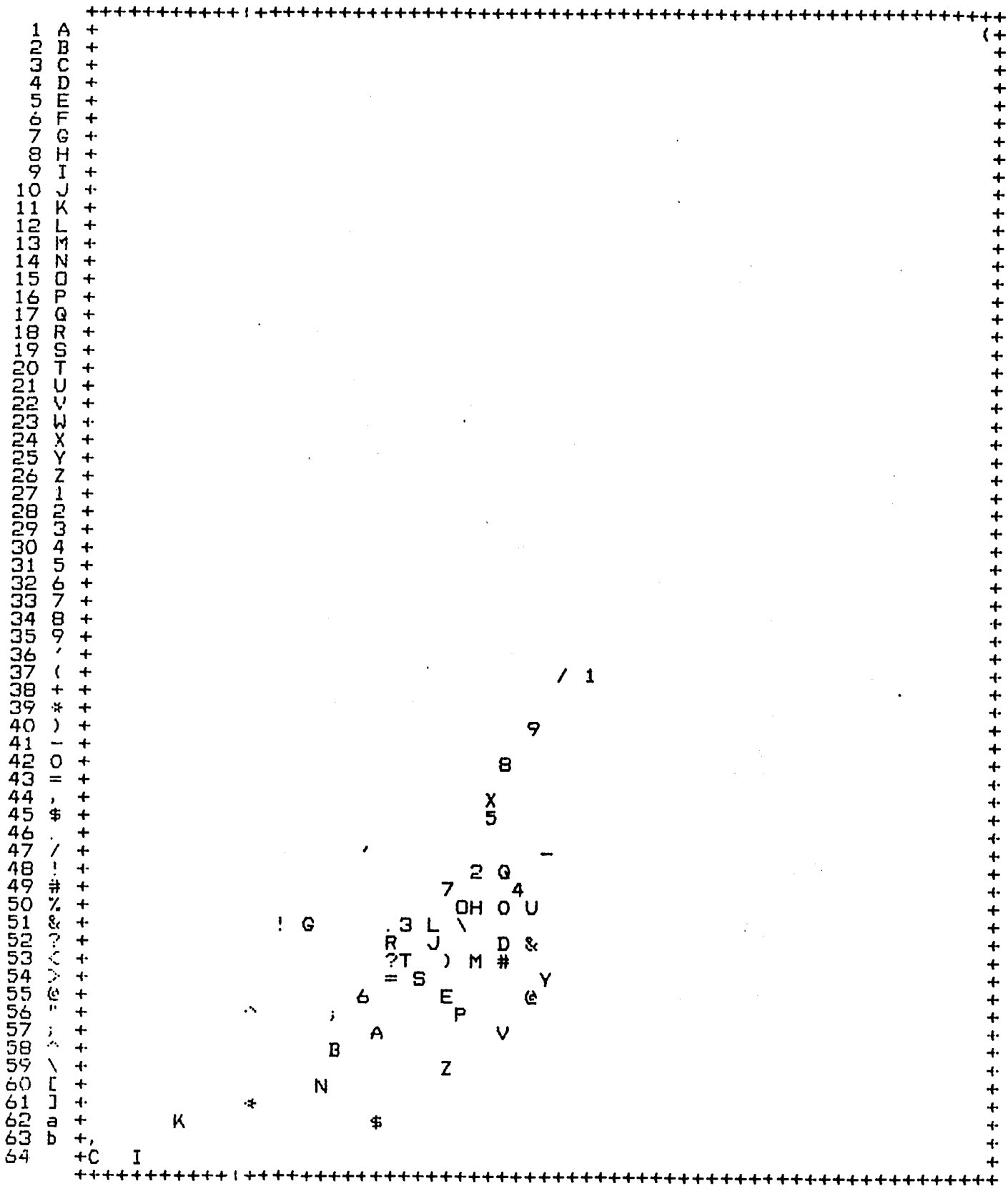


Figure 9: TM May 1990 Spectral Classes

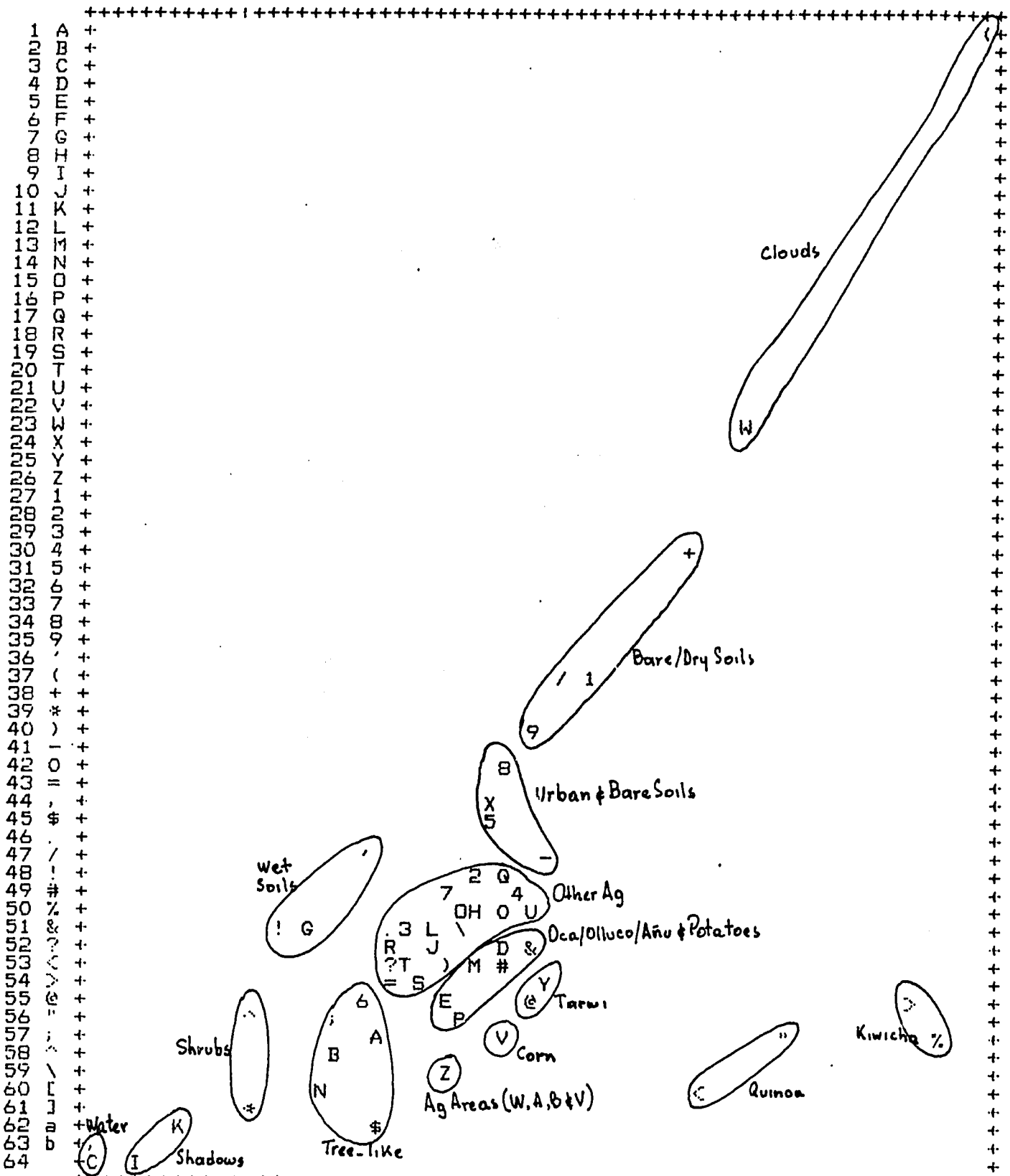


Figure 10: TM May 1990 Controlled Unsupervised Classification

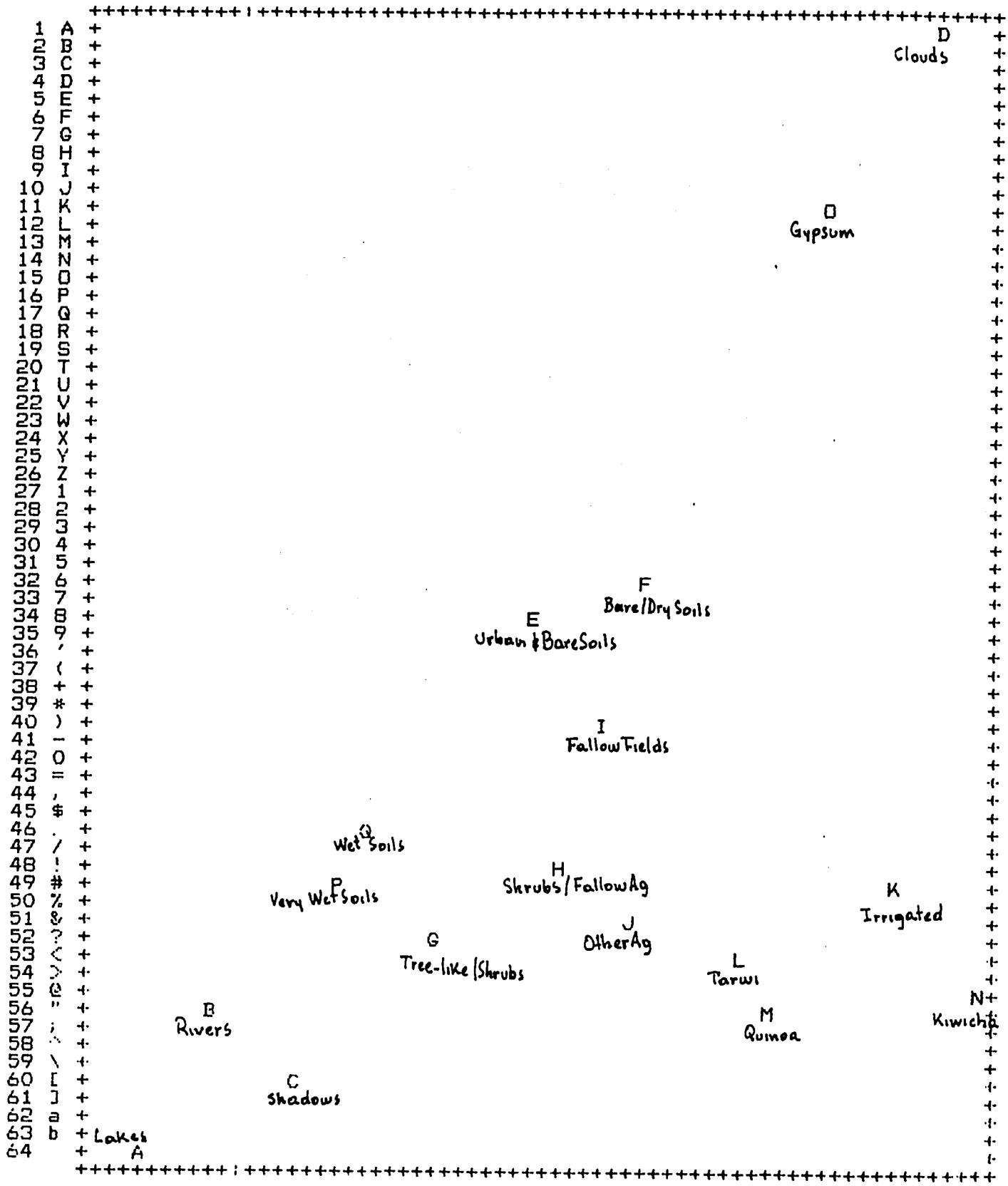


Figure 11: SPOT May 1990 Clustered Classification

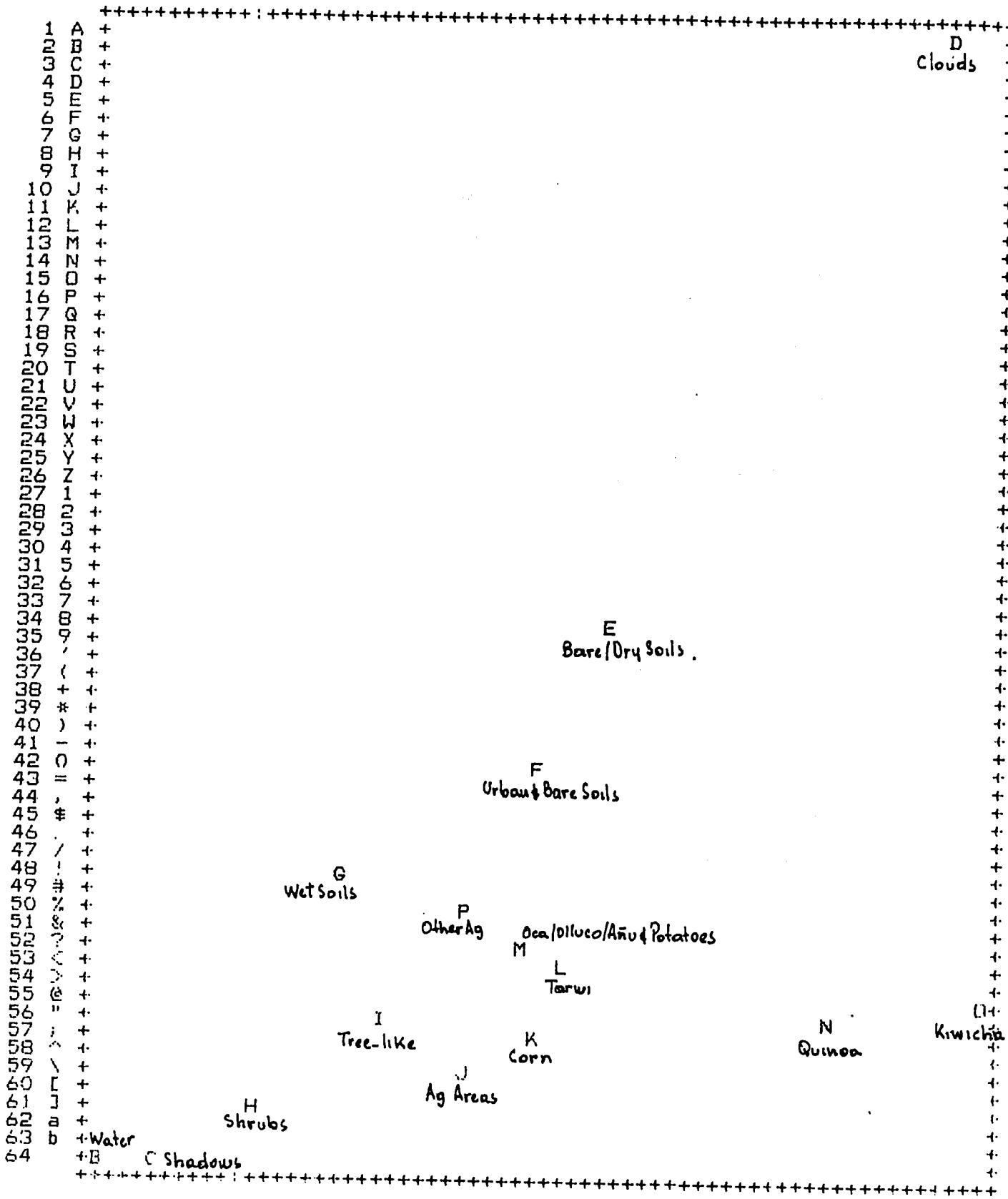


Figure 12: TM May 1990 Clustered Classification

APPENDICES

1. Satellite Data
2. Aerial Photography
3. Cartographic Data
4. Radiometric Field Data
5. Resulting Spectral Signatures of Studied Crops
6. Classification of Studied Crops

APPENDIX 1: Satellite Data

The following were the satellite data obtained for this project. These data, in CCT form, are available at TAC and are being kept in TAC's CCT Library.

Tape Number	Image ID Number	Path/Row	Date	Cloud Cover %	Remarks	BPI
H007 SPOT	16593778805121459531X	659/377	12 May 88	25	Multispectral	6250
H012 SPOT	16593778806061519261X	659/377	6 June 88	10	Multispectral	6250
H013 SPOT	16593778806061519241P	659/377	6 June 88	10	Panchromatic	6250
H014 SPOT	26593779005021504491X	659/377	2 May 90	10	Multispectral	6250
C074 TM	Y42848-14234	4/69	3 May 90	40	Multispectral	6250

Asides from these CCTs, containing the raw data, several intermediate products in digital format are also stored at TAC's Library.

APPENDIX 2: Aerial Photography

There were a total 106 aerial photographs obtained for this project. These photos are listed in Table 8 in the text, and are being kept at TAC for future reference and use. The aerial photography was obtained from the Servicio Aerofotografico Nacional (SAN) of Peru.

APPENDIX 3: Cartographic Data

The series of maps listed in Table 8 numbere a total of 132. There are another eight communications and tourist maps collected for the project. These maps are all housed in TAC for future reference and use.

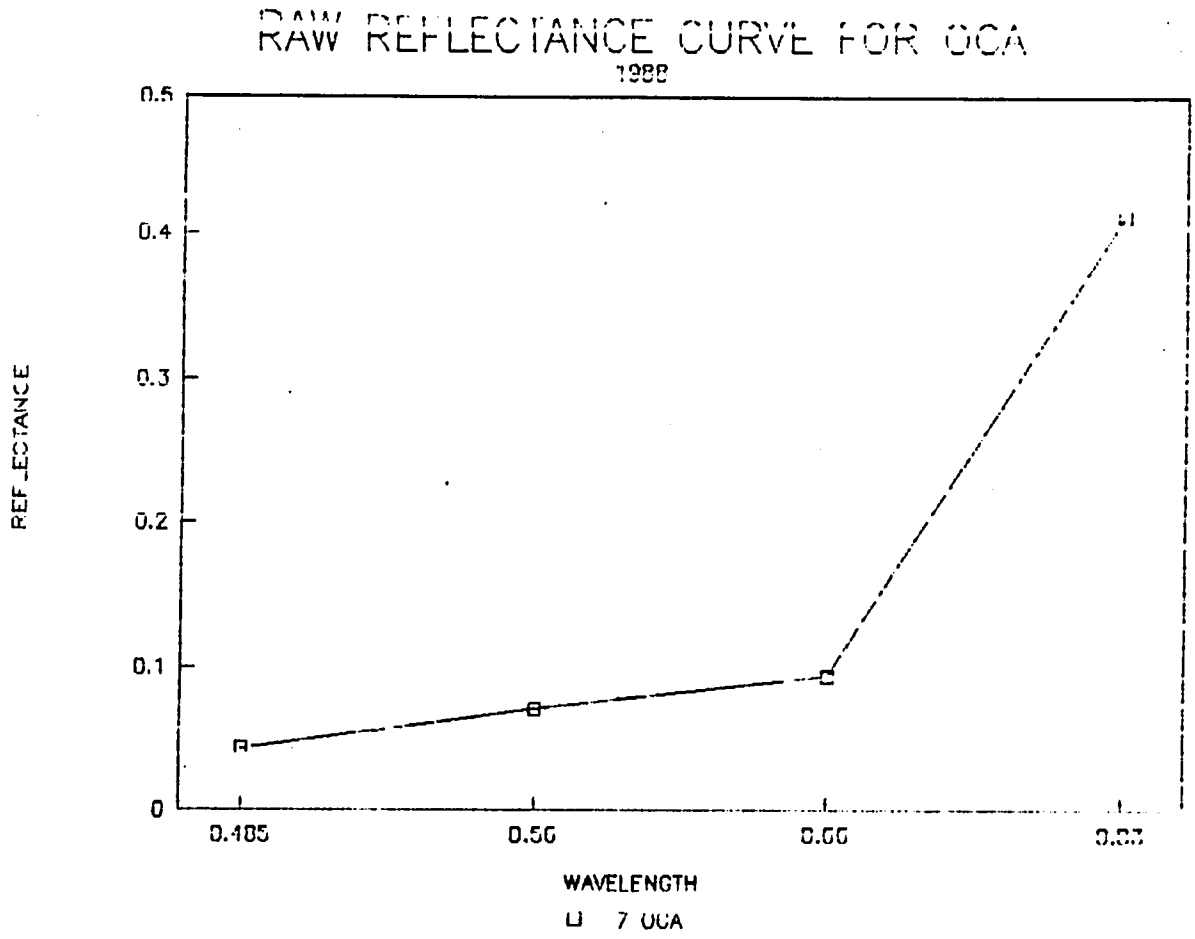
APPENDIX 4: Radiometric Field Data

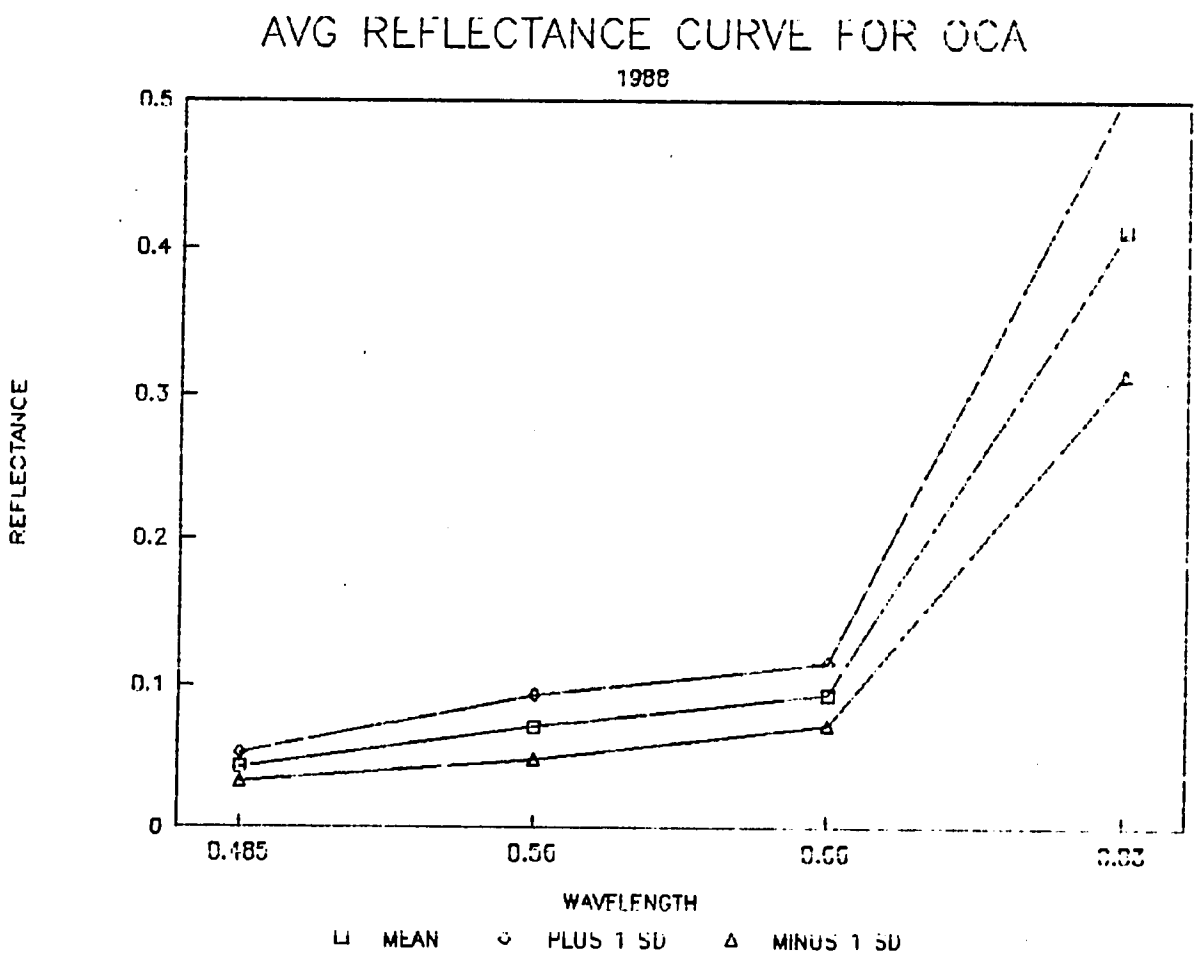
Five field notebooks containing the radiometric data collected during the three visits to the study area are housed at TAC for reference and use. The radiometric data contained in these notebooks were input into our PC system and can be accessed for reference and use.

APPENDIX 5: Resulting Spectral Signatures of Studied Crops

Spectral signature curves for the studied crops are presented for the data and years collected.

Reflectance Curves, 1988


RAW REFLECTANCE CURVE FOR OCA
1988
0.5
0.4
0.3
0.2
0.1
0
REFLECTANCE
0.485
0.56
0.66
0.83
WAVELENGTH
7 OCA


AVG REFLECTANCE CURVE FOR OCA
1988
0.5
0.4
0.3
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0
REFLECTANCE
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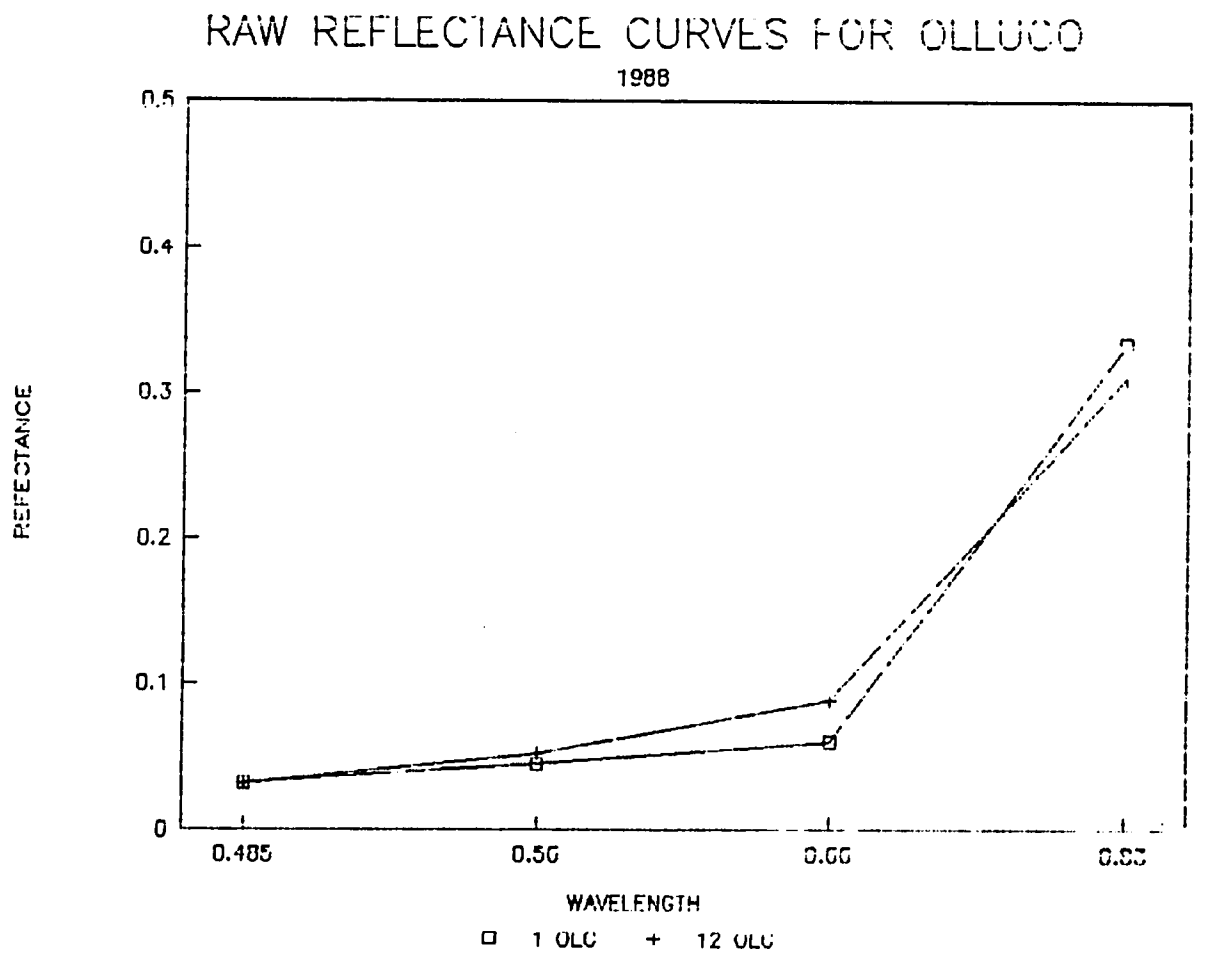
0.66
0.83
WAVELENGTH
MEAN
PLUS 1 SD
MINUS 1 SD


RAW REFLECTANCE CURVES FOR OLLUCO
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0.4
0.3
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0.1
0
REFECTANCE
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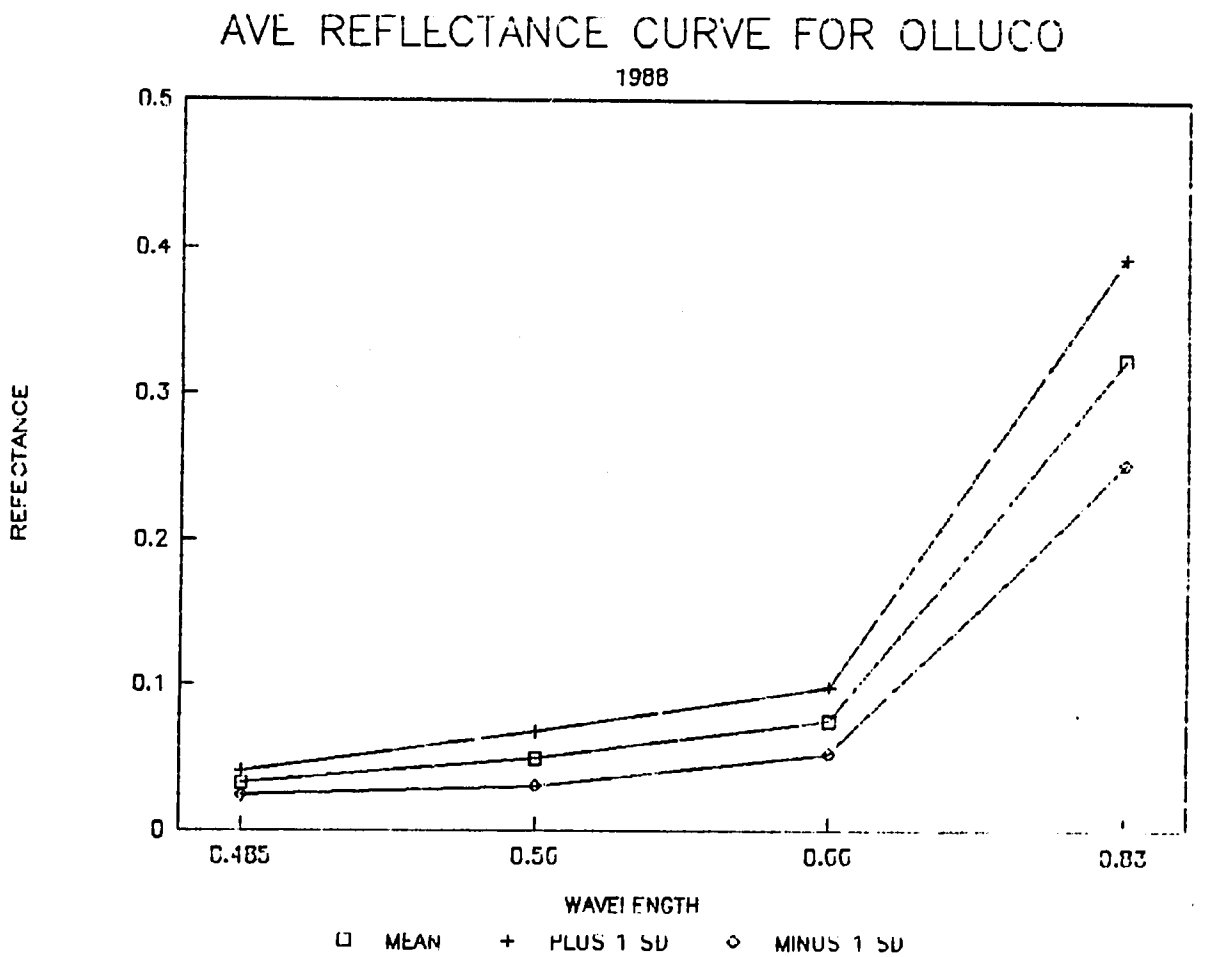
0.56
0.66
0.83
WAVELENGTH
1 OLC
12 OLC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1988
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0.4
0.3
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REFECTANCE
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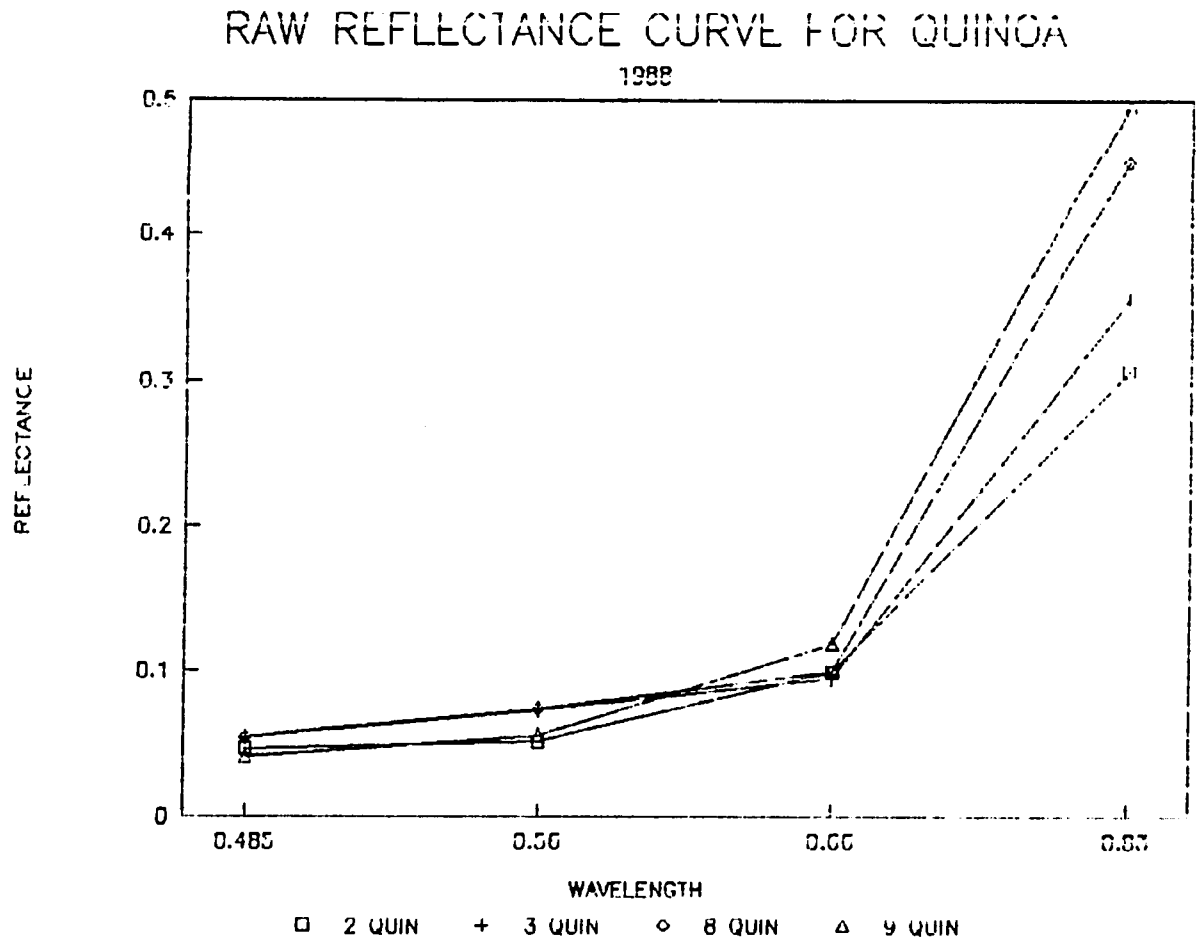
0.66
0.83
WAVELENGTH
MEAN
PLUS 1 SD
MINUS 1 SD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REFLECTANCE
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0.4
0.3
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0.1
0
0.485
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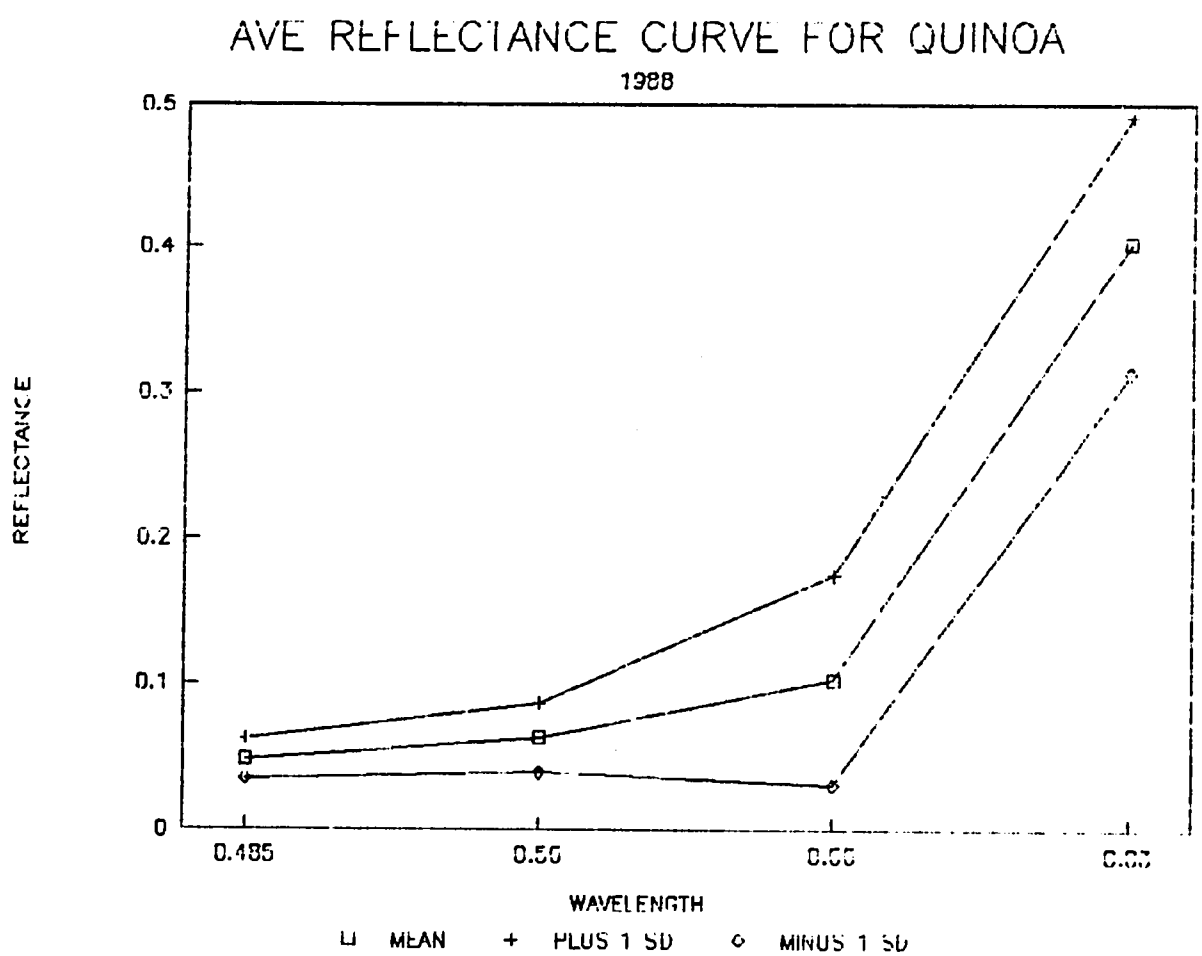
0.66
0.83
WAVELENGTH
2 QUIN
3 QUIN
8 QUIN
9 QUIN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REFLECTANCE
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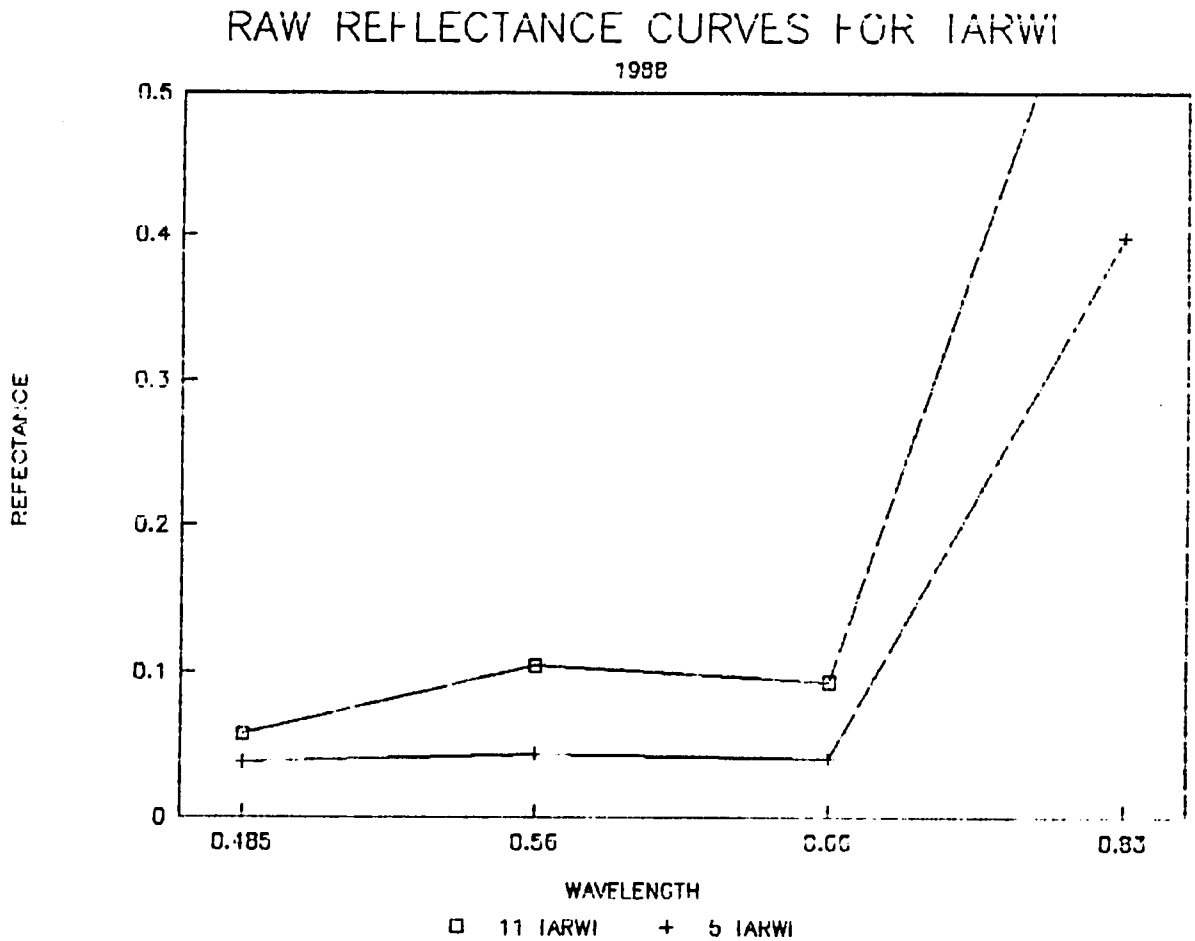
WAVELENGTH
MEAN
PLUS 1 SD
MINUS 1 SD


RAW REFLECTANCE CURVES FOR TARWI
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0
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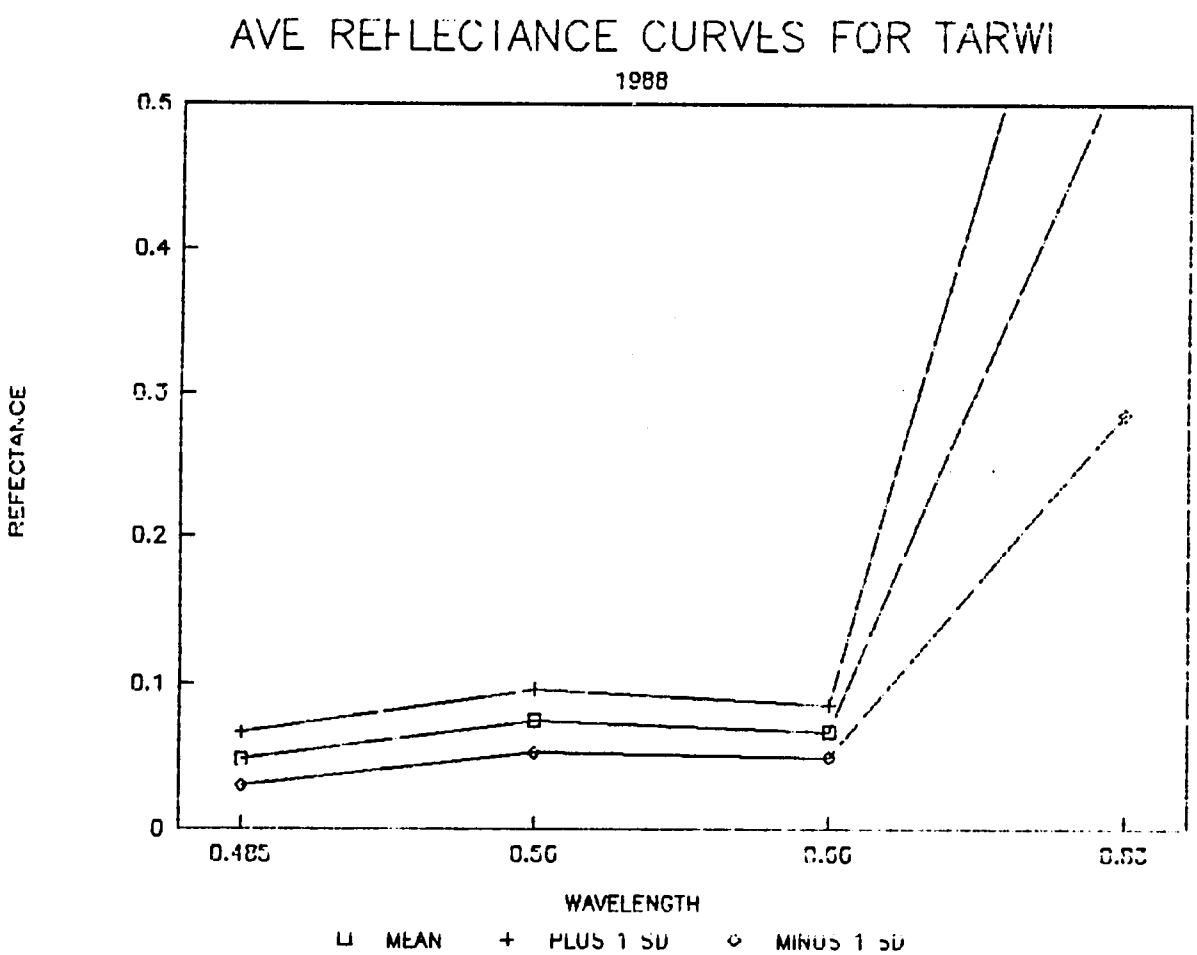
0.83
WAVELENGTH
11 TARWI
5 TARWI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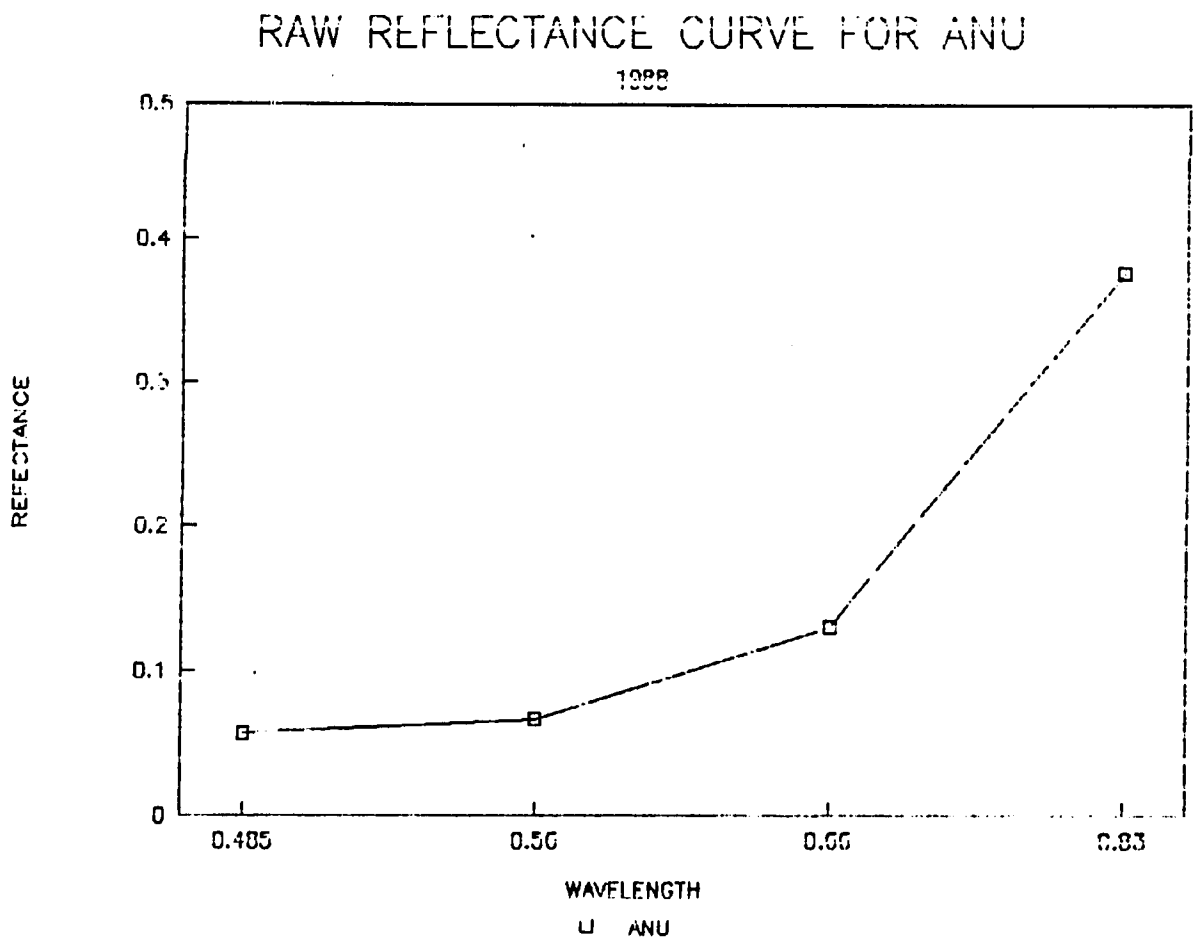
WAVELENGTH
MEAN
PLUS 1 SD
MINUS 1 SD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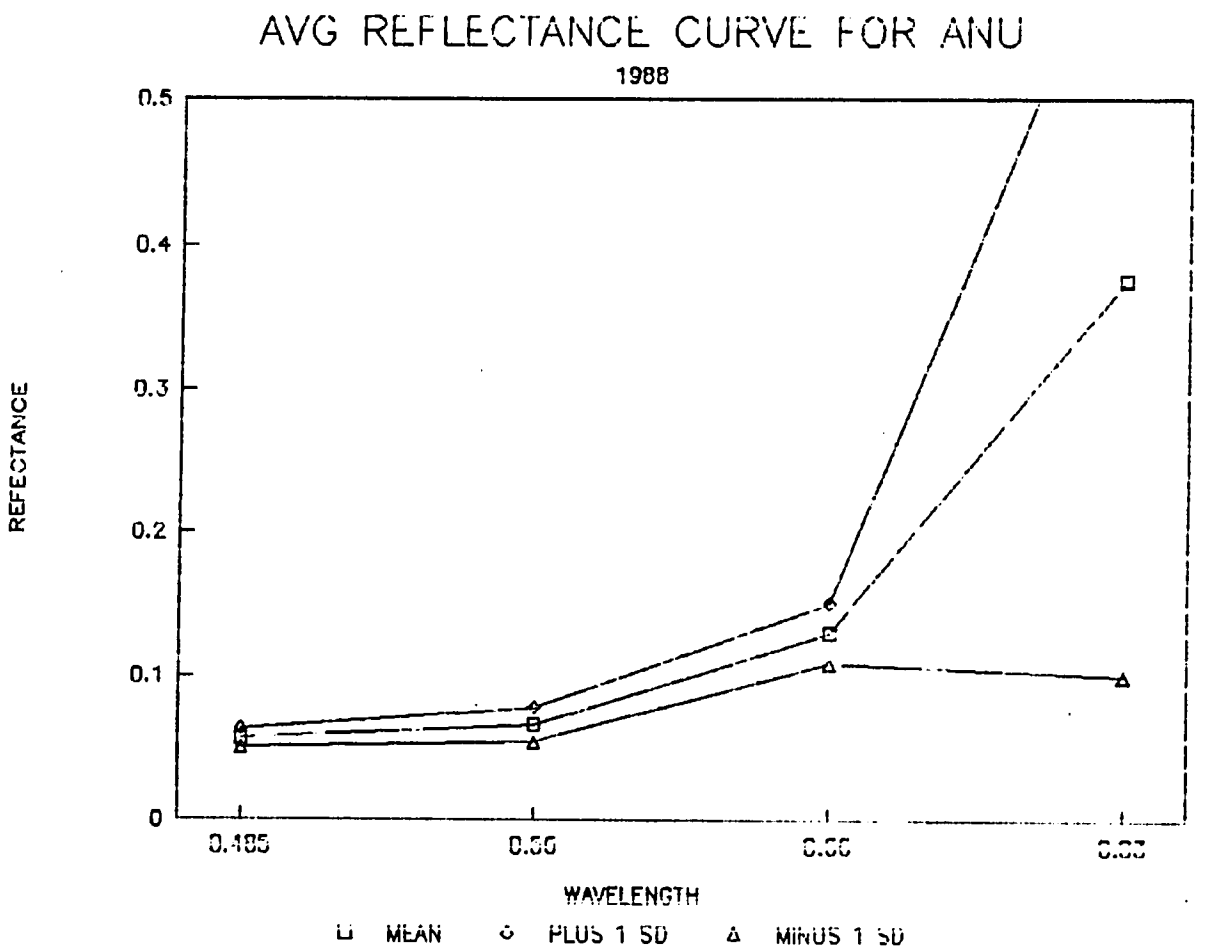
WAVELENGTH
ANU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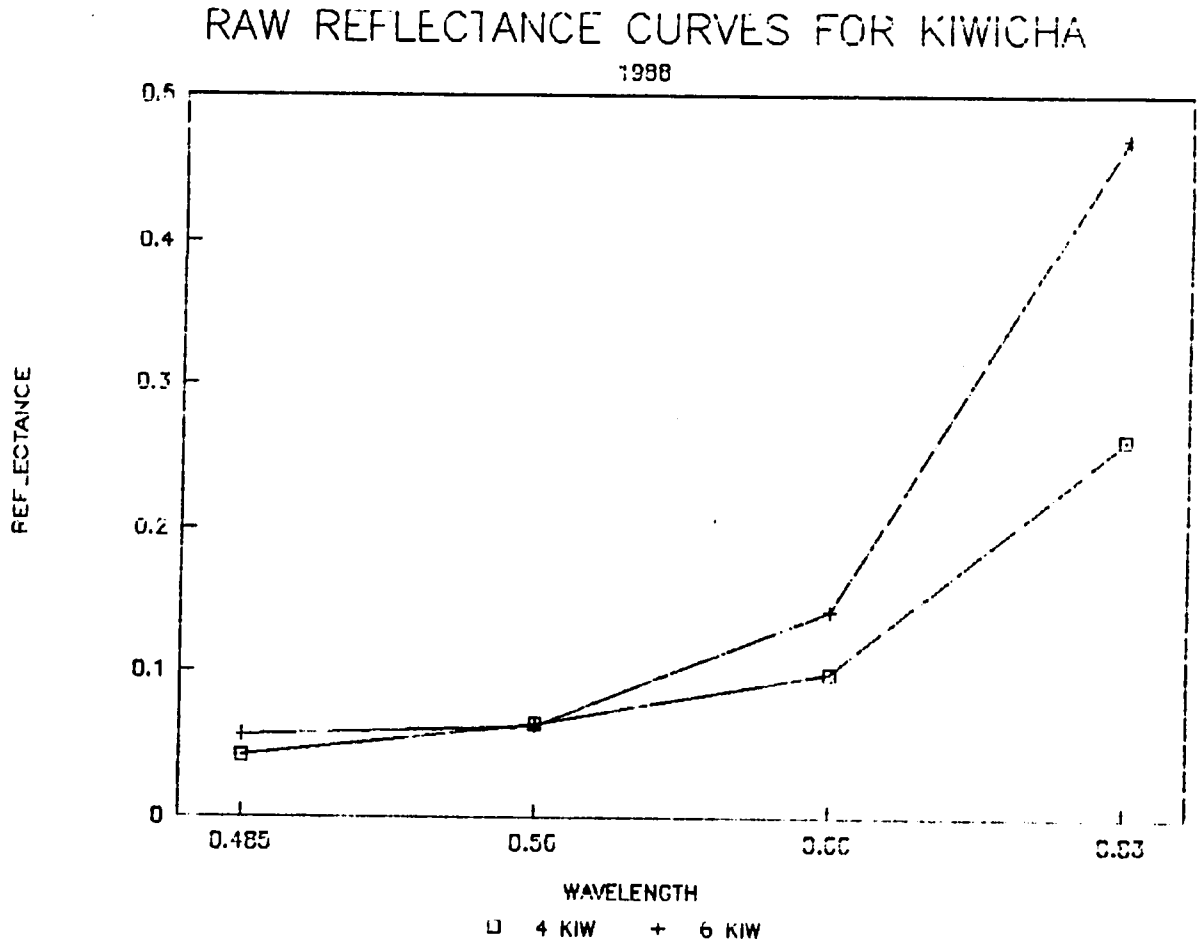
WAVELENGTH
MEAN
PLUS 1 SD
MINUS 1 SD


RAW REFLECTANCE CURVES FOR KIWICHA
1988
REFLECTANCE
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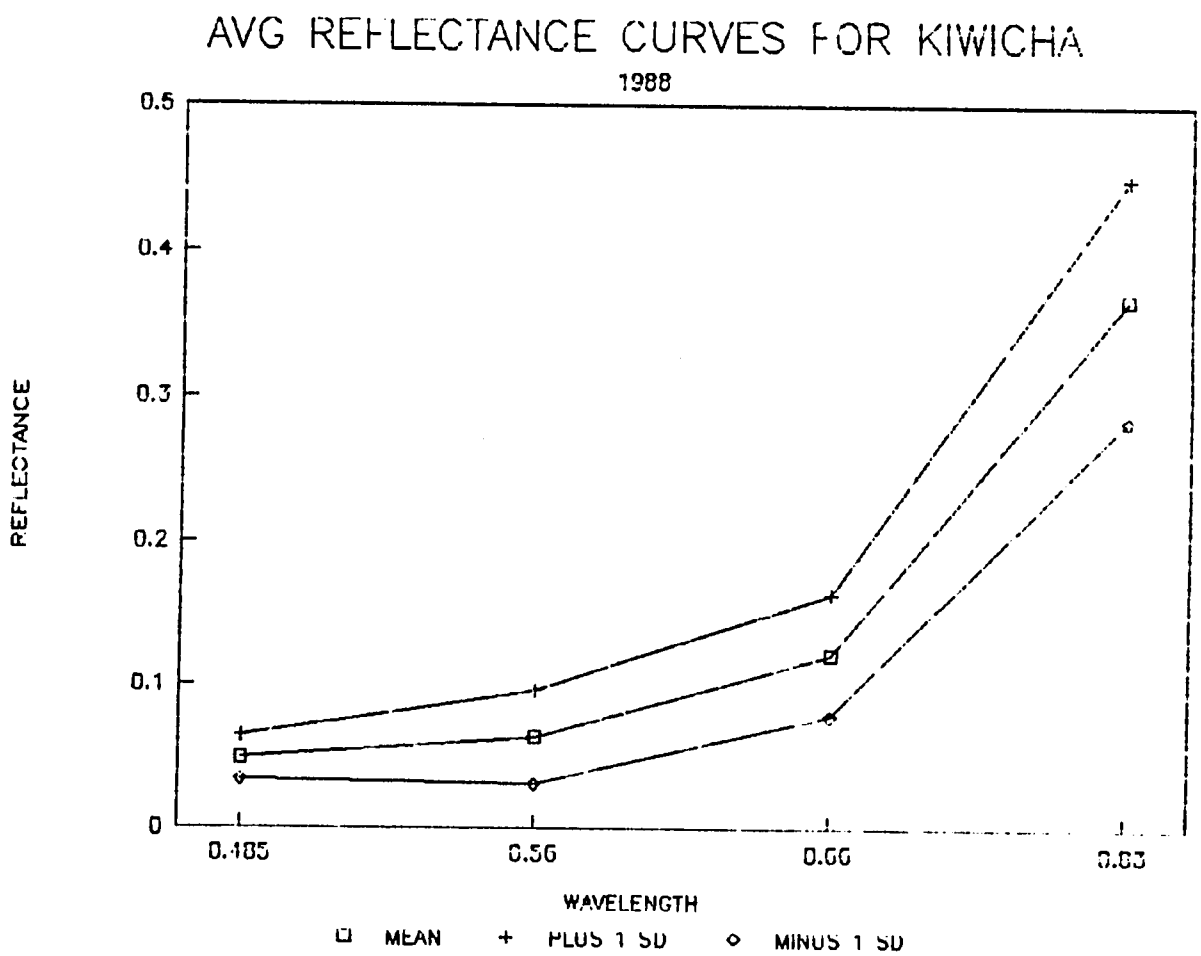
0.66
0.83
WAVELENGTH
4 KIW
6 KIW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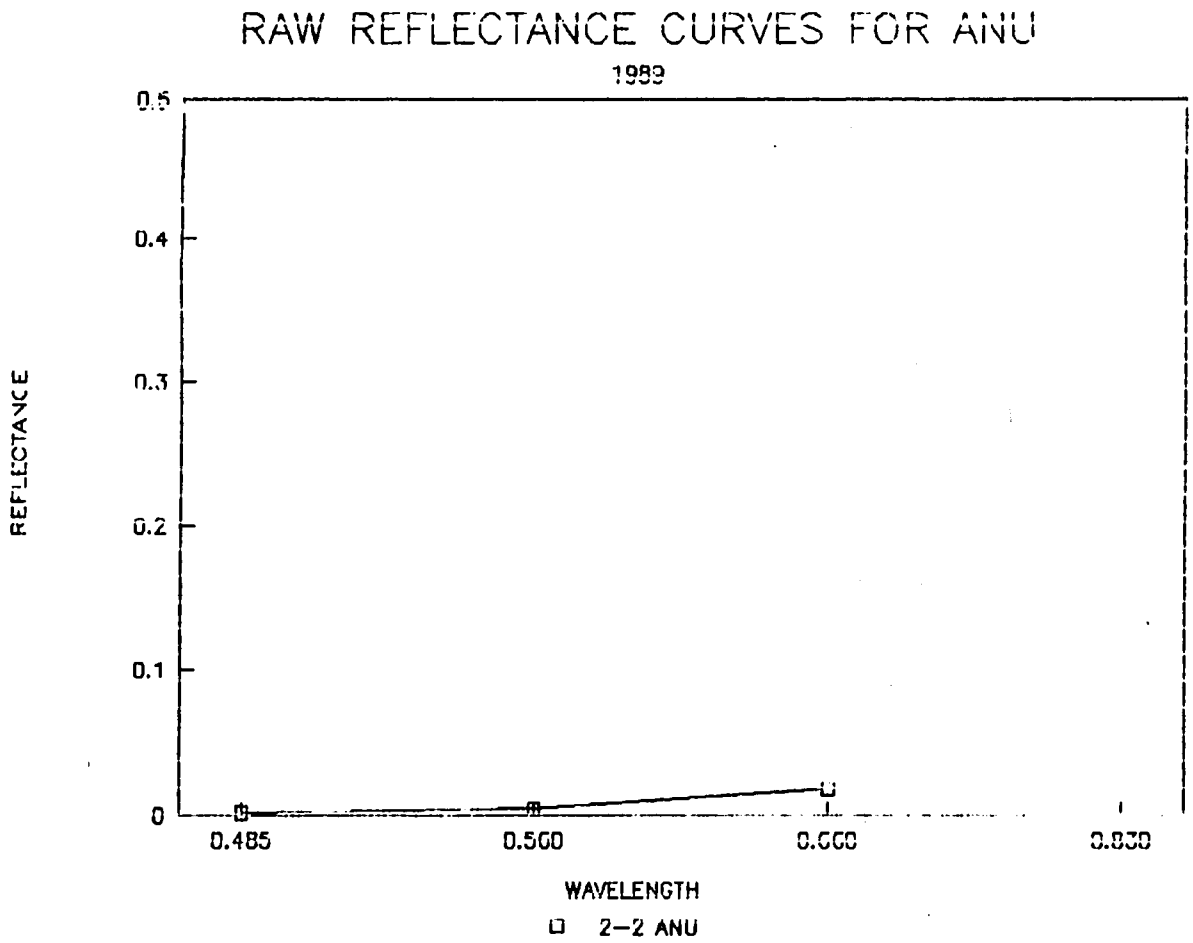
0.66
0.83
WAVELENGTH
MEAN
PLUS 1 SD
MINUS 1 SD

Reflectance Curves, 1989


RAW REFLECTANCE CURVES FOR ANU
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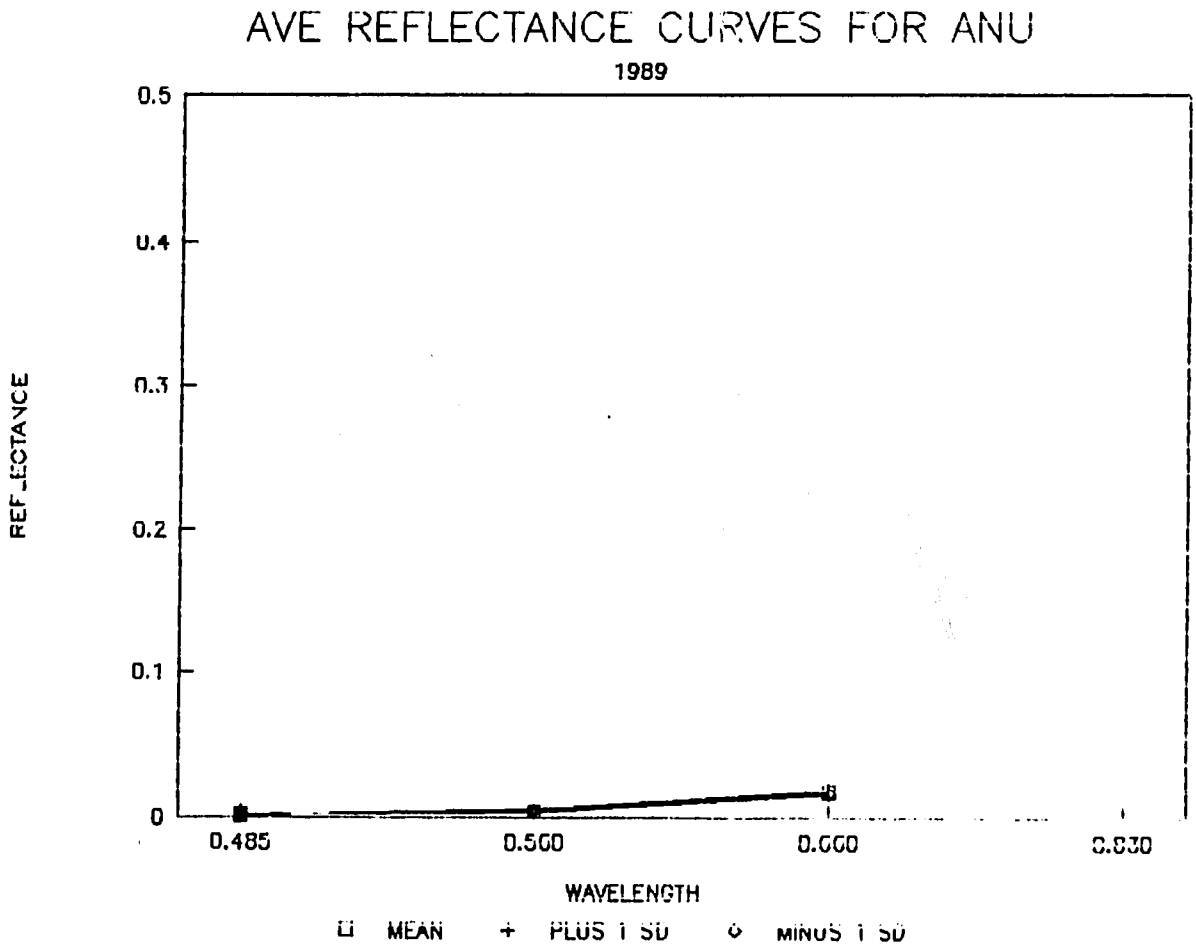
0.830
WAVELENGTH
2-2 ANU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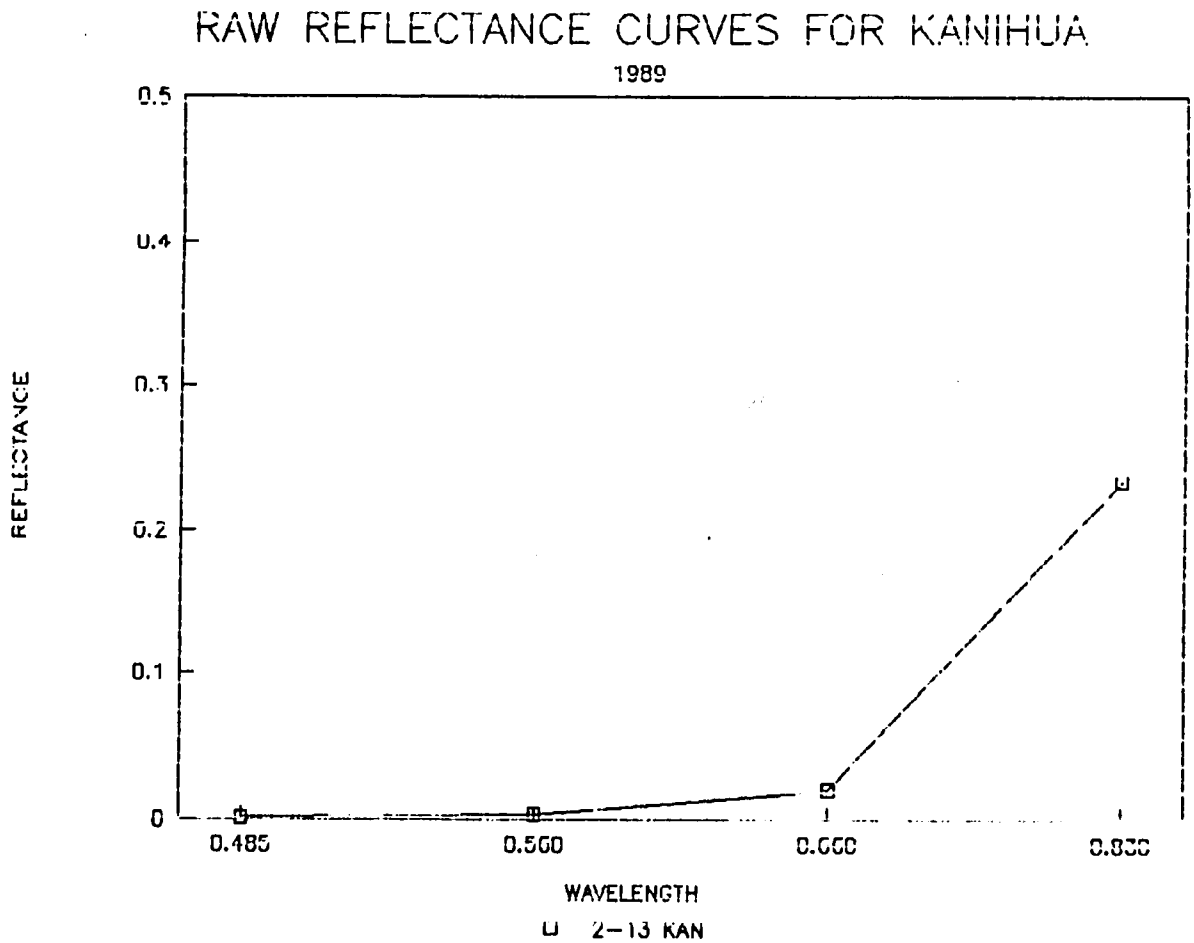
0.4
0.3
0.2
0.1
0
REFLECTANCE
0.485
0.500
0.660
0.830
WAVELENGTH
MEAN
PLUS 1 SD
MINUS 1 SD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WAVELENGTH
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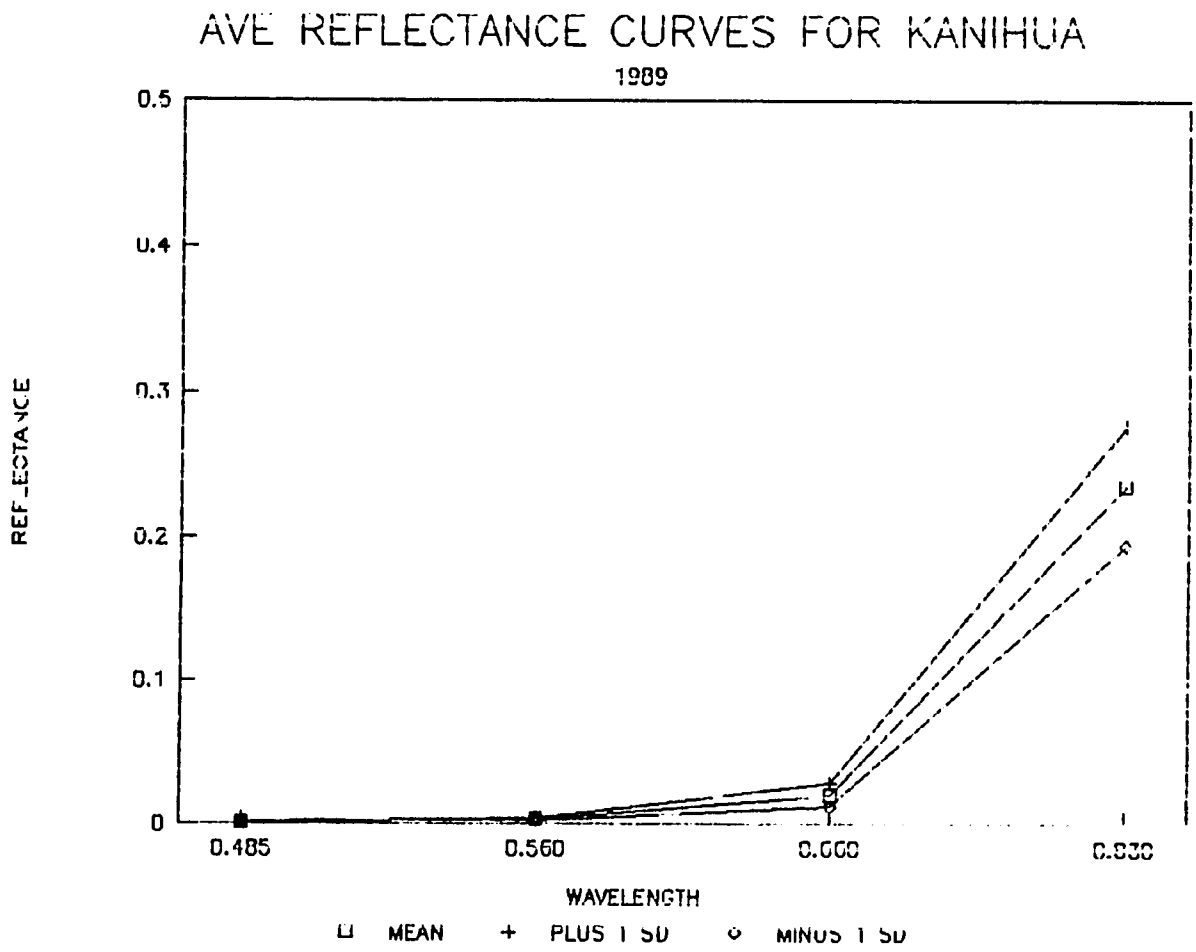
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MEAN
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MINUS 1 SD

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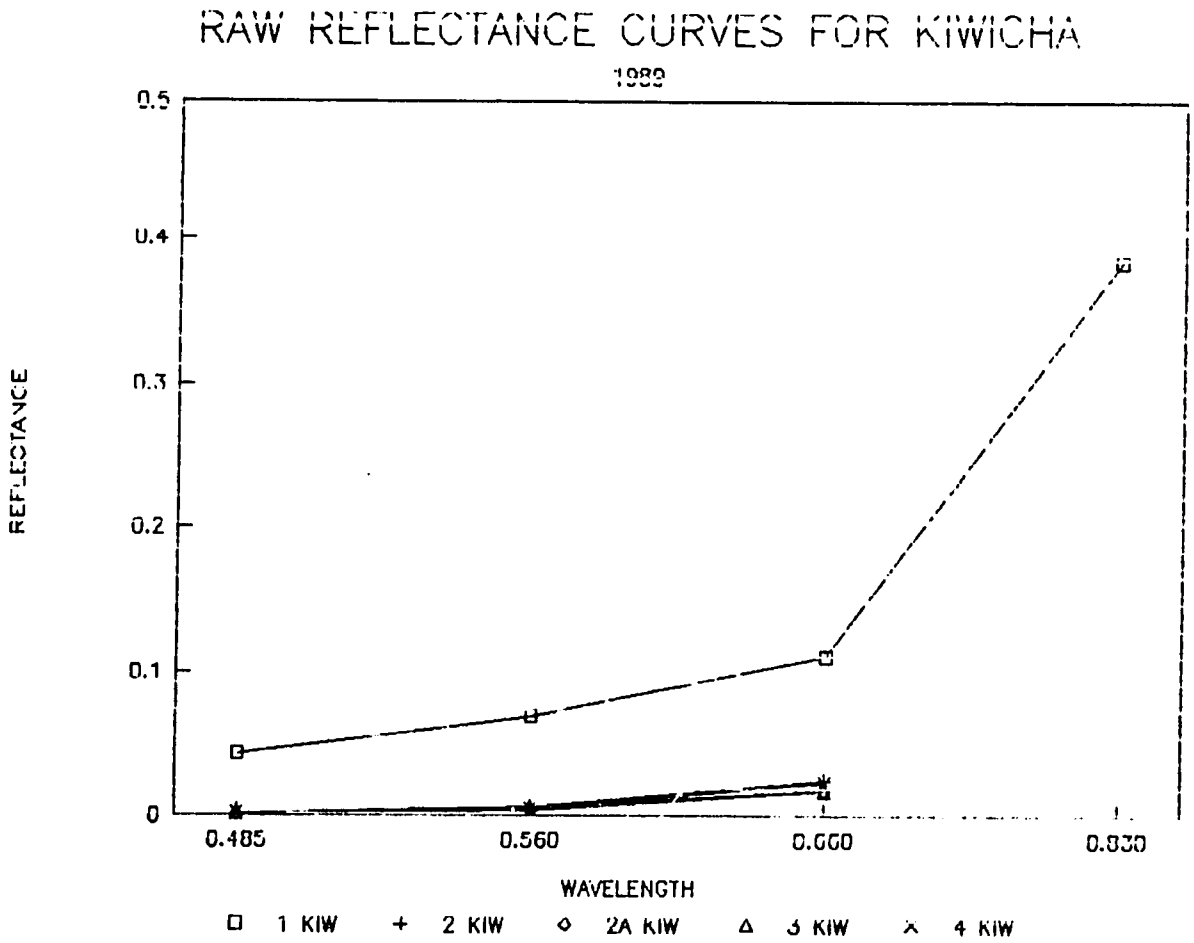
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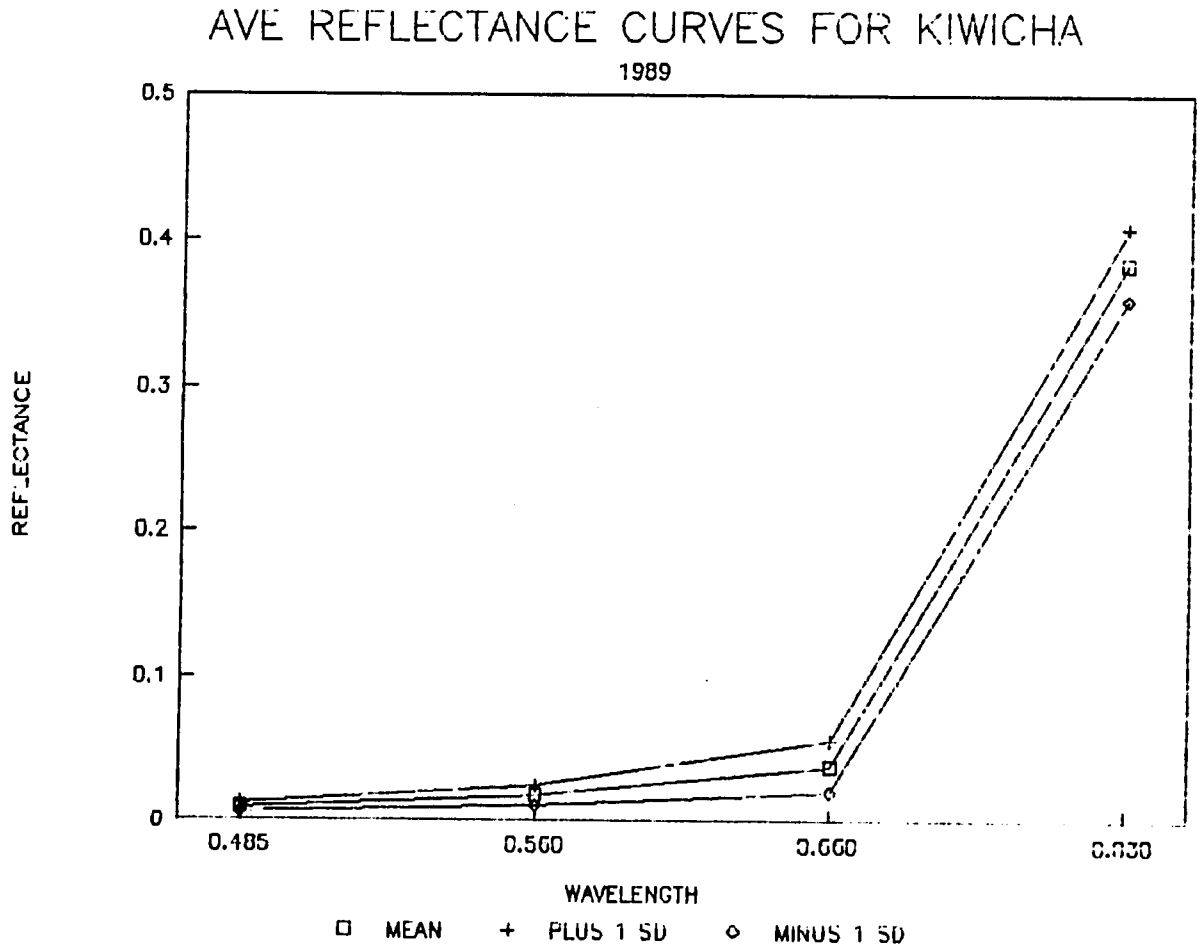
2 KIW
2A KIW
3 KIW
4 KIW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PLUS 1 SD
MINUS 1 SD

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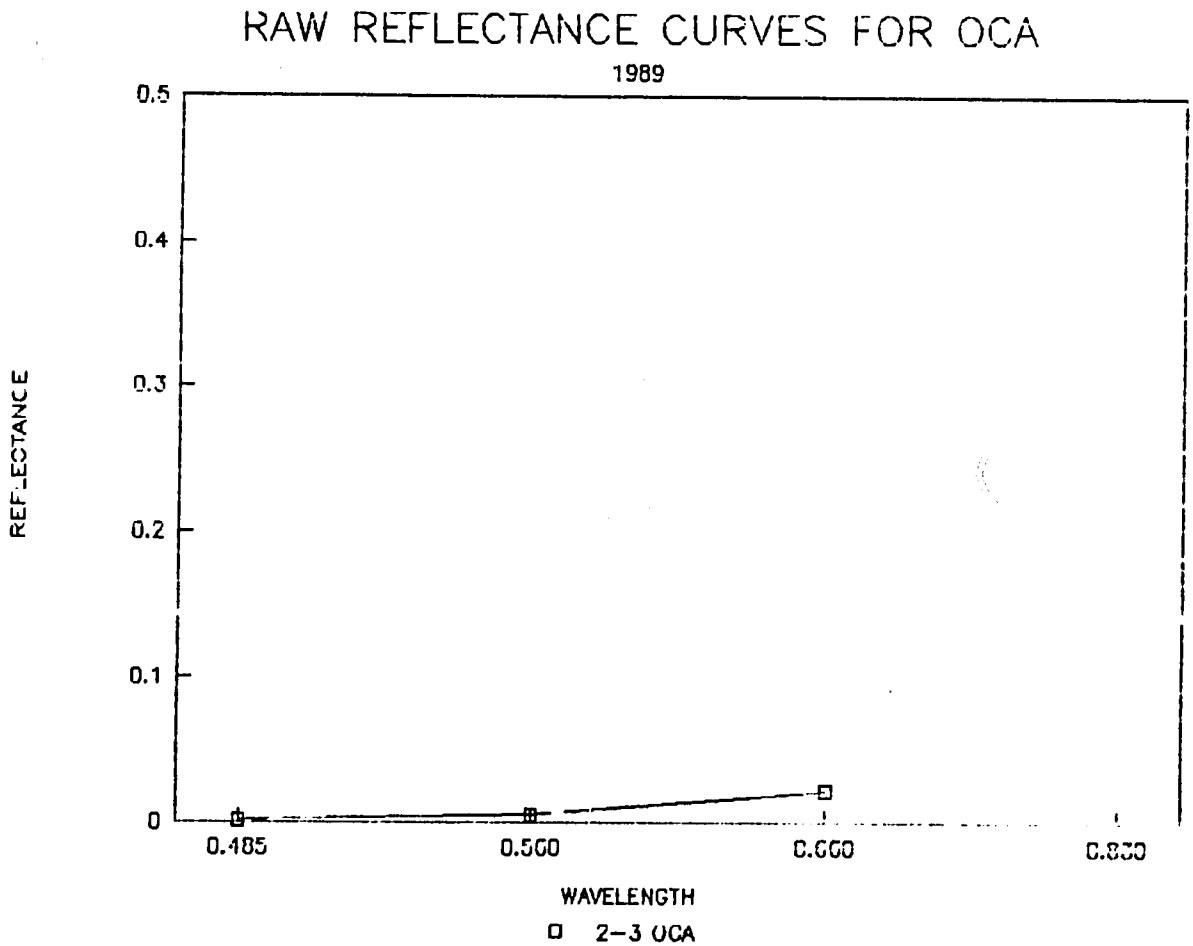
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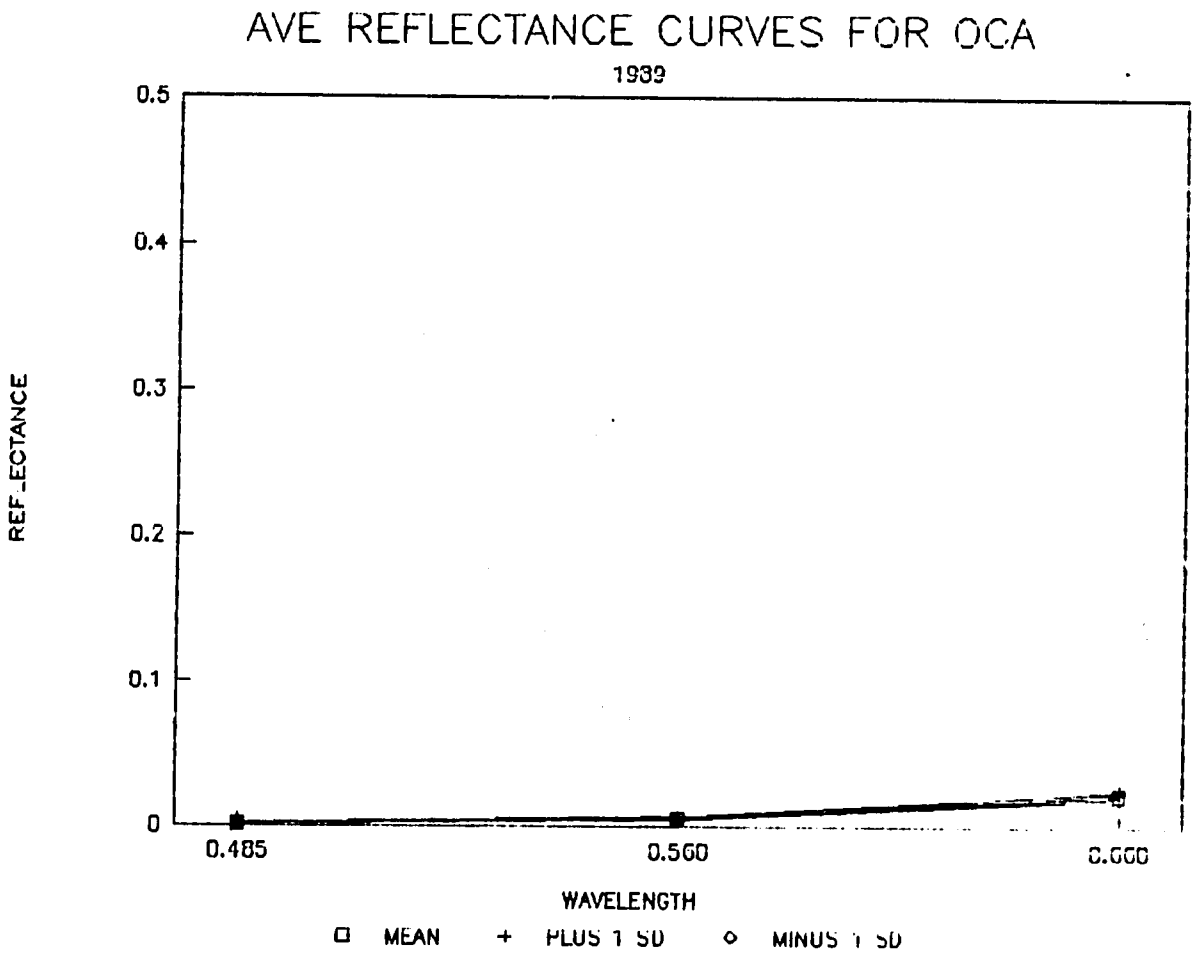
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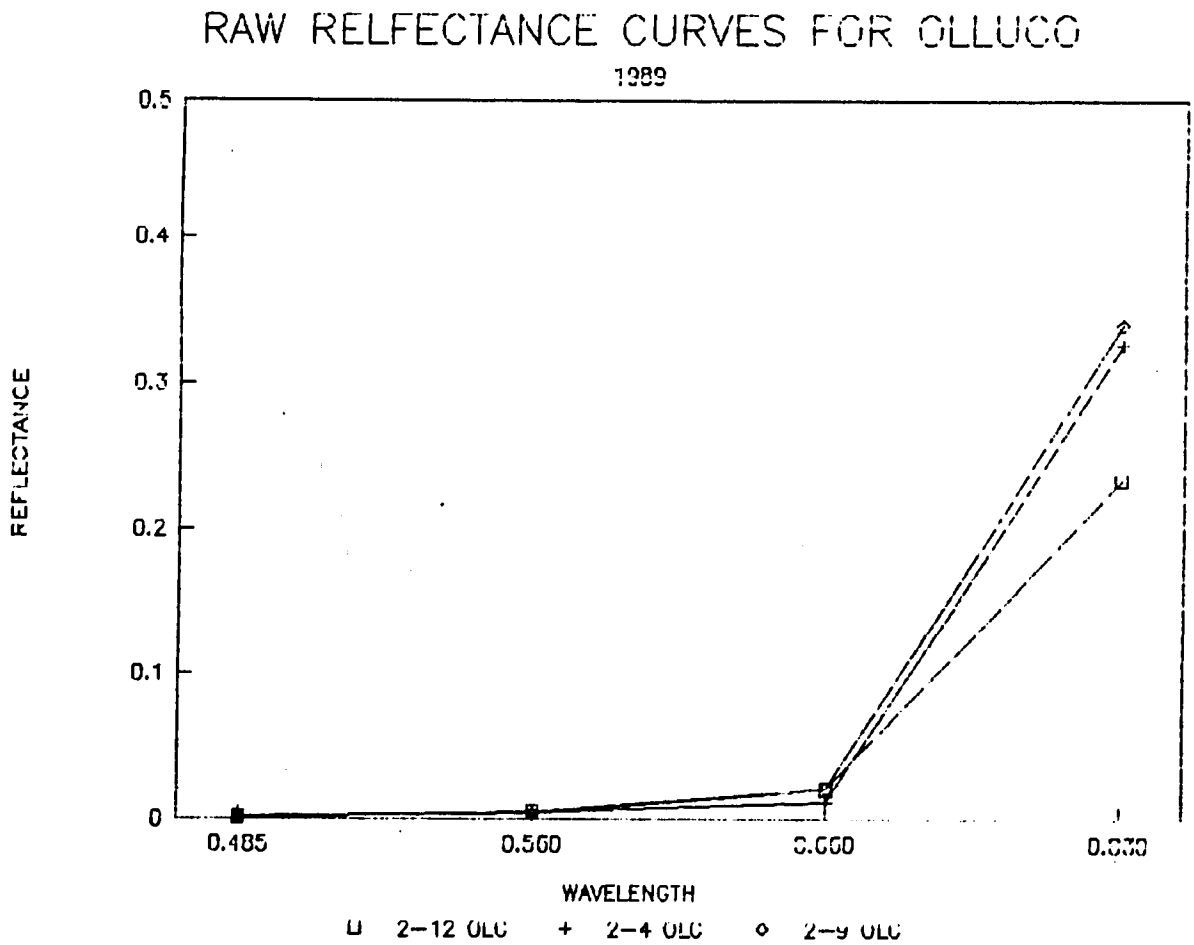
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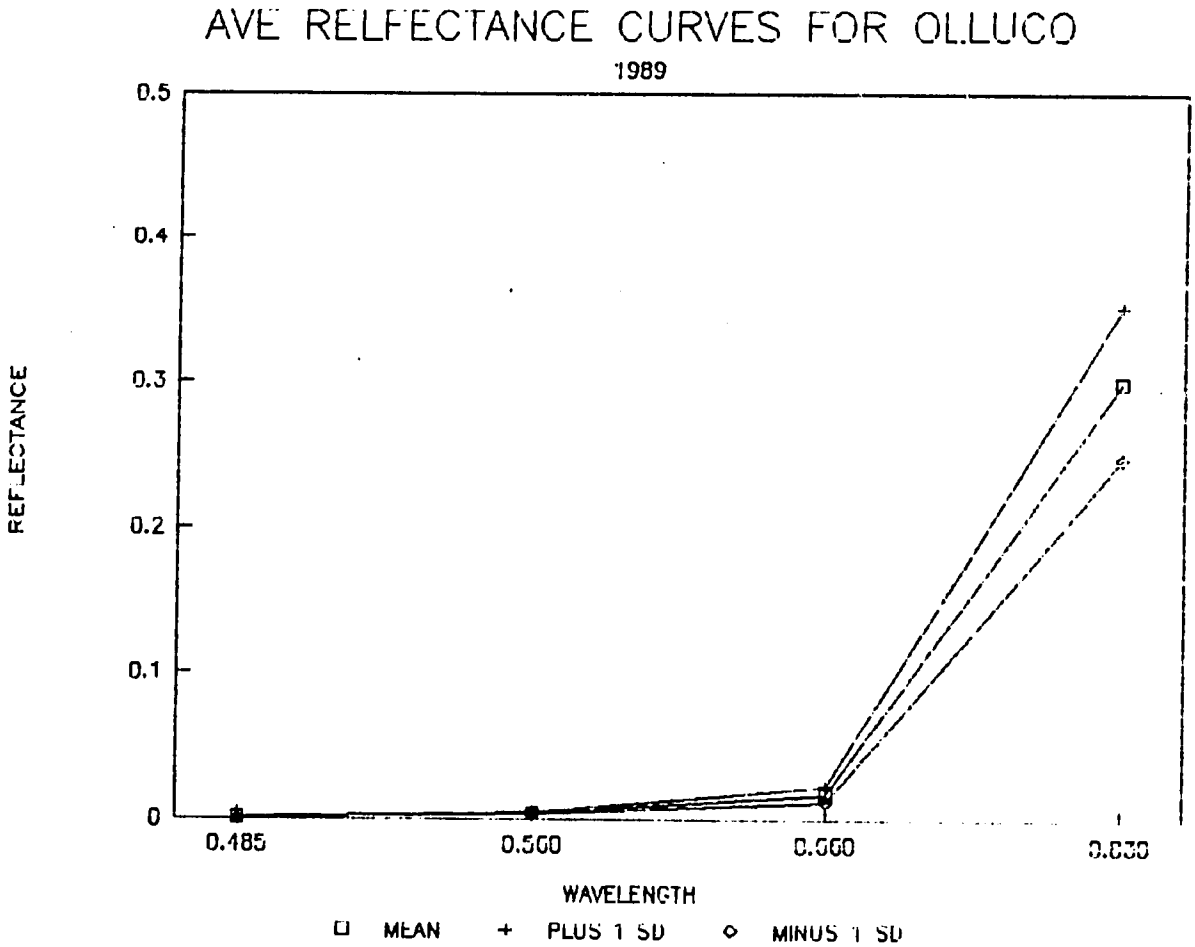
2-9 OLC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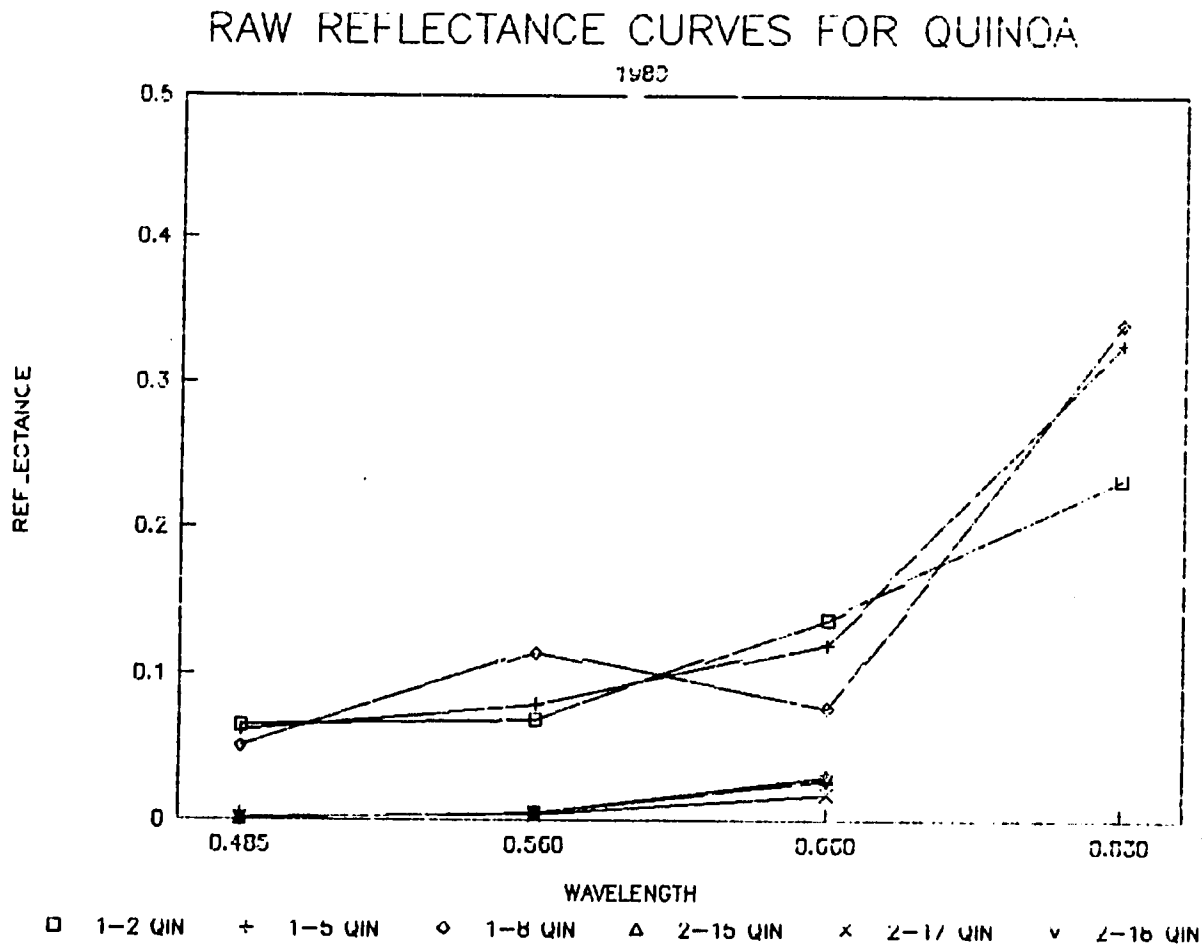
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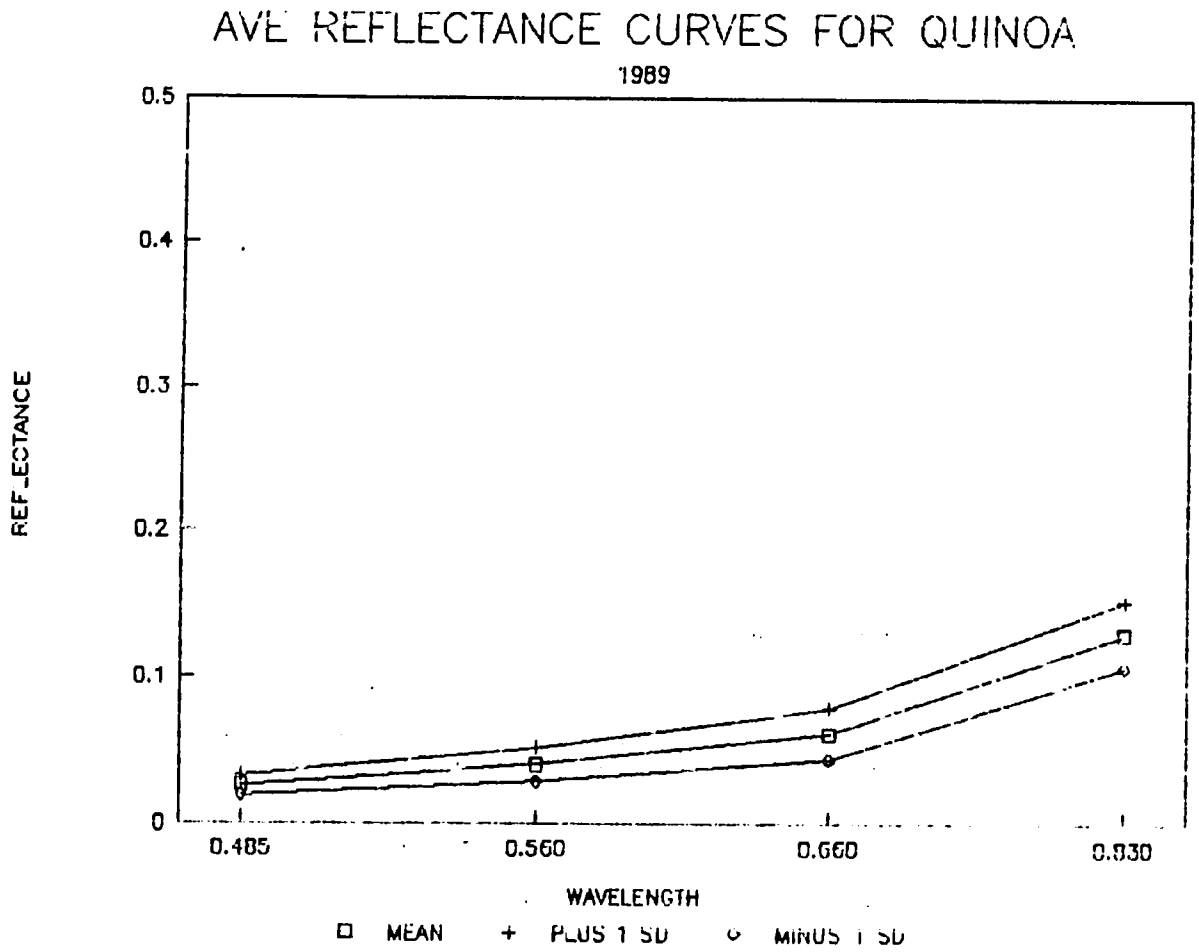
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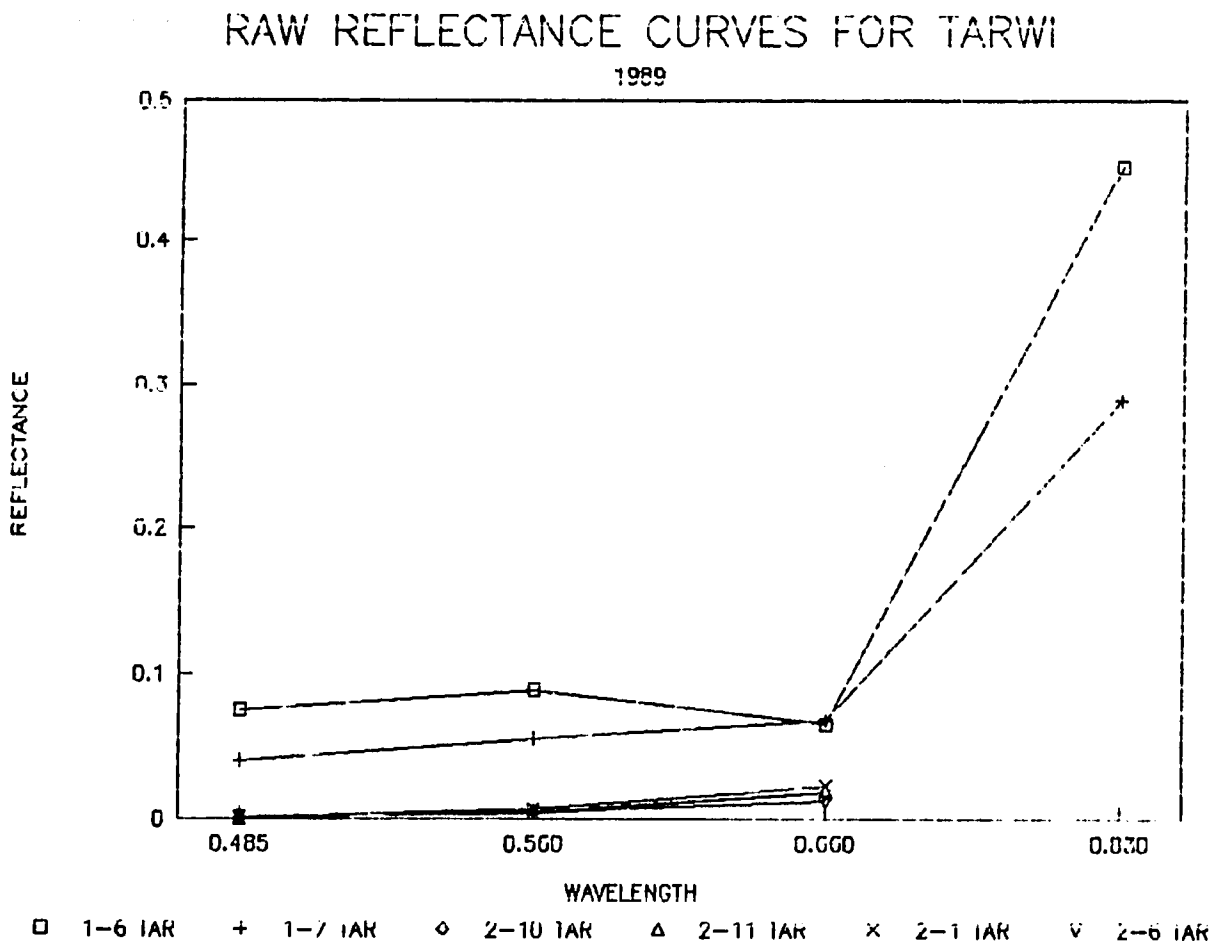
MEAN
PLUS 1 SD
MINUS 1 SD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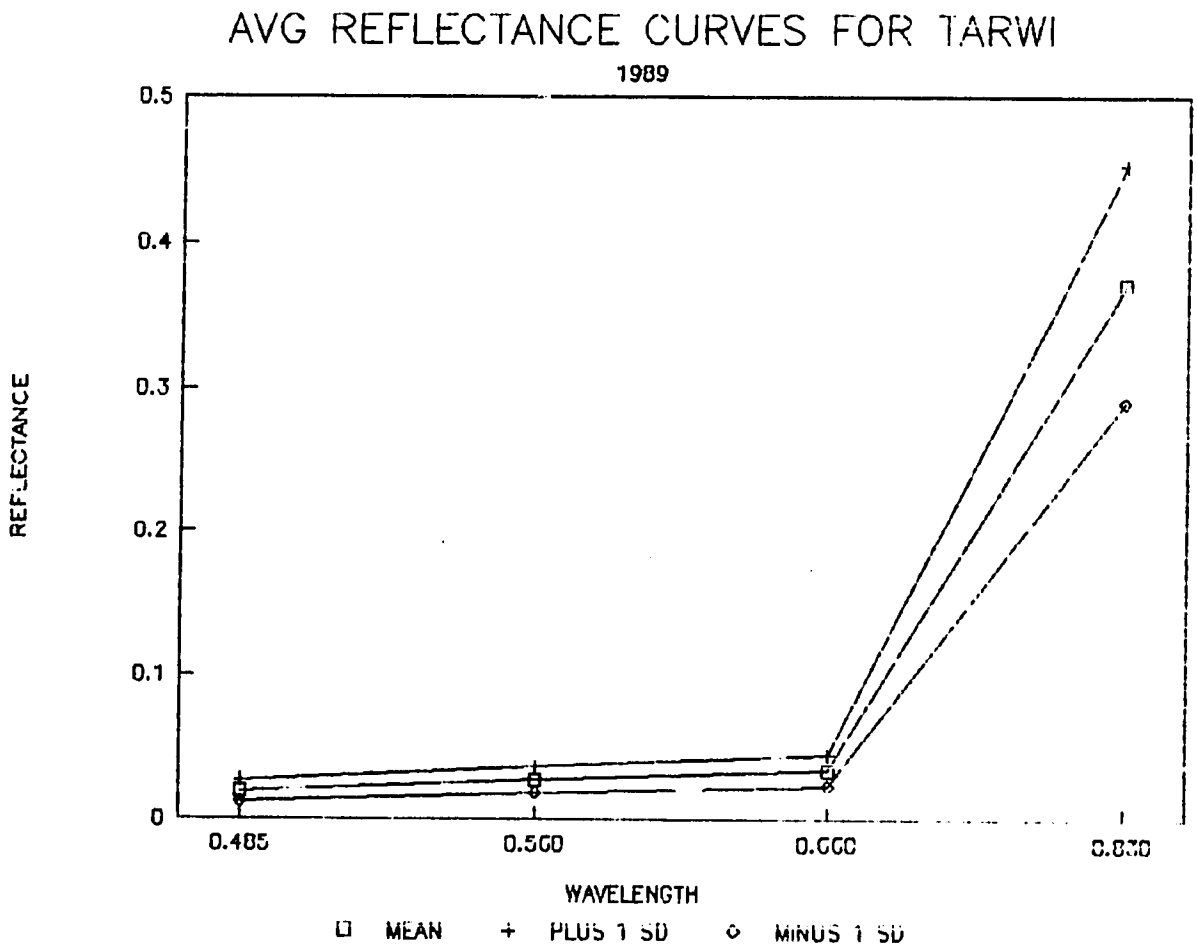
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0.830
WAVELENGTH
MEAN
PLUS 1 SD
MINUS 1 SD

APPENDIX 6: Classification of Studied Crops

Aside from the information on clustered classes contained in Tables 15 an 16 in the text, two tapes containing the classified data for SPOT and TM 1990 were generated. These tapes, as well as the two diapositives produced from them, are being kept at TAC for refrence and use.

ATTACHMENTS

1. Papers and Articles
2. Color Prints of SPOT and TM Classifications

19 - 20

III SIMPOSIO LATINOAMERICANO SOBRE SENSORES REMOTOS

MEMORIA

Sociedad de Especialistas Latinoamericanos en Percepción Remota

Instituto de Geografía
Universidad Nacional Autónoma de México

México, 1989

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SELPER SYMPOSIUM IN ACAPULCO - DEC '88

CARACTERIZACION ECOGEOGRAFICA DE CULTIVOS ANDINOS Y EL USO DE LA PERCEPCION REMOTA EN CUSCO, PERU*

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Generalidades

La diversidad biológica se ha visto amenazada por la rápida eliminación de vastas extensiones de vegetación natural, así como por la substitución de cultivos agrícolas tradicionales por los llamados cultivos "modernos". Esta situación se ha observado sobre todo el mundo pero se ha hecho evidente en las últimas décadas en los países del Tercer Mundo, debido especialmente a su necesidad de desarrollo económico.

Es la substitución de la gran diversidad de cultivos tradicionales por una pequeña variedad de cultivos agrícolas modernos la que nos ocupa en ésta presentación. De las 7,000 especies de plantas de las cuales la humanidad ha dependido para su substento a través de la historia, la gran mayoría de la alimentación humana hoy en día proviene de menos de dos docenas de plantas. Posiblemente más de la mitad proviene de trigo, arroz, maíz , papa, cebada, papa dulce y yuca (casava) . Esta substitución ha causado un detrimento en la extensión de cultivos tradicionales con la consecuente posibilidad de , sino de extinción, al menos de una fuerte pérdida del material genético que dió lugar a los presentes cultivos "modernos". Los cultivos tradicionales representan una fuente valiosa de diversidad genética, cuya desaparación sería catastrófica para la humanidad.

La situación actual de una base genética restringida es extremadamente seria, especialmente debido a las poblaciones crecientes y las carestías de alimentos que se experimentan en los paises en desarrollo. Baste recordar la catástrofe experimentada por los irlandeses en los años 1840s. Los cultivos de papas en Irlanda provenían de una sola variedad, originalmente traida del Perú por los españoles. Prácticamente todas las papas irlandesas eran idénticas genéticamente. Cualquier enfermedad que afectara una planta afectaría a todos los cultivos de papa en Irlanda; lel atacaque de roña que ocurrió se extendió rápidamente por todos los cultivos. La hambruna causada por la roña en Irlanda causó por lo menos un millón de muertos.

Esta clase de problema agrícola aparece más serio en los países en desarrollo, donde la carestía de alimentos y la falta de defensa contra epidemias agrícolas los hace más vulnerables. La tendencia a los monocultivos y a la substitución de cultivos por variedades de alto rendimiento (y de alta demanda de insumos agrícolas), la llamada

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1* El presente artículo se basa en trabajos preliminares del TAC y del Centro de Investigación de Cultivos Andinos de Cusco, Perú. Los trabajos se realizan bajo los auspicios del Programa de Cooperación de Ciencia y Tecnología, Oficina del Consejero en Ciencias de la USAID.

Revolución Verde, ha causado la desaparición de parte de la riqueza genética de los paises en desarrollo. La paradoja es que los cultivos "modernos" están siendo amenazados por su mismo éxito en extenderse y en substituir a los tradicionales; la pérdida del material genético original puede acarrear el deterioro y la eventual extinción de los cultivos "modernos".

La combinación genética de las variedades agrícolas actuales se basa en los esfuerzos de milenios de los agricultores tradicionales , una población restringida casi exclusivamente a los paises en desarrollo. Hoy parece posible que la herencia genética de miles de años de experimentación en el Valle Sagrado de los Incas pueda desaparecer en el desayuno de una sola persona.

Lo anterior hace imperante la identificación y localización de los cultivos tradicionales, dondequiera que ellos se encuentren. El objetivo del presente esfuerzo del TAC y del Centro de Investigación de Cultivos Andinos de Cusco es precisamente la caracterización ecogeográfica de varios cultivos de la región Andina del Departamento de Cusco en Perú. Una vez que estos cultivos han sido caracterizados es posible iniciar su protección, manejo, introducción a áreas ecológicamente símiles, o su re-introducción a aquellas áreas donde otrora existían.

Metodología

Una de las regiones más ricas en diversidad genética y foco de cultivos agrícolas tradicionales es la región Andina del Perú. Es en ésta región donde los Incas desarrollaron una de las civilizaciones más ricas en términos de manejo del agua, del suelo y de los cultivos agrícolas. Esta región se caracteriza por sus numerosos micro-medios ambientes, causados por diferencias altitudinales significativas sobre distancias relativamente cortas. En estos micro-medios ambientes se han desarrollado variedades genéticas de un mismo cultivo tradicional. Esta región es de terreno muy quebrado, de difícil acceso y en donde las técnicas de percepción remota pueden ser de gran ayuda.

Varios cultivos han sido seleccionados dentro de ésta región para su caracterización ecogeográfica. Las razones de su selección son múltiples y variadas, pero dos aparecen como las más importante: (1) son cultivos que en su mayor parte datan de épocas de antes de la llegada de los españoles a América y fueron muy importantes en la dieta de los Incas, y (2) varios de ellos han caido en desuso y existe la posibilidad de su extinción o al menos de pérdida de algunas de las variedades que contribuyen a su diversidad genética.

Los cultivos seleccionados para su estudio son:

* Olluco (Ollucus tuberosa) es un tubérculo poco conocido fuera de su medio ambiente pero aún bastante importante en las regiones Andinas El olluco es una papa pequeña de diversos colores, bastante resistente a plagas y enfermedades y a heladas. La planta prefiere suelos húmedos.

* Tarwi (Lupinus mutabillis) es un garbanzo o haba que produce una flor de color violeta de una belleza muy especial. El fruto verde es de sabor muy amargo pero posee casi 40 porciento de proteína y 20 porciento de aceites. Su potencial está en su alto contenido de aceite lo que lo ha hecho una de las oleaginosas más importantes en el mundo. La necesidad es de conservar tantas variedades de la planta como sea posible.

* Oca (Oxalis tuberosa) es otra tuberosa, de gran importancia en toda la región Andina. Es una planta de una resistencia excepcional que puede crecer a más de 4,000 m de altura. Los tubérculos de la oca son de sabor dulce y un tanto ácido. Su potencial está en la posibilidad de ser cultivada en las zonas templadas del resto del mundo.

* Kiwicha (Amaranthus caudatus) es una planta de hoja ancha productora de un grano. De crecimiento rápido, se adapta rápidamente a nuevos medios, es resistente a las sequías y pestes. Se le cultiva en pequeñas parcelas en los Andes, pero un programa reciente (Programa Nacional de la Kiwicha) ha tratado de establecerla en grandes plantaciones y a una escala más amplia. Su porcentaje proteíco es muy elevado así como también su contenido del aminoácido lisina. La kiwicha parece haber sido una super-planta para los Incas (segunda solo a la quinoa) por su valor nutritivo y puede convertirse de nuevo en la respuesta alimentaria de regiones de suelos pobres.

* Quinoa (Chenopodium quinoa) es otra planta de hoja ancha productora de un grano parecido al de la Kiwicha. Puede crecer a más de 4,000 m de altura en suelos secos y congelados del Altiplano Boliviano-Peruano. La quinoa era aún más importante que la kiwicha para los Incas y hoy todavía se cultiva extensa e intensivamente. Su textura es parecida a la del arroz y se prepara de la misma manera. La quinoa contiene 19 porciento de proteína, esto es más de 50 porciento que el trigo, arroz o maíz. Su valor nutricional es tan alto que sirve como substituto de la carne.

* Añu (Tropaeolum tuberosum) es un tubérculo parecido al de la oca que parece haber sido utilizado por los Incas como inhibidor del líbido sexual. Información de terreno lo pone en vías de extinción; se siembra en áreas muy pequeñas, esporádicamente y normalmente mezclado con oca y/u olluco.

El área seleccionada para el presente estudio se encuentra en el Departamento del Cusco, en la parte alta del Centro-Sur peruano. Esta área pertenece a la Cordillera Oriental peruana y se puede considerar como una extensión del Altiplano Boliviano-Peruano. El área de estudio se centra en la antigua capital del Imperio Inca, Cusco. En Cusco se encuentra la Universidad Nacional San Antonio Abad del Cusco (UNSAAC) con su Centro de Investigación de Cultivos Andinos, y el Programa Nacional de Investigación Amaranthus.

Tomando como centro a la ciudad de Cusco se determinaron varias sub-areas de estudio dentro de las cuales se localizaron los cultivos seleccionados. Las sub-áreas escogidas fueron Kayra, Corao, Pisaq y Chincheros. El area general de estudio y las sub-áreas se muestran en la Figura 1.

En los cultivares ubicados en el terreno se toman varias mediciones con un radíometro. El radíometro es tal que los sensores del mismo obtienen información sobre las mismas bandas espectrales de los sensores de los dos satélites de los cuales se obtendrán imágenes: Landsat y SPOT.

En cada cultivo/muestra , además de los datos radiométricos, se obtienen datos sobre la altura sobre el nivel del mar, la hora del día, las condiciones ambientales (soleado o nublado), la altura del cultivo, la distancia entre plantas, la distancia entre franjas (si el cultivar es en franjas), el estado fitosanitario, y la madurez aproximada del mismo.

Una vez localizado el cultivo/muestra y tomadas las mediciones radiométricas se procede a ubicarlo en la fotografía aérea existente. También es necesario obtener toda

la información cartográfica, ecológica, de suelos, geológica, datos de precipitación, uso/cobertura del suelo, etc.

En este caso en particular fué necesario obtener las imágenes de satélite más recientes. Para ello se comisionó la toma de imágenes por Landsat TM y por SPOT, dando a las dos compañías ciertos parámetros de calidad. Las dos compañías son EOSAT para el Landsat TM y SPOT Image Corporation para SPOT.

Resultados

Se obtuvo información en el terreno de un total de 12 cultivos/muestras: uno en la sub-área Kayra, cinco en la sub-área Chincheros, cuatro en la sub-área Pisaq y dos en la sub-área Corao. La localización de estas sub-áreas se indican en la Figura 1. En la Tabla 1 se presentan los cultivos/muestras donde se obtuvieron los datos.

En cada una de estos cultivos/muestras se obtuvo una serie de mediciones radiométricas utilizando el radíometro Exotech, Modelo 100AX. Este instrumento observa el objeto en cuatro bandas del espectro electromagnético: banda 1, de 450 a 520 nm; banda 2 , de 520 a 600 nm; banda 3, de 630 a 690 nm, y banda 4 de 760 a 900 nm. Estas bandas coinciden con las regiones espectrales cubiertas por los sistemas de Landsat y SPOT.

Imágenes de los satélites Landsat y SPOT fueron comisionadas durante la misma época en la cual se tomaron los datos de terreno. La razón es poder comparar datos de satélite y de terreno contemporáneos. Desafortunadamente, solo SPOT obtuvo datos sobre el área durante las fechas aproximadas solicitadas. No información fué obtenida por el sistema Landsat. Los datos de terreno se obtuvieron entre el 22 de Abril y el 3 de Mayo de éste año. Es aproximadamente en ésta época cuando los cultivos seleccionados llegan a su madurez y comienzan a ser recolectados, aunque la recolección no termina hasta fines de Mayo o principios de Junio.

La imágen SPOT que se pudo obtener con cero porciento de nubosidad y una alta calidad radiométrica fué tomada el 6 de Junio. Para ésta época ,casi todos los cultivos habían sido recolectados. Esto significó que no se pudo obtener una correlación directa entre los datos radiométricos de terreno y de satélite de los cultivos/muestras. Sinembargo, fué posible analizar la imágen con los datos adicionales que se obtuvieron en el terreno.

Una otra consideración en la utilización de imágenes de alta resolución espacial fué la de determinar si los cultivos en cuestión podían ser detectados dadas sus dimensiones, casi siempre pequeñas. Como se observa en la Tabla 1, el area mínima observada en el terreno fué de 0.07 ha. El área mínima posible, teóricamente, observable con el sistema SPOT es de 0.04 ha (20m de resolución en el modo multiespectral) o de 0.01 ha (10m de resolución en el modo pancromático). Esto significa que teóricamente es posible "resolver" los cultivos/muestras obtenidos.

El análisis preliminar indica que ésto es posible, especialmente en las sub-áreas de Pisaq y Kayra. Los resultados que aquí se presentan se basan más que todo en el análisis de la sub-área Pisaq. Dentro de ésta región se pudo ubicar un cultivo de alfalfa, que sirvió de base para nuestras correcciones radiométricas y calibración de todas las bandas espectrales.

La interpretación de la imágen se hizo utilizando el paquete de análisis de imágenes ELAS del TAC. Con éste paquete es posible corregir radiométrica y geométricamente la imágen, al mismo tiempo que se convierte el sistema de coordenadas de la imágen a la proyección UTM, la cual se utiliza en el Perú. Esto nos permite más tarde la sobreposición de la información digital de satélite con la de un sistema de información geográfrica (SIG). El SIG que se maneja en TAC es el ARC/INFO que nos servirá para manipular toda la información cartográfica, geológica, ecológica, de suelos, de cobertura, de precipitación, etc. que ha sido previamente digitalizada. Esta sobreposición de información nos dará como resultado la caracterización ecogeográfica de los cultivos Andinos.

Con el paquete ELAS se procedió a una interpretación automática no supervisada. Esta clasificación arrojó un total de 52 clases espectrales. El significado de estas clases no es totalmente claro, excepto que cada una tiene una reflectancia diferente. Existe la necesidad de agrupar éstas clases en un número menor y que tenga un significado basado en la realidad de terreno. Experiencias anteriores indican que la correlación entre las reflectancias de las bandas espectrales del rojo y el infra-rojo cercano (bandas 2 y 3 del SPOT) sirven como indicadores de la cobertura vegetal del suelo (o contrariamente, la ausencia de cubierta vegetal). Esto se muestra gráficamente en la Figura 2.

La Figura 3 muestra las 52 clases espectrales resultado de la clasificación no supervisada. Basados en lo expuesto en la Figura 2 y en los datos y experiencias de terreno, se agruparon las 52 clases en las 16 clases que se muestran en la Figura 4 y se describen en la Tabla 2. La imágen clasificada a colores se muestra en la exhibición de TAC en ésta reunión de SELPER.

Es coveniente anotar que el resultado presentado en la Tabla 2 es una clasificación no supervisada controlada. Esto significa que luego de la primera aproximación de clasificación no supervisada se controla ésta para producir clases de significado más definitivo. Esto es, se controla la clasificación no supervisada.

Experiencias anteriores indican que la combinación del modo multiespectral con el modo pancromático de SPOT dá como resultado una imágen de resolución intermedia entre las dos componentes; la resultante tiene una mejor resolución que la componente multiespectral de 20m. Esto se hizo evidente durante el procesamiento de los datos y se procedió a combinar las dos resoluciones; se produjo una compuesta a falso color (CFC) combinando las bandas 1 y 3 con el modo pancromático. La CFC resultante se asemeja a una foto a color infra-roja, aunque no es exactamente lo mismo. La banda 1 se registra en azul, el modo pancromático en verde y la banda 3 en rojo. Este producto presenta una obvia alta resolución, necesaria y útil durante la sobreposición de informacioón del ELAS al ARC/INFO. En la exhibición de TAC en el congreso se presenta el producto resultante de la combinación descrita, mostrando la ciudad de Cusco y alrededores.

Conclusiones

Los análisis preliminares nos permiten concluir lo siguiente:
(1) La resolución espacial del sistema SPOT es suficiente para localizar cultivos tradicionales de dimensiones relativamente pequeñas.
(2) Es posible observar varias clases diferentes de cultivos agrícolas y de vegetación de baja, mediana y alta densidad.

(3) La resolución espectral del sistema SPOT parece que no es lo suficientemente amplia para detectar la variedad de posibles combinaciones ecogeográficas de cultivos. Posiblemente el uso de TM, con una resolución espectral mucho más alta, sea conveniente.
(4) La combinación de modos del sistema SPOT permite el fácil registro de coordenadas y la eventual sobreposición de datos de satélite con datos de un SIG. El producto resultante parece más que adecuado para la actualización de vías de comunicación de la ciudad de Cusco y alrededores.

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Cultivo/Muestra	No.	Fecha	Localidad	Sub-área	Altitud(m)	Area (m2)
Olluco	1	22Abr88	Corimarca	Chincheros	3,750	4,216
Quinoa	2	25Abr88	Corao	Corao	3,400	2,618
Quinoa	3	25Abr88	Corao	Corao	3,400	2,275
Kiwicha	4	25Abr88	Tancarpata	Pisaq	2,960	8,430
Tarwi	5	26Abr88	Huaillarcocha	Chincheros	3,650	3,864
Kiwicha	6	26Abr88	Est. Kayra	Kayra	3,300	12,802
Oca	7	27Abr88	Chincheros	Chincheros	3,800	1,064
Quinoa	8	29Abr88	Calca	Pisaq	2,920	4,312
Quinoa	9	30Abr88	Calca	Pisaq	2,930	7,980
Añu	10	30Abr88	Chincheros	Chincheros	3,700	697
Tarwi	11	2May88	Pisaq	Pisaq	3,000	5,600
Olluco	12	3May88	Corimarca	Chincheros	3,750	4,140

Tabla 1. Cultivos/Muestras obtenidos en el terreno.

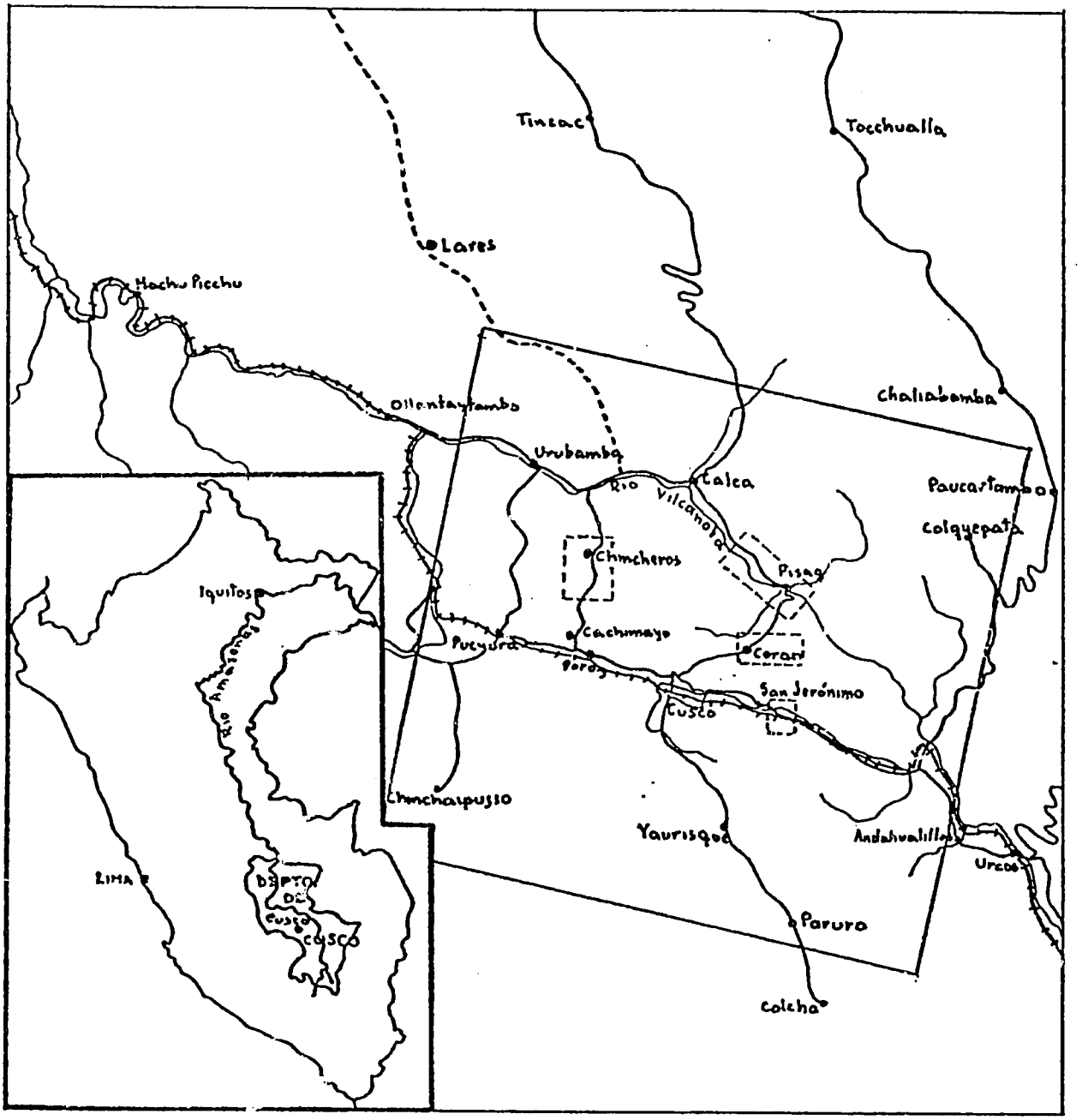

Figura 1. Localización de área y sub-áreas de estudio.

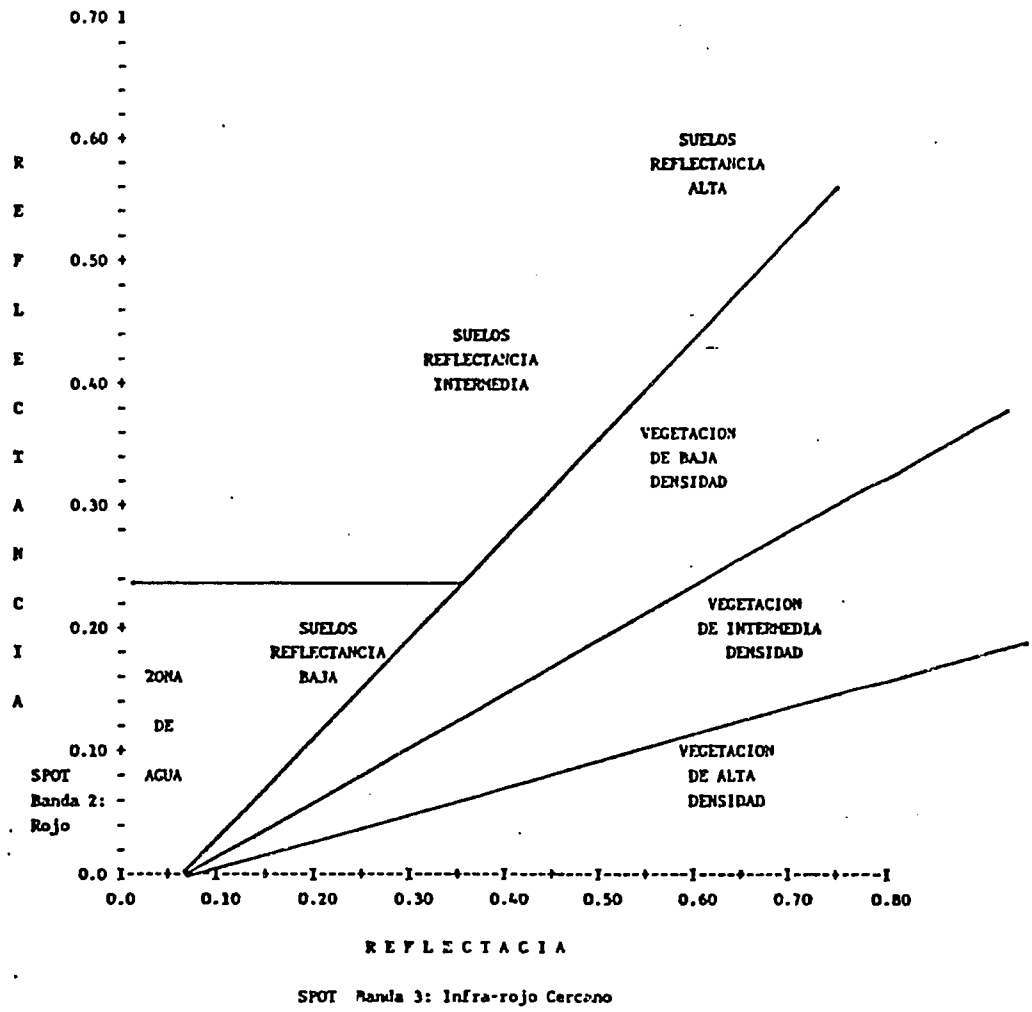

Figura 2. Definición de clases en función de la relación rojo/infra-rojo.

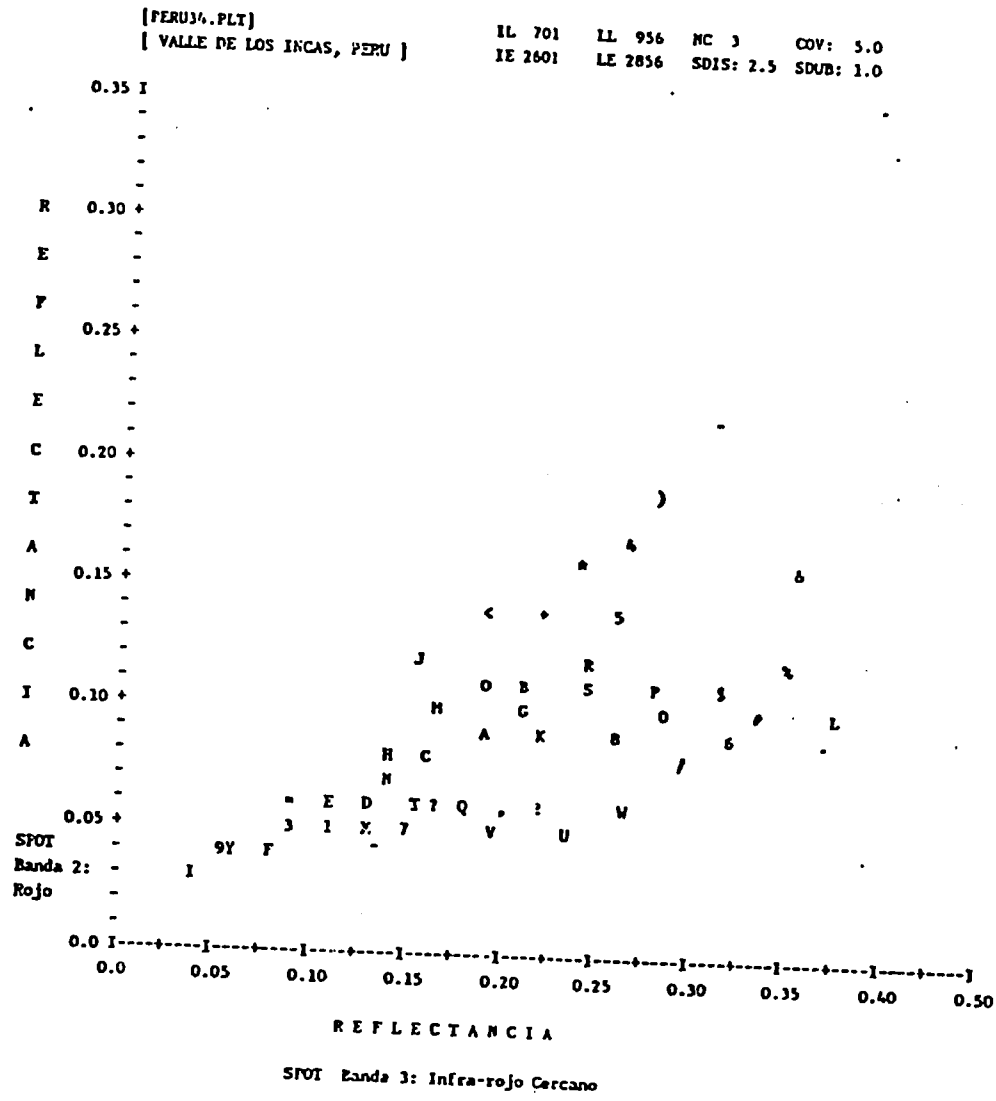

Figura 3. Clasificación no supervisada de datos SPOT. Las bandas corresponden a la Banda 2 (610nm - 680nm) del rojo y Banda 3 (790nm - 890nm) del infra-rojo cercano.

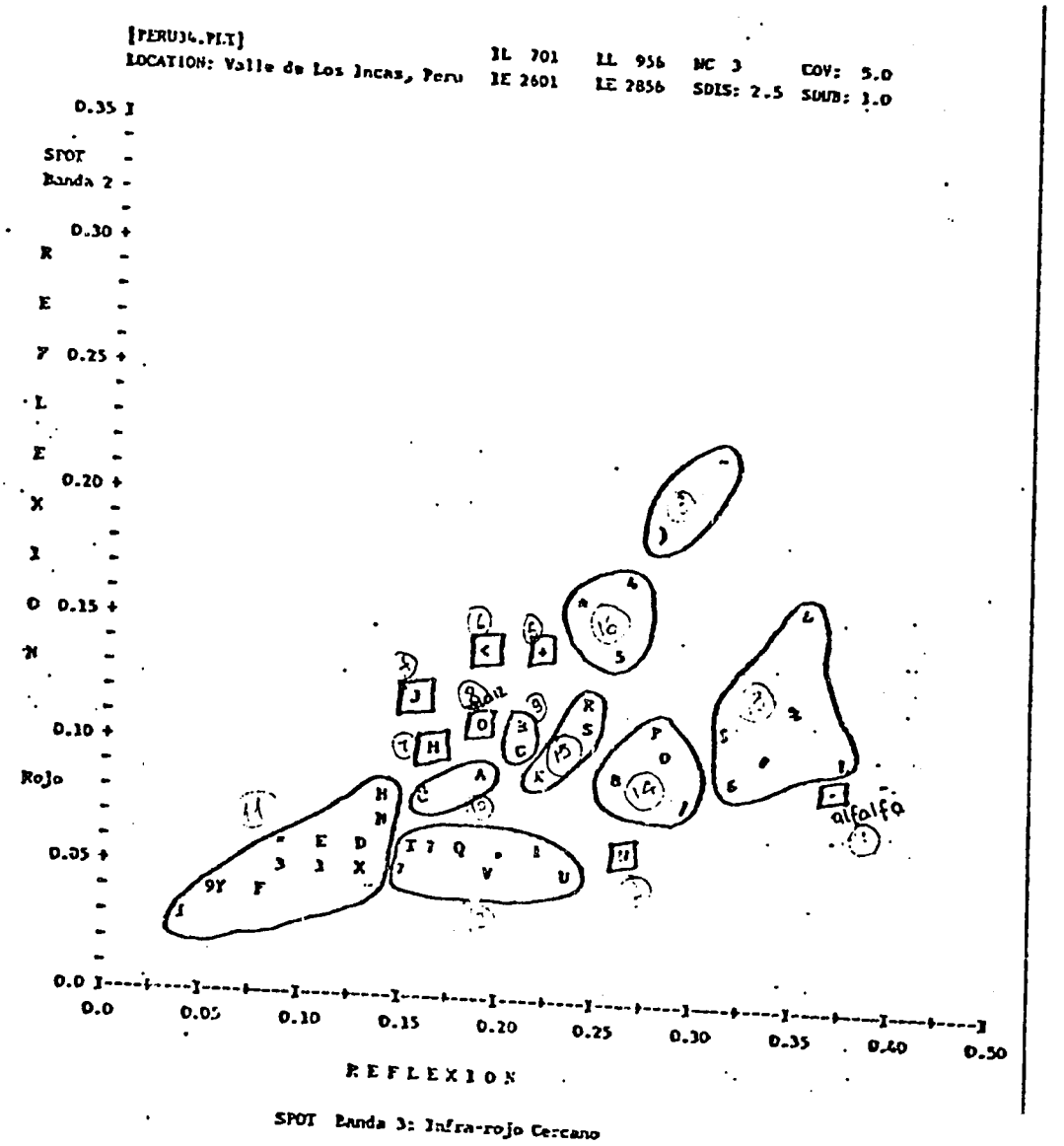

Figura 4. Agrupación de clases resultantes de la clasificación de datos SPOT.

	[CLASE] No./Symbol	[DESCRIPCION]	[AREA] (m2)	[REFLEXION] (SPOT2) ROJO	(SPOT3) IR CERCANO
1	46 / .	Cultivo agricola (Alfalfa) Vegetacion de alta densidad.	2540.0	.0879	.3691
2	23 / W	Area boscosa. Vegetacion de alta densidad.	5660.0	.0621	.2647
3	41 / - 40 /)	Campo agricola sin cultivos. Suelos arenoso desnudo. Reflectancia intermedia.	1100.0	.2255	.3119
4	10 / J	Campo agricula sin cultivos. Suelos humedo, possiblemente arcilloso. Reflectancia baja.	16840.0	.1164	.1547
5	38 / +	Cubierta vegetal baja. Suelos de reflectancia intermedia.	25380.0	.1378	.2205
6	53 / <	Areas agricolas. Suelos desnudos de reflectancia intermedia.	10720.0	.1449	.1904
7	13 / M	Areas agricolas irrigadas. Suelos humedos de reflectancia baja.	68800.0	.0971	.1652
8	15 / O	Areas agricolas, cultivos de maize parcialmente recolectados. Cobierta vegetal baja.	119360.0	.1085	.1883
9	2 / B 7 / G	Cubierta vegetal baja.	143720.0	.1156 .1031	.2126 .2129
10	1 / A 3 / C	Cubierta vegetal baja y intermedia.	242700.0	.0909 .0345	.1873 .1609
11	8 / H 14 / N 4 / D 24 / X 5 / E 27 / 1 29 / 3 43 / = 6 / F 25 / Y 35 / 9 9 / I	Cubierta vegetal baja a intermedia. Arboles y matorrales de regiones alta.	41450.0	.0844 .0762 .0626 .0524 .0571 .0460 .0473 .0566 .0429 .0444 .0348 .0327	.1396 .1376 .1316 .1290 .1099 .1069 .0913 .0877 .0825 .0613 .0537 .0367

Tabla 2. Clases resultantes de la clasificación no supervisada (controlada).

12	20 / T	Cubierta vegetal intermedia a alta.	86260.0	.0614	.1550
	17 / Q	Preponderantemente plantaciones de		.0631	.1797
	52 / 7	Eucaliptos.		.0554	.1656
	33 / 7			.0460	.1512
	26 / ¨			.0406	.1333
	36 / ,			.0558	.1984
	48 / 1			.0619	.2227
	22 / V			.0455	.1935
	21 / U			.0489	.2345
13	51 / &	Cubierta vegetal intermedia a alta.	2480.0	.1643	.3530
	45 / $	Areas agricolas pequenas (Cebada).		.1116	.3159
	50 / %			.1193	.3512
	49 / #			.0991	.3325
	12 / L			.1036	.3727
	32 / 6			.0899	.3191
14	16 / P	Cubierta vegetal intermedia. Areas	25300.0	.1132	.2700
	42 / 0	agricolas pequenas.		.0981	.2833
	34 / 8			.0916	.2597
	47 / /			.0815	.2933
15	18 / R	Cubierta vegetal intermedia. Campos	114600.0	.1207	.2440
	19 / S	agricolas en terrazas.		.1062	.2458
	11 / K			.0917	.2188
16	39 / *	Vegetacion agricola de densidad baja.	14920.0	.1551	.2401
	30 / 4			.1677	.2649
	31 / 5			.1392	.2595

Tabla 2. (Cont.)

BALTIMORE

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1991 ACSM-ASPRS
ANNUAL CONVENTION

Volume 3
Remote Sensing

DROUGHT EFFECTS ON LAND USE AND LAND COVER IN CUSCO, PERU[1]

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ABSTRACT

Satellite data were examined to obtain information about changes of agricultural areas between 1988 and 1990 in a region centered around Cusco, Peru. The changes sought were those caused by the drought conditions and early and severe frost experienced in the area during the crop season 1989-1990 (September-November to April-May). Atmospheric and radiometric corrections were applied to Spot May 1988 and 1990 data and to Landsat TM 1990 data. These data were then used to produce Normalized Difference Vegetation Indices (NDVIs) for 1988 and 1990, and to examine the thermal data of TM Channel 6.

The comparison of NDVIs from Spot 1988 and 1990 clearly demonstrated a change of average reflectivity and thus of green vegetation. The vegetation decrease was not as clear when comparing Spot 1988 and Landsat TM 1990, but was nonetheless demonstrable. Visual and statistical comparison of Landsat TM Channel 6 (thermal data) to NDVIs for 1990 established only a general similarity that need to be further studied. Based on the sampled area, the studied region experienced a decrease of green vegetation from 18 to 23 percent between 1988 and 1990. This decrease can be atributed to drought and early frost conditions reported by NOAA's Climate Analysis Center for the weather station in Cusco.

INTRODUCTION

This paper is part of an on-going research project that the Technology Application Center (TAC) initiated in 1988 to eco-geographically characterize ancient Inca agricultural crops using remote sensing techniques and geographic information systems. The ultimate aim of the research is to contribute to the protection and preservation of genetic diversity of native agricultural systems.

Satellite images obtained over an area in the Department of Cusco, Peru, in May 1988 and 1990 were used in this study. No data for 1989 were possible because of adverse climatic conditions and unusual high cloud cover. At the same time, field radiometric data were obtained; the chosen date for imagery and radiometric data acquisition was the end of the agricultural season, which is in April-May in the region.

During the 1989-1990 agricultural crop season (September-November to April-May) drought and early and severe frost conditions occurred in the Andes region, from Ecuador to northern Bolivia. These conditions

[1]This research was supported under Grant No. DPE-5542-G-SS-8060, Program in Science and Technology Cooperation, Office of the Science Advisor, U.S. Agency for International Development.

caused serious losses of production and extensive damage to agricultural areas in the highlands of Peru, including the Deparment of Cusco (El Comercio, 1990). The particular prevalent weather conditions of the area in April-May 1990 allowed the acquisition of almost cloud-free imagery by the Landsat and Spot system that TAC had requested. This offered a window of opportunity to study the effects of these drought conditions on the agricultural areas of a region centered around Cusco, ancient capital of the Inca Civilization. The objective was to detect agricultural area (no major forested areas exist in the studied area) changes between 1988 and 1990 using satellite imagery and digital analysis techniques.

METHODOLOGY

The April-May 1990 visit to the study area made evident earlier reports by the Peruvian researchers that drought conditions were severe and had disrupted agricultural production in the region (Sumar, 1990). These reports were confirmed by the data collected over several weather stations in Peru and reported by the Climate Analysis Center of the National Oceanic and Atmospheric Administration (NOAA). NOAA's data for Cusco station (elevation: 3,248 m) indicated a decrease of 96 mm of precipitation over the normal of 261 mm during the period September to December 1989, dates during which agricultural crops should receive sufficient rain for full development (NOAA, 1990; Sumar, 1990). Similar conditions were reported for the station at Juliaca (elevation: 3,824 m) and Ayacucho (elevation: 2,762 m). Compounding the decrease in precipitation, the Cusco region also experienced early and severe frost during the same period (average mimimum, 5.8°C; period average minimum, 1.7°C) (NOAA,1990).

By early June 1990 TAC had obtained satellite imagery covering the region for 12 May 1988 (Spot), 2 May 1990 (Spot) and 3 May 1990 (Landsat Thematic Mapper, TM) data. These data were atmospherically corrected using the Lowtran 6 correction package as updated by TAC (Campos-Marquetti, 1990). A geometric correction was also performed on these data using a grid of control points obtained from 1/10,000, 1/50,000 and 1/100,000 maps produced by Peru's Geographic Institute. Additionally, the TM data (28.5 m resolution) were rotated and resampled to 20 m resolution to be able to overlay over the Spot multispectral data (20 m resolution). These data had been and are being used to detect several Inca crops and part of this work is included here (Rodriguez-Bejarano and Campos-Marquetti, 1988; Rodriguez-Bejarano, 1990).

The Normalized Difference Vegetation Index (NDVI) has been widely used to monitor vegetation conditions and detect changes caused, among other things, by drought (Jensen, 1986; LeCompte, 1989). An NDVI consists of ratioing a visible band and a near infrared band of a sensing system. Usually the red and near infrared bands of NOAA's AVHRR, Landsat MSS and TM, and Spot satellites are used. We used the ratio (Near Infrared - Red)/(Near Infrared + Red); for the TM data this corresponded to (Ch4 - Ch3)/(Ch4 + Ch3), and for the Spot data this corresponded to (Ch3 - Ch2)/(Ch3 + Ch2).

The Landsat TM data offered the added advantage of a thermal band (Ch6) and it was decided to use it to compare to the NDVIs generated from the other data. Since drought and frost cause vegetation stress, then the apparent soil temperature data measured by Ch6 could be correlated to surface cover in agricultural areas, especially during the drought conditions experienced in the Cusco region.

RESULTS AND DISCUSSION

Three NDVIs for 1988 and 1990 were obtained from the two Spot and one TM sub-images, covering 1200 x 1500 pixels. Their histograms and frequency distributions are presented in Figures 1 to 3 and Tables 1 to 3. The reflectance values (Value column) indicate that a zero (0) corresponds to an area with little or no vegetation cover (witness the water bodies and relief/cloud shadows), while the highest values 37 or 41 represent areas with plenty of green vegetation (witness the irrigated plots along the Vilcanota river and the grassy area around Cusco's International airport). The cummulative percentage (Cum. Percent column) indicates the area (number of pixels) covered by the reflectance values.

The comparison of Spot 1988 and 1990 NDVIs clearly shows that there was a radical change in vegetative cover over the study region. The 12 May 1988 NDVI indicates a mean reflectance value of 19.8; values above or below this figure reflect more or less vegetative cover in 1988. The cummulative percentage below this value is 33 percent, indicating that at least 67 percent of the area was covered with green vegetation in 1988.

The 2 May 1990 NDVI indicates a mean reflectance value of 16.1, with a cummulative percentage at or below 56 percent, indicating that at least 44 percent of the area was covered with green vegetation in 1990. That is, a decrease of 23 percent over the two dates. It is important to also indicate that the 12 May 1988 date is two weeks <u>later</u> than the 2 May 1990 date. The later the date the more harvest has occurred; most likely on 12 May 1988 more area had been harvested than on 2 May 1990. That is, more green vegetation would have appeared on a 2 May 1988 image than on a 12 May date.

The 3 May 1990 NDVI from Landsat TM showed similar patterns as that from Spot 1990. The mean reflectance was, though, 24.3, a bit higher than the "best" year of 1988. The cummulative percentage at or below this figure tells us, however, that 51 percent of the region had a low green vegetation cover. It could be argued then that 49 percent was covered with a green vegetative cover in 1990 as compared to 67 percent in 1988.

The visual comparison of the TM thermal data and the TM NDVI indicated a striking similarity of soil temperature and vegetative cover. The minimum and maximum values were the same but cummulative percentages disagreed slightly. Fifty three percent of the area was at or below the mean reflectance as compared to 51 percent for the NDVI. This difference and the presence of several "spikes" in the Ch6 histogram were not clear and warrant further analysis. The thermal data histogram and frequency values appear in Figure 4 and Table 4.

CONCLUDING REMARKS

This analysis showed the impact of drought and frost conditions in the region centered around the city of Cusco. The studied region showed a decreased of at least 18 to 23 percent in agricultural area between 1988 and 1990. It is possible to estimate agricultural vegetation changes using satellite imagery and do it on near real-time basis.

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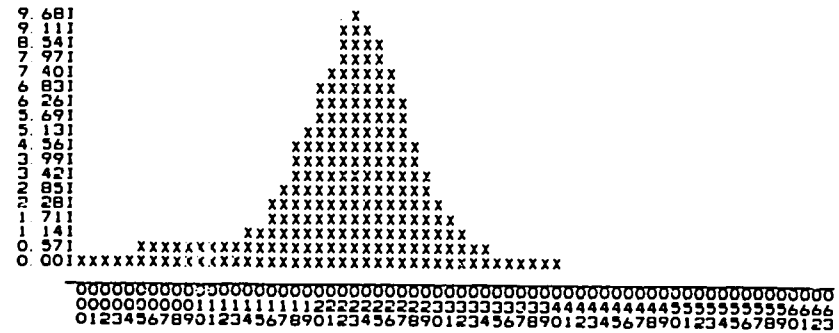

Figure 1. NDVI of 1988 Spot Image

FREQUENCY DISTRIBUTION

VALUE	FREQ	PERCENT	CUM PERCENT
0	64501	13.334	13.334
1	2	0.000	13.334
2	20	0.004	13.338
3	123	0.025	13.364
4	441	0.091	13.455
5	1129	0.233	13.688
6	2024	0.418	14.106
7	1320	0.273	14.379
8	3186	0.659	15.038
9	1927	0.398	15.436
10	1376	0.284	15.721
11	1763	0.364	16.085
12	1824	0.377	16.462
13	2988	0.618	17.080
14	2589	0.535	17.615
15	3906	0.807	18.423
16	4196	0.867	19.290
17	8603	1.778	21.068
18	15409	3.185	24.254
19	19470	4.025	28.279
20	25896	5.353	33.632
21	38093	7.875	41.506
22	43086	8.907	50.413
23	42628	8.812	59.225
24	44858	9.273	68.498
25	40560	8.385	76.882
26	31349	6.480	83.363
27	23734	4.906	88.269
28	17429	3.603	91.872
29	14307	2.958	94.830
30	9774	2.020	96.850
31	7230	1.495	98.345
32	3965	0.820	99.164
33	1973	0.408	99.572
34	1180	0.244	99.816
35	525	0.109	99.925
36	223	0.046	99.971
37	87	0.018	99.989
38	40	0.008	99.997
39	11	0.002	99.999
40	5	0.001	100.000

MEAN FOR CHANNEL 1 IS 19.841391
STANDARD DEVIATION IS 8.943177
TOTAL NO OF POINTS SAMPLED = 483749
MINIMUM VALUE = 0.00
MAXIMUM VALUE = 40.00

Table 1. Frequency Distribution for 1988 Spot

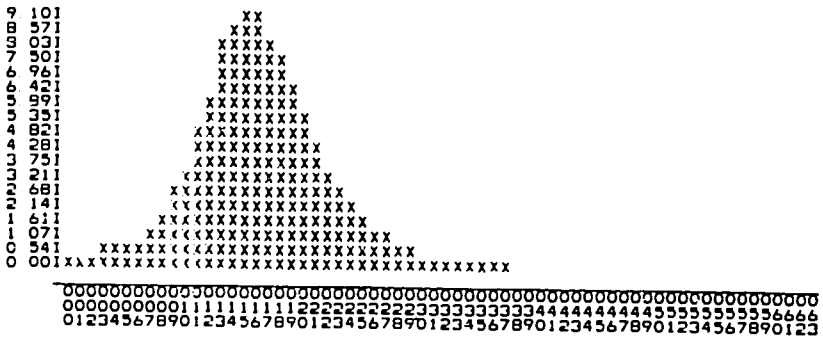

Figure 2. NDVI of 1990 Spot Image

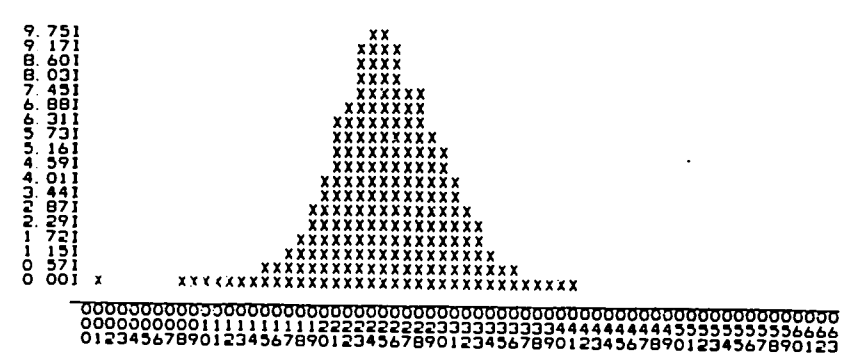

Figure 3. NDVI of 1990 Landsat TM Image

FREQUENCY DISTRIBUTION

VALUE	FREQ	PERCENT	CUM. PERCENT
0	417	0.086	0.086
1	401	0.083	0.168
2	798	0.164	0.333
3	1358	0.280	0.612
4	1860	0.383	0.995
5	2382	0.490	1.486
6	3341	0.688	2.174
7	4957	1.021	3.194
8	8554	1.761	4.955
9	12037	2.478	7.434
10	16698	3.438	10.872
11	22460	4.624	15.496
12	27603	5.683	21.180
13	37799	7.783	28.962
14	41646	8.575	37.537
15	43822	9.023	46.560
16	44206	9.102	55.662
17	38841	7.997	63.659
18	35514	7.333	70.991
19	30334	6.246	77.237
20	25057	5.159	82.396
21	20274	4.174	86.570
22	16734	3.445	90.016
23	13409	2.761	92.777
24	10396	2.140	94.917
25	7770	1.600	96.517
26	5679	1.169	97.686
27	4099	0.844	98.530
28	2853	0.587	99.118
29	1814	0.373	99.491
30	1138	0.234	99.726
31	685	0.141	99.867
32	372	0.077	99.943
33	173	0.036	99.979
34	61	0.013	99.991
35	29	0.006	99.997
36	10	0.002	99.999
37	4	0.001	100.000

MEAN FOR CHANNEL 1 IS 16.128899
STANDARD DEVIATION IS 4.868446
TOTAL NO OF POINTS SAMPLED = 485684
MINIMUM VALUE = 0.00
MAXIMUM VALUE = 37.00

Table 2. Frequency Distribution for 1990 Spot

FREQUENCY DISTRIBUTION

VALUE	FREQ	PERCENT	CUM PERCENT
1	1	0.000	0.000
3	2	0.000	0.001
5	174	0.036	0.037
6	581	0.120	0.157
7	839	0.173	0.330
8	996	0.206	0.536
9	1044	0.216	0.752
10	1458	0.301	1.053
11	2042	0.422	1.475
12	2338	0.483	1.959
13	2829	0.585	2.543
14	3229	0.667	3.211
15	3784	0.782	3.993
16	5152	1.065	5.058
17	7062	1.460	6.518
18	12125	2.506	9.025
19	15793	3.265	12.289
20	21570	4.459	16.748
21	31869	6.588	23.336
22	34777	7.189	30.525
23	48019	9.926	40.452
24	49626	10.259	50.710
25	47227	9.763	60.473
26	43046	8.898	69.371
27	35474	7.333	76.704
28	30933	6.394	83.099
29	22879	4.730	87.828
30	19350	4.000	91.828
31	13916	2.877	94.705
32	10283	2.126	96.831
33	6911	1.408	98.239
34	4159	0.860	99.099
35	2394	0.495	99.593
36	1152	0.238	99.832
37	532	0.110	99.942
38	215	0.044	99.986
39	54	0.011	99.997
40	14	0.003	100.000
41	1	0.000	100.000

MEAN FOR CHANNEL 1 IS 24.317677
STANDARD DEVIATION IS 4.712110
TOTAL NO OF POINTS SAMPLED = 483749
MINIMUM VALUE = 1.00
MAXIMUM VALUE = 41.00

Table 3. Frequency Distribution for 1990 Landsat TM

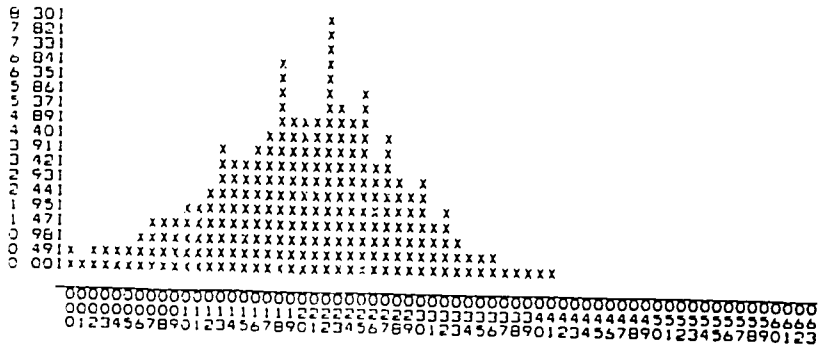

Figure 4. Landsat TM Channel 6

FREQUENCY DISTRIBUTION

VALUE	FREQ	PERCENT	CUM PERCENT
0	1673	0 346	0 346
1	769	0 159	0 505
2	859	0 178	0 682
3	1151	0 238	0 920
4	1638	0 339	1 259
5	2406	0 497	1 756
6	3767	0 779	2 535
7	5407	1 118	3 653
8	6514	1 347	5 020
9	7899	1 633	6 653
10	9899	2 046	8 699
11	11676	2 414	11 113
12	12726	2 631	13 743
13	21397	4 423	18 167
14	18251	3 773	21 939
15	19842	4 102	26 041
16	21872	4 521	30 563
17	23143	4 784	35 347
18	36641	7 574	42 921
19	24442	5 053	47 974
20	23232	4 802	52 776
21	23766	4 913	57 689
22	38211	7 899	65 588
23	24203	5 003	70 591
24	21127	4 367	74 959
25	27045	5 591	80 549
26	15671	3 239	83 789
27	19783	4 090	87 878
28	12040	2 489	90 367
29	9952	2 057	92 424
30	12428	2 569	94 993
31	6724	1 390	96 383
32	8023	1 659	98 042
33	3738	0 773	98 815
34	3174	0 656	99 471
35	1191	0 246	99 717
36	997	0 206	99 923
37	302	0 062	99 986
38	37	0 008	99 993
39	17	0 004	99 997
40	13	0 003	99 999
41	4	0 001	100 000

MEAN FOR CHANNEL 6 IS 19 762392
STANDARD DEVIATION IS 6 663575
TOTAL NO OF POINTS SAMPLED = 483749
MINIMUM VALUE = 0 00
MAXIMUM VALUE = 41 00

Table 4. Frequency Distribution for TM Channel 6

CLASIFICACION DIGITAL DE CULTIVOS TRADICIONALES INCAS EN LA REGION ANDINA DE CUSCO, PERU

Dario Rodriguez Bejarano
Tecnology Application Center
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Albuquerque, NM 87131-6031 - USA

Resúmen

La detección y clasificación de cultivos tradicionales Incas en la región Andina de Cusco se logró utilizando datos radiométricos de terreno, fotografía aérea existente, mapas topográficos e imágenes de satélite.

Se localizaron áreas con seis cultivos tradicionales Incas (kiwicha, quinoa, tarwi, oca, olluco y añu) en regiones cercanas a la Ciudad de Cusco. Los datos radiométricos de los cultivos se obtuvieron durante los períodos abril-mayo de 1988, 1989 y 1990, y su ubicación fué localizada sobre fotos y mapas del área. Imágenes de Spot y Landsat TM se obtuvieron el 12 de mayo de 1988 (Spot), 2 de mayo de 1990 (Spot) y 3 de mayo de 1990 (Landsat TM).

El análisis digital, clasificación de Máxima Similitud, arrojó una serie de clases espectrales que fueron luego aglomeradas (controladas) en diversas clases de uso agrícola: cultivos de kiwicha, de quinoa, de tarwi, de oca/olluco/añu/papa, de maíz, de trigo/alfalfa/avena/verduras, y otras áreas agrícolas. Tambien se obtuvieron varias clases de uso/cobertura del suelo: urbano/suelos desnudos o secos, suelos desnudos/secos, suelos húmedos desnudos, matorrales, arboledas, agua, sombras y nubes.

V SIMPOSIO LATINOAMERICANO DE PERCEPCION REMOTA

28 Oct. – 01 Nov. 1991
Cuzco–Peru

SELPER – CAPITULO PERUANO – Ap. Postal 4992, Lima – Peru, Tel. 410425–38 Fax 5114–414606

Lima 30 de Mayo de 1991

Drs
Dario Rodriguez Bejarano
Technology Application Center
University of New Mexico
Albulquerque, NM 87131-6031
U.S.A.

Estimado Colega:

En nombre del Comité Técnico del **5to Simposio Latinoamericano de Percepción Remota**, nos es grato comunicarle la aceptación de su trabajo"**CLASIFICACION DIGITAL DE CULTIVOS TRADICIONALES INCAS EN LA REGION ANDINA DEL CUSCO, PERU"**, para su presentación oral e inclusión en las memorias del Simposium. El Programa Preliminár le será enviado el proximo mes de Julio y en el se indicará la sesión y la hora de su presentación.

Adjunto a la presente, encontrará la hoja de instrucción para la presentación de su trabajo. Por favor, tenga a bien preparárlo de acuerdo a las indicaciones y remitirlo para que sea recibido hasta el **30 de Julio de 1991.** Los trabajos recibidos despues de esa fecha no serán incluidos en las memorias del Simposio Si tiene alguna consulta o desea información adicional,por favor comuníquese con los miembros del Comité Técnico o la Secretariá del Simposio.

Esperando tener un gran evento evento científico y deseando que disfrute del indescriptible misterio del Cusco, le agradecemos por su valiosa contribución.

Atentamente

Ing. Victor Barrena
Ing. Jorge Espinoza
COMITE TECNICO

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COMPARACION DE DATOS DIGITALES NO CORREGIDOS Y CORREGIDOS ATMOSFERICAMENTE: FIRMAS ESPECTRALES DE ALGUNOS CULTIVOS INCAS

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Resúmen

Los datos originales de satélite contienen una serie de interferencias atmosféricas que tienden a afectar su clasificación. La eliminación de estas interferencias crea una serie de nuevos datos cuya clasificación puede o no verse afectada por una corrección atmosférica. La mayoría de los modelos de correción atmosférica están diseñados para ciertas regiones del mundo en donde existe suficiente información sobre los parámetros que intervienen en el modelo. Los paises en vía de desarrollo no tienen generalmente datos atmosféricos para su entrada en estos modelos.

La meta eventual es aplicar modelos de corrección atmosférica existentes a datos digitales obtenidos por satélites de regiones de países en desarrollo para determinar si existe una ventaja de los datos corregidos sobre los no corregidos al efectuar una clasificación de uso/cobertura del suelo.

Se obtuvieron datos radiométricos en el terreno de varios cultivos tradicionales Incas en la región de Cusco, Perú, durante 1988, 1989 y 1990. Estos datos, el modelo atmosférico Lowtran 6, y la función de correción geométrica del paquete de análisis digital de imágenes ELAS fueron usados para corregir datos SPOT obtenidos sobre Cusco el 2 de mayo de 1990.

Los resultados indican diferencias significativas entre los datos no corregidos y los corregidos. La reflectividad de los datos corregidos cambió en forma substantiva, en especial en los canales 2 (rojo) y 3 (infra-rojo). La reflectividad más alta en el canal 2 casi se duplicó, y en el canal 3 se incrementó en un 50 porciento. Usando los datos no corregidos y corregidos de las imágenes se obtuvieron las firmas espectrales de cinco cultivos Incas y de cinco clases de uso/cobertura. Las diferencias más grandes ocurrieron en las firmas espectrales de los cultivos y las menos prominentes en la firma espectral del agua. Al comparar los datos radiométricos de terreno con las firmas espectrales generadas a partir de las imágenes solo se encontró una pequeña diferencia, probablemente debido a la naturaleza espectral restringida de los datos usados.

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108

EFECTOS DE LA SEQUIA DE 1989-1990 EN EL AREA DE CUSCO, PERU

Dario Rodriguez Bejarano
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University of New México
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Resúmen

Se examinaron datos digitales de satélite para obtener información sobre los cambios en las áreas agrícolas de la región centrada en la Ciudad de Cusco durante el período 1988-1990. Los cambios que se buscaban fueron los causados por la sequía y las heladas tempranas experimentadas durante la cosecha 1989-1990 (septiembre-noviembre a abril-mayo). Se obtuvieron datos de los satélites Spot de mayo de 1988 y mayo de 1990, y del TM de Landsat de mayo de 1990. A estos datos se le aplicaron correcciones atmosféricas y radiométricas. Los datos corregidos se usaron para obtener Indices Vegetacionales de Diferencias Normalizadas (IVDN) para 1988 y 1990, y para examinar los datos del canal térmico del Landsat TM.

La comparación de los IVDNs obtenidos de Spot en 1988 y 1990 demostró claramente los cambios de reflectividad promedio y por ende de la cobertura vegetacional. La reducción de área vegetativa no pareció tan evidente al comparar Spot 1988 con TM 1990, pero fué posible demostrarla. La comparación visual y estadística del canal 6 del TM (datos térmicos) con los IVDNs de 1990 solo arrojó una cierta similitud que es necesario estudiar más a fondo. Basándonos en el área muestreada, la región experimentó una disminución de área vegetativa de 18 a 23 porciento entre 1988 y 1990. Esta disminución puede ser atribuida a las condiciones de sequía y a las heladas registradas por la estación metereológica de Cusco y reportadas por el Centro de Análisis Climático de la NOAA.

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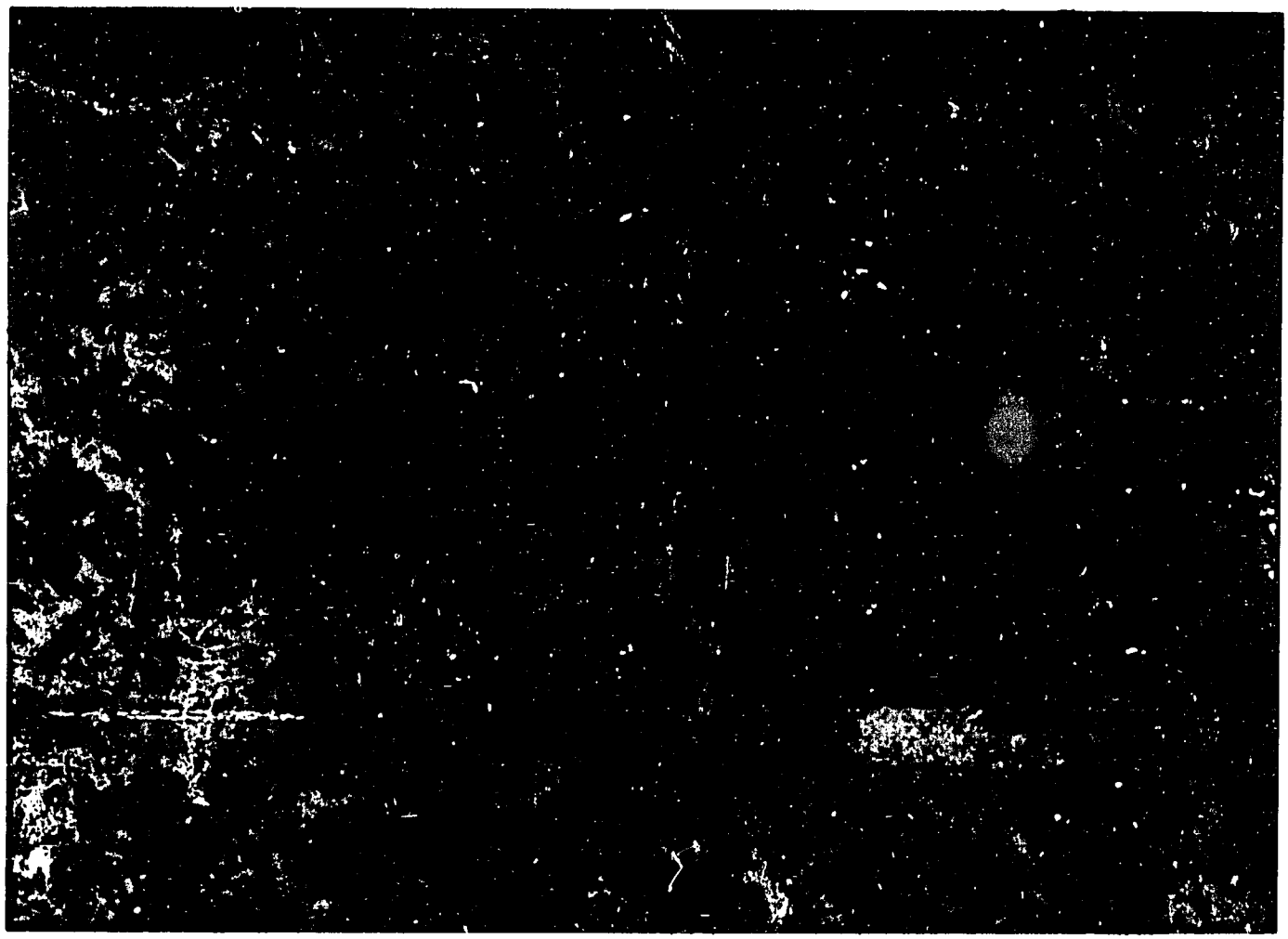
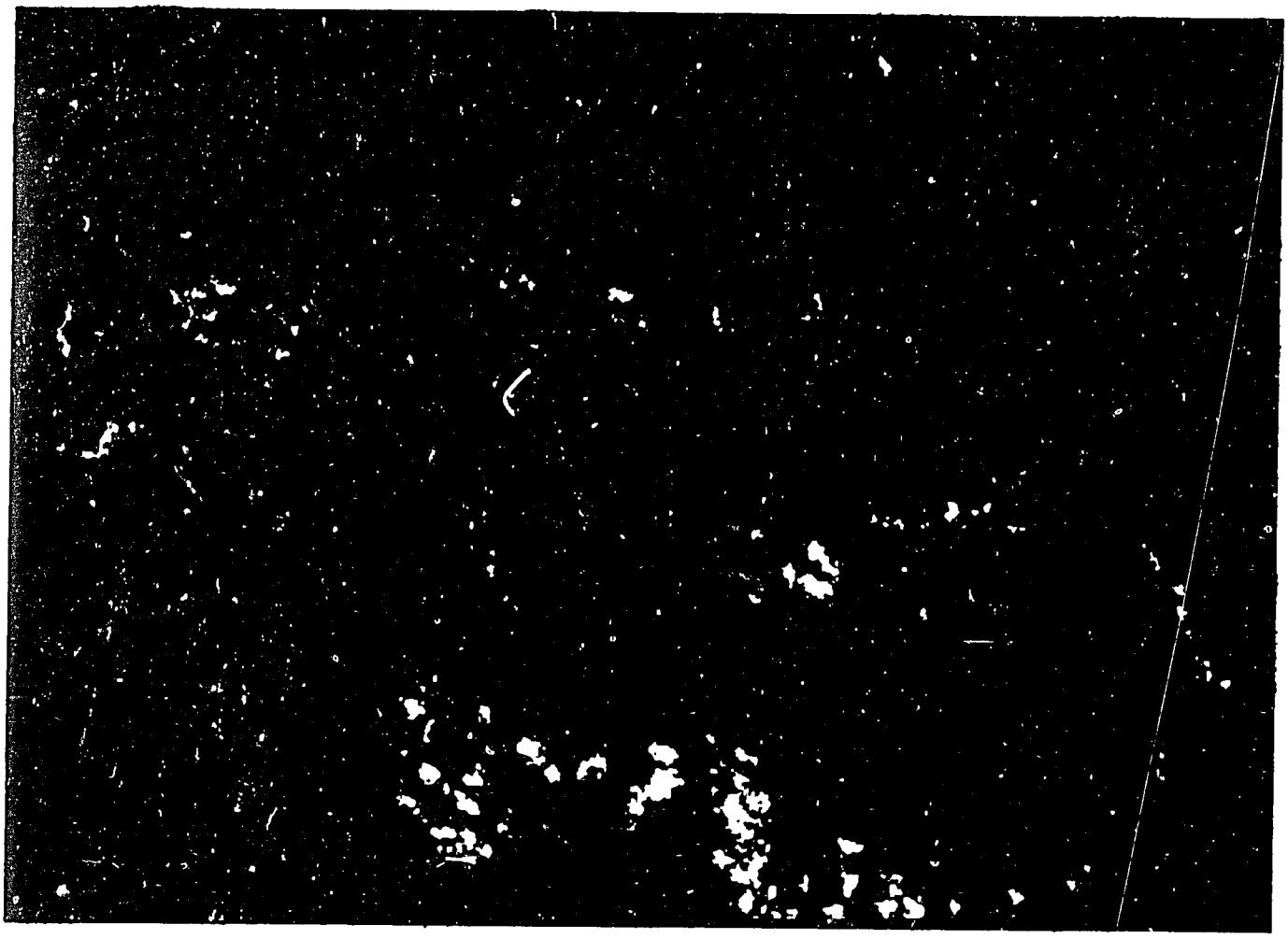
SPOT Classification, 1990 (See also Figure 11 and Table 13)



TM Classification, 1990 (See also Figure 12 and Table 14)