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# Prototype land-cover mapping of the Huascarán Biosphere Reserve (Peru) using DEM, NDSI and NDVI indices

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Abstract. On the basis of Landsat 7 ETM+ imagery, a prototype land-cover map was prepared for the Huascarán Biosphere Reserve (Peru). This document should contribute to the sustainable management of the Huascarán Biosphere Reserve, while making it possible to establish a regional planning policy and to prepare a natural risks map, which is still lacking in the region. The influence of the topography on radiometry was attenuated by using NDSI and NDVI indices, which were segmented using their histogram. A digital elevation model (DEM) was introduced to define the "highlands" and "lowlands". In the latter, the slope derived from the DEM was combined with the NDVI to map the agricultural surfaces. Twenty-one spectral classes were defined and their correspondence with land-cover themes was checked by field observations. The land-cover map provides original information on the extent of the glacial cover, debris-covered glaciers, 881 lakes, vegetation density, agricultural surfaces, urban zones and mines.

Keywords: remote sensing, sustainable development, snow and vegetation indices, landcover, Andes, DEM, Landsat 7 ETM+.

## **1 INTRODUCTION**

Because of the beauty of its landscapes, the diversity of its flora and fauna and its ecological characteristics, the Cordillera Blanca, located in the Peruvian State of Ancash, was declared Huascarán National Park (HNP) in 1975 [1]. The Cordillera Blanca attracts more than one hundred thousand tourists annually. However, this human presence, being added to the direct and indirect users of the HNP, is not without consequences: pressure on fauna and flora in sectors with a precarious ecological equilibrium; competition for space; conflicts for the water resources; and waste production [2]. Hence, an integrated management of the Huascarán Biosphere Reserve (HBR) is urgently needed. To this end, we have proposed elsewhere a prototype Geographic Information Systems (GIS) for this protected area [3,4].

The land-cover map is an important part of the Geographic Information System and constitutes an instrument for the understanding and management of the territory [5]. Moreover, in the context of sustainable development, this type of information is essential for the management of hydrological reserves in high mountain regions [4]. The socio-economic context of Peru and the dimensions of Huascarán Biosphere Reserve explain why this information is not yet available.

In the Ancash region, mining activity has been growing since the launch of the Pierina (1998) and Antamina (1998) ventures [3]. As a consequence, conflicts over water resources have arisen with the local population. Furthermore, these mines are located within the

Biosphere reserve, thereby inducing significant landscape changes and threats for the ecosytsem [4]. In this context, a land cover map provides a useful inventory of both the natural landscape types and impacts upon them caused by mining activities.

In a previous study, we used the Normalized Difference Snow Index to map the glacier area of the Cordillera Blanca [1] for the years 1987 and 1996, excluding the other land cover types. We present and discuss here the approach we have taken for the production of the first complete land-cover map of the Huascarán Biosphere Reserve, based on the 2002 Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite imagery [6].

## **2 STUDY AREA**

The Cordillera Blanca (CB) is located between the geographical co-ordinates  $08^{\circ}30'-10^{\circ}10'$  S latitude and  $77^{\circ}00'-78^{\circ}00'$  W longitude, in the Peruvian State of Ancash, 400 km north of capital city of Lima, 100 km east from the Pacific Ocean and 1000 km south of the Equator. Its dimensions are, approximately, 180 km by 30 km (Fig. 1). The Cordillera Blanca is covered partly by the Huascarán National Park (HNP), recognized by UNESCO, in 1985, as a "Natural World Heritage" [7,8]. The altitude varies between 1100 and 6768 m.



Fig. 1. The location of the study area; a) in the national territory of Peru; b) Landsat ETM+ image coverage; c) Huascarán Biosphere Reserve (HBR) and its three elements: Huascarán National Park (HNP), Buffer-zone, Transition-zone (georeferenced to the Universal Transverse Mercator, zone 18 south).

The Cordillera Blanca includes 101 mountains higher than 5000 m [9], of which 27 are higher than 6000 m, such has Huascarán Sur (6768 m), the highest summit in Peru. The Cordillera Blanca also harbours numerous lakes and glacial valleys [3,10]. According to Silverio [4], 881 lakes were identified in 2002, flowing either into the Pacific or into the Atlantic Oceans. The flora is exuberant and the fauna very rich [7]. In this zone, there is also a great social diversity [4].

According to Kaser et al. [11], the oscillation of the Inter-tropical Convergence Zone (ITCZ) causes the seasonal distribution of the precipitations. This leads to a succession between a dry (May–September), and a wet season (October–April) [12,13]. The most intense rains occur between January and March, the wettest month of the year [4].

In 1977, under the UNESCO's Man and Biosphere Convention, the Cordillera Blanca was recognized as a Biosphere Reserve [14]. This includes the "core zone" (represented by the HNP), surrounded by a buffer zone and a transition zone [4]. According to INRENA [15], the Huascarán Biosphere Reserve covers a surface of 11765 km<sup>2</sup>, distributed between Huascarán National Park (3400 km<sup>2</sup>), the buffer zone (2594 km<sup>2</sup>) and the transition zone (5771 km<sup>2</sup>). However, these figures differ from those advanced by UNESCO, respectively, 3400, 1702 and 6456 km<sup>2</sup> [14].

According to INRENA [16], the Huascarán National Park is devoted to the biodiversity and natural environment protection, the buffer zone being an envelope protecting the park and intended for the development of ecotourism. The transition zone is dedicated to urban development, commercial activities and tourism infrastructures. According to Silverio [4], the majority of the villages which surround the Cordillera Blanca are located in the buffer zone; the transition zone includes the valleys of Callejón de Huaylas and Conchucos, where the principal cities and the chief towns of the districts are concentrated.

## **3 SATELLITE AND TOPOGRAPHIC DATA**

UNEP/GRID-Sioux Falls (USA) provided a mosaic image (Path: 008; Rows: 066-067) from ETM+ satellite, taken on 17 June 2002. Its pixel resolution is 30 m. It is of good quality (no visible haze, and cloud cover of only 0.2%). The dimensions of the image are 360 km by 250 km.

The topographic contour lines of the Peruvian National Geographic Institute (IGN) were provided by Peruvian National Institute of Natural Resources (INRENA). The original information was georeferenced in Geographic Coordinate System and covered an area of  $63775 \text{ km}^2$ , between 7°56'3"-10°53'10" S latitude and 76°35'58"-78°45'16" W longitude. This area is larger than the Peruvian State of Ancash (35936.5 km<sup>2</sup>). The topographic contour lines have a 50 m equidistance, and the minimum and maximum altitudes are 25 m and 6700 m respectively.

The Digital Elevation Model (DEM) was interpolated from the corrected topographic contour lines with *ARC/INFO*® (50 m pixel). This DEM was resampled to a 25 m resolution using the script "*Grid Utilities*" for Spatial Analyst of *ARCVIEW 3.2*® [4]. Resampling was done to match the DEM resolution with that of the imagery, both of them being combined to estimate the area of cultivation (see Fig. 2, step 10).

## **4 METHODOLOGY**

The Cordillera Blanca's complex topography induces a strong relief effect on the images and hence, on the spectral signatures of land-cover classes [2]. This effect should be ideally corrected by a topographic normalisation using digital elevation models (DEM) [17], which must have a spatial resolution of at least four times better than the image needing correction [18]. The DEM interpolated by Silverio [4] using IGN's contour lines (50 m resolution) does not meet this condition and the normalisation attempted using the cosine correction available from the *ERDAS* software [19] was of poor quality [2,3]. Instead, we used Landsat ETM+

band ratios (indices) that enable a certain amount of relief attenuation [1]. Our methodology is summarised in the flowchart of Fig. 2.



(14)-[Clip: AV/Script

Fig. 2. Flowchart of methodology followed for the prototype land cover map of the Huascarán Reserve (AV = ArcView).

#### 4.1 Image preparation

Bands 1, 2, 3, 4, 5 and 7, respectively (in  $\mu$ m), 0.45-0.52, 0.52-0.60, 0.63-0.69, 0.76-0.90, 1.55-1.75 and 2.0.8-2.35, were stacked and a sub-image (3733 columns by 7000 lines) was extracted from the 17 June 2002 ETM+ mosaic. Based on the 31 May 1987 baseline image, which was rectified in our previous study [1], an image-to-image registration was carried out with 55 ground-control points (GCPs), a first-degree polynomial transformation and a nearest neighbour resampling (25 m pixel), in UTM coordinate system, zone 18 south. The root-mean-square (RMS) error was 1 pixel. From the resulting image, another extract was taken using the following coordinates:

 $\begin{array}{l} E_{min};\,N_{min}:\,180\;000;\,8\;872\;000\\ E_{max};\,N_{max}:\,276\;000;\,9\;048\;000 \end{array}$ 

The dimension of this image is of 3840 columns by 7040 lines.

No atmospheric correction was carried out on the imagery because a careful visual inspection revealed no haze over the study area, and no ground data on the atmosphere was available. This precluded the application of a correction scheme such as advocated by Liang et al [20]. Moreover, atmospheric corrections do not necessarily yield convincing results [21, 22].

#### 4.2 Calculation of indices

According to Colby [23], indices or spectral band ratios are known for their ability to eliminate, or at least minimise, illumination differences due to topography. These ratios must be calculated using little correlated channels (visible and near infra-red) and ideally, after elimination of additive noise [24]. Since no mist was actually visible on the images, this last treatment was not deemed necessary [2].

In order to have an optimal representation of the Huascarán Biosphere Reserve highaltitude land-cover themes for 2002, ranging from pure ice to rock outcrops, and including the vegetation, we have used two indices:

- Normalized Difference Vegetation Index (NDVI); it can be determined using digital numbers (DN) of ETM+ two bands from the following equation:

NDVI = (Band 4 - Band 3) / (Band 4 + Band 3)

The NDVI is traditionally used for the weekly evaluations of biomass and as support of the modelling programs of planetary changes [24]. We have used it here to discriminate bare soils from various vegetation density classes.

- Normalized Difference Snow Index (NDSI) computed from digital numbers (DN) using two ETM+ bands from the following equation [25]:

$$NDSI = (Band 2 - Band 5) / (Band 2 + Band 5)$$

The NDSI makes it possible to distinguish snow from soil, rocks and clouds [26]. The effectiveness of this index was demonstrated for snow and ice mapping in uneven topography [1,2,27].

#### 4.3 Spatial segmentation using NDSI

For the 2002 image, the NDSI values range from -0.70 to 0.94. Based on visual interpretation of the ETM+ 7/4/2 composite image (coded in red, green and blue) and on the histogram (Fig. 3), glacier limits were segmented at NDSI  $\ge$  0.51 [28]. We have tested several threshold values, and chosen NDSI  $\ge$  0.51 because it gave the best match with the glacier limits seen on the colour composite image [1]. The external margins of glaciers were obtained by raster to vector conversion [2].



Fig. 3. NDSI Histogram (from digital numbers: DN) for Landsat ETM+ image (2002). Glacier ice is above the 0.51 threshold.

Rock outcrops, located inside the glaciers, were also obtained by a NDSI  $\ge 0.51$  threshold, and debris-covered glacier limits were visually digitized using an ETM+ 7/4/2 composite image [29].

## 4.4 Digitisation of the vector themes and creation of masks

Using the ETM+ 7/4/2 composite image and based on our field knowledge, 8 themes (plus clouds) were visually digitized (Table 1). We carried out the union of the polygon themes with that of the study area. In the same way, glaciers, debris-covered glaciers and rock outcrops, resulting from the NDSI analysis, were integrated in this procedure. Vector themes were used for their own classification, as well as to define two types of masks.

Mask 1 (Fig. 4, left; Fig. 2) results from the subtraction operation between study area and polygon themes (digitized themes, without cloud, and polygons from NDSI analysis) [2,4]. Mask 2 is computed by subtracting the cloud polygon theme from the study area (Fig. 2).

Themes	Themes Form Description		Based on	
Towns	Polygon	Zones occupied by cities and major towns of the districts	2002 ETM+	
Mines	Polygon	Zones affected by the mining activity	Idem	
Avalanche	Polygon	Zone affected by the 1995 avalanche	Idem	
Debris flow	Polygon	Zone affected by the debris flow in 1999 Iden		
Lakes	Polygon	All lakes in the study zone	Idem	
Rivers	Line	Limited to those having a permanent source Idem (glaciers or lakes) and which run during the entire year		
Asph. Roads	Line	Asphalted roads	Idem	
Uns. Roads	Line	Unsealed roads Iden		
Cloud	Polygon	Restricted to the eastern side of Cordillera Blanca, Idem this theme was used for the creation of Mask 2 (Fig 2, step 8)		

Table 1. Digitized themes.



Fig. 4. Left: Mask 1 resulting from the addition of digitized themes (polygon); right: NDVI image outside digitized polygon themes.

#### 4.5 Spatial segmentation using NDVI and DEM integration for classification

The masks were applied to the NDVI image, yielding values between -0.726 to 0.748. They were thresholded in four arbitrary, ordinal classes (Fig. 5; Table 2).



Fig. 5. Histogram of the NDVI image outside digitized themes (polygon) and the segmentation classes values.

Table 2. Thresholding of the NDVI outside digitized themes.

Classes	NDVI values	Interpretation
1	[-0.726 - 0.011]	Bare soil
2	[0.011 - 0.209]	Sparse vegetation
3	[0.209 - 0.345]	Dense vegetation
4	[0.345 - 0.748]	Very dense vegetation

Sparse, dense and very dense vegetation [2] cover the range of vegetation density for the Huascarán Biosphere Reserve outside the polygon themes. However, in HBR region, there is the presence of agricultural surfaces, which are not differentiated from other vegetation, because they have the same spectral signature. Differentiation between crops and other plants was established by introducing the altitude and slope parameters, derived from the Digital Elevation Model (DEM) [4].

The criteria were established on the basis of our field knowledge (Table 3). Indeed, the majority of the cultures have an upper altitude limit of 3650 m.a.s.l. and slopes  $\leq 30^{\circ}$  [4]. Some crops, like potato, wheat, broadbean and quinoa may extend up to 3950 m.a.s.l. [10]. However, they represent small surfaces and in the majority of cases, their dimension is less than one pixel (25x25 m<sup>2</sup>). We could not differentiate them from other plants, lacking field spectral data to perform spectral unmixing [30]. The terms *lowlands* and *highlands* refer to a partition of altitudes at 3650 m.a.s.l. based on field work [4].

DEM		NDVI	Themes
Altitude	Slope		
≤ 3650 m	$\leq 30^{\circ}$	≥ 0.209	Cultivation
≤ 3650 m	Not used	[-0.726 - 0.011]	Bare soil lowlands (≤3650m)
≤ 3650 m	Not used	[0.011 - 0.209]	Sparse vegetation lowlands (≤3650m)
≤ 3650 m	Not used	[0.209 - 0.345]	Dense vegetation lowlands (≤3650m)
≤ 3650 m	Not used	[0.345 - 0.748]	Very dense vegetation lowlands (≤3650m)
> 3650 m	Not used	[-0.726 - 0.011]	Bare soil highlands (>3650m)
> 3650 m	Not used	[0.011 - 0.209]	Sparse vegetation highlands (>3650m)
> 3650 m	Not used	[0.209 - 0.345]	Dense vegetation highlands (>3650m)
> 3650 m	Not used	[0.345 - 0.748]	Very dense vegetation highlands (>3650m)

Table 3. Criteria for definition of the vegetation density classes.

## 4.6 Vector to raster conversion of the vector theme

The urban, mines, avalanches, debris flow, lakes, rivers and roads themes were rasterized to a 25 m pixel resolution. The same procedure was applied to the glaciers, debris-covered glaciers and rock outcrops, which result from the NDSI analysis.

The river class is only indicative, because rivers did not show any distinctive spectral signature at the resolution used [3]. It represents permanent watercourses, together with their minor and major beds, as well as their banks [2].

#### 4.7 Vector to raster conversion of "agglomeration centre" (villages) points

The *Mapa Digital de Centros Poblados del Perú*, produced by the INEI [31], represents the location of the country's inhabited zones. Its table of attributes holds the number of houses per agglomeration (based on the 1992 census). Unfortunately, these houses are undetectable in the ETM+ 7/4/5 composite image or spectrally in the ETM+ images. Generally, in the villages, houses are scattered and there is vegetation in their neighbourhood with variable density, as well as crops. The average dimension of a house is approximately  $10x10 \text{ m} (100 \text{ m}^2)$ , therefore less than one pixel ( $25x25 \text{ m}^2$ ) [4].

Since we could not recognize the radiometry of the houses in the image, we represented the village by a circle of radius *r* around the coordinate point of location.

$$r = [(N*100)^{1/2}] / 2$$

where

*N*: number of houses in each village

 $100 \text{ (m}^2$ ): average dimension of each house

The circle area is then equivalent to that of all the village houses. Around each agglomeration centre, a circular buffer of r meters was computed by the GIS software. The buffer theme was rasterized to a 25 m pixel resolution. However, during this procedure, the villages with a number of houses  $\leq 7$  posed a problem (disappearance of the villages with the value of r between 5 and 13). To overcome this difficulty, we set the number of houses between 1 and 7 as being 8. With this last operation, an acceptable difference on the number of house pixels was observed: 9231 pixels (without edition) and 9681 after changing.

#### 4.8 Field work and quality control

The land cover map quality was evaluated with the help of data collected in the field at 199 control points. Data collection took place in May-June 1999; April-September 2000; June-August 2001; May-September 2003, and June-September 2004. The land cover type was evaluated visually according to the 21-term legend (Table 4) within a radius of 50 meters about the control point, and photographs were taken. Field and classified values were compared in a contingency matrix using the *KappaAnalysis v.2* extension in ArcView 3.2. [32].

## **5 RESULTS**

The land-cover map of the Huascarán Biosphere Reserve results in the overlay of all the individual maps obtained in the preceding stage (Fig. 2). As a whole, it comprises twenty-one thematic classes (Table 4; Fig. 6): nine classes were obtained by thresholding of the NDVI and combined with the DEM; three classes were obtained by thresholding of the NDSI; and nine other classes were obtained by vector to raster conversion of the vectors themes.

Table 4 presents a first estimate of the areal distribution of the various land cover classes in the Huascaran Biosphere Reserve. It is representative of the situation at the beginning of the 21<sup>st</sup> century, centered on year 2002. Broadly speaking, the land-cover of the Huascarán Biosphere Reserve is distributed between the vegetation (66% of surface), bare soils and rock exposures (17%), cultivation (8%) and glaciers (6%).

N°	Theme	Area (ha)	Area (%)
1	Rock outcrops	373	< 1
<u>2</u>	Avalanche (1995)	7	< 1
<u>3</u>	Debris flow (1999)	100	< 1
4	Bare soils and rock exposures $\leq$ 3650 m	33 151	3
5	Bare soils and rock exposures > 3650 m	146 239	14
6	Glaciers	57 474	6
7	Debris-covered glaciers	1 759	< 1
<u>8</u>	Lakes	4 236	< 1
<u>9</u>	Water flow (rivers)	8 370	1
10	Sparse vegetation $\leq$ 3650 m	161 521	16
11	Dense vegetation $\leq$ 3650 m	8 109	1
12	Very dense vegetation $\leq$ 3650 m	2 145	< 1
13	Sparse vegetation > 3650 m	362 941	35
14	Dense vegetation $t > 3650 \text{ m}$	125 353	12
15	Very dense vegetation > 3650 m	36 080	3
16	Cropland	86 511	8
<u>17</u>	Mines	1 606	< 1
<u>18</u>	Towns	1 503	< 1
<u>19</u>	Villages	600	< 1
<u>20</u>	Asphalted roads	883	< 1
<u>21</u>	Unsealed roads	3 727	< 1
	Total	1 041 660	100

Table 4. Statistics of the land-cover map of the Huascarán Biosphere Reserve. Underlined in first column: the 9 themes derived by digitization and vector to raster conversion.



Fig. 6. Land-cover map of the Huascarán Biosphere Reserve. The A-G letters refer to the location of photos (see Fig. 7).

The quality control of the cartography was carried out in two steps. First, all the 21 themes were considered, i.e. those derived from the image-based classification (numbering 12) as well as the 9 vector-based ones: 8 by digitization and 1 by point to raster conversion (villages) (Table 4). A global estimate of the map accuracy is given by the *Kappa* coefficient, reaching here  $92 \pm 0.4$  percent (Table 5). This satisfactory value is confirmed by the other overall quality parameters, such as the low commission and omission error levels (8 and 0.4 percent, respectively). The rather high map accuracy is partly due to the inclusion, in the analysis, of the 8 themes obtained by digitization, the accuracy of which is 100 percent by essence.

In a second step, these digitized themes were not considered. Hence, the results of Table 5 (third column) pertain only to the 12 *classified* themes. The overall quality of the map is only marginally lower (*Kappa* =  $90 \pm 0.5$  percent).

Finally, the question of the adequacy of the sample size for the computation of *Kappa* was addressed as well [33]. It was found that for 12 classes, a maximum classification proportion of 35% (Class 13, Table 4), 199 points were enough to yield a precision of 12% with a confidence level of 95% in the computation of Table 5 parameters.

Parameter	Value in %	
Number of classes	21	12
Overall accuracy	92	91
Overall missclassification rate	8	9
Overall sensitivity	92	91
Overall specificity	100	99
Overall omission error	8	9
Overall commission error	0.4	0.8
Kappa $\pm 20\%$ confidence int.	$92\pm0.4$	$90 \pm 0.5$

Table 5. Results of Kappa analysis

#### **6 DISCUSSION**

#### 6.1 Map accuracy

The estimates of map accuracy given in Table 4 have to be considered in the context of the applied methodology. Although the sample size of 199 locations is globally adequate, its distribution among the various classes may not be so. From the contingency tables (not shown), it can be seen that classes 1 (Rock outcrops), 7 (Debris-covered glaciers) and 12 (Very dense vegetation  $\leq 3650$  m) are represented by only 1-2 points each. This seemingly undersampling is due to the the very low areal coverage of these themes in the Huascaran Reserve (much less than 1%; Table 4). Conversely, other themes are oversampled with respect to their surface area (class 15, Very dense vegetation  $\geq 3650$  m). These characteristics could stem from the non-random distribution of the control points, collected along constrained foot and car itineraries. Finally, the producer's and user's accuracy for the individual classes in the contingency table indicate that only two of them (12: Very dense vegetation  $\leq 3650$  m, and 19: Villages) show omission error rates higher than 10%.

In spite of these caveats, and allowing for a possible overestimation of the quality criteria of, say, 10%, the accuracy of the prototype land cover map would still be around 80%. It is quite acceptable for this kind of document.

## 6.2 Cartographic reliability

Since the georeference of the satellite images was carried out with topographic maps at 1:100,000 scale (about  $\pm 100$  m accuracy), we estimate that the land-cover map will be usable at the same scale order, in spite of the higher pixel resolution of the images (25 m). Generalization was not carried out, because the operation was irreversible [2].

In the absence of a DEM with a sufficient resolution (approximately 5 m) to carry out topographic corrections, we estimate that the segmentation of the classes using NDVI represents fairly well the density of the vegetation populations, including the three chosen classes (i.e. *sparse, dense* and *very dense*).

Even if some species develop up or down from 3650 m.a.s.l., the vegetation types of the highlands and the lowlands are sensibly different (Table 6).

.N°	Classes	Interpretation	Species and their habitat (m), and local name
10	Sparse	Prairie / meadow	Various grasses
	vegetation		
	$\leq$ 3650 m	<b>D</b> 1	
11	Dense	Bush	Kagengekia lanceolata* (lloque) (2800-3400), Cassia
	vegetation	(shrub between	hookeriana (wishllaq) (2600-3300), Jungia paniculata
10	$\leq$ 3650 m	1-4 m tall)	(qaramati) (3100-3800)
12	Very dense	Mixed forest	Alnus acuminata* (aliso, wayo) (1200-3800),
	vegetation	(tree > 4  m tall)	Eucalyptus (≈2500-3800), <i>Schinus molle</i> * (molle) (<
	$\leq$ 3650 m		3300), etc.
13	Sparse	High grasses <sup>1</sup>	Prédominance: <i>Stipa ichu**</i> ( <i>ichu, ocsha</i> ) (3300-
	vegetation		4700)
	> 3650 m		Others species Puya raimondi <sup>**</sup> (cuncush) (4000),
<u> </u>	_		etc.
14	Dense	Bush and mixed	Bush: <i>Escallonia resinosa</i> <sup>**</sup> (chachacoma) (3800),
	vegetation	forest	Oreocallis grandiflora** (tsacpa) (3400-4000),
	> 3650 m		Barnadesia dombeyana (qontsi casha) (3600-4100),
			etc.
15	Very dense	Mixed forest	Gynoxis sp** (japru) (3300-4500), Polylepis**
	vegetation	(15a)	(quenual) (3700-4600), Buddlejia
	> 3650 m		$incana^{**}$ (quishuar) (3400-4200), Tristerix
		1/	longibracteatus ** (pupa) (3/00-4600), Passiflora
		and/or	$trifoliata^{**}$ (purush) (3/00-4400), etc.
			Plantago rigida ** (tsampa estrella) (4600-4800),
		Low grasses <sup>1</sup>	Distichia muscoides** (qachqa) (4400), etc.
		(15b)	
16	Cropland	Cereals, market	Predominance: several varieties of wheat
		gardening and	
		fruit crops	Others: market gardening (located at the bottom of
			Callejón de Huaylas valley)

Table 6. Correspondence between density classes and vegetal associations

\*Scientific name of the species according to: \* Kolff and Kolff [34]; \*\* Kolff and Kolff [34] and PNH [8].

<sup>1</sup> According to Silverio and Jaquet [2].

The classes resulting from the NDSI segmentation represent the glacierized areas (glaciers and debris-covered glaciers) and the rock outcrops inside the glaciers. Indeed, NDSI clearly differentiates snow from the other surrounding elements (rocks, soils, clouds). In this way, rock islands are very clearly defined by this index [1,24,25,35].

## **6.3 Interpretation**

The land-cover map of the Huascarán Biosphere Reserve that we propose here is provisional and should be improved in the future. In fact, this is the first land-cover map of the eastern and western slopes of the Cordillera Blanca, going through the Callejón de Huaylas and Conchucos valleys, up to the eastern slope of the Cordillera Negra.

In a previous study, Silverio and Jaquet [2] validated the radiometric classes, defined by segmentation of the spectral indices for the highlands inside the Huascarán National Park. For the rest, including the lowlands, the thematic classes complete the land-cover map established by Silverio [3] and Silverio and Jaquet [2], and allow a better apprehension of the region [4].

Concerning the glacial cover, we did not distinguish subclasses (ice, snow of different texture; see [36]). In the same way, inside the debris-covered glaciers, no subcategories were differentiated [2,3].

In the study area, no phyto-sociological map is available [4]. Hence, we examined the correspondence between the density classes and the vegetation associations observed in the field by visual comparison in 7 control zones labelled A - G [2] (Fig. 7).



D) Q. Llaca: debris-covered glacier at 4600 m



View N-NE E) City of Huaraz at 3090 m



F) Waste of mining activity, Ticapampa 3457 m







View SW

G) Andean plateau (> 4000 m) and Nevados Caullaraju (> 5500 m)





View SE

Fig. 7. Examples of ground truthing areas for land-cover classes. Left: view from the ground, with class numbers as per table 3. Right: extract of land-cover map. White arrows indicate direction of photo shots. Photos I. Machguth: A and E (2003). C. Bugniet: B and C (2000). W. Silverio: D (2001), F (2000), and G (2003).

In the highlands, the sparse vegetation is mainly composed of high grass (*Stipa ichu*), whereas the dense vegetation essentially consists of shrubs. The very dense class of vegetation does not allow distinguishing between the mixed forest with *Gynoxis* and *Polylepis* and low grasses, located at the bottom of the valleys [2] (Table 6).

In the lowlands, the sparse vegetation is composed of various grasses, while the dense vegetation is also shrub, the most widespread species being *Kagengekia lanceolata*, *Cassia hookeriana*, *Jungia paniculata*. The very dense vegetation is dominated by *Alnus acuminata*, *Eucalyptus* and *Schinus molle*.

Concerning the bare soils and the rock outcrops, in the highlands they consist mainly of rocks and recent moraines due to the glacial retreat. In the lowlands, they encompass arid lands, where the lack of precipitations is associated with steep slopes, and in certain cases flood beds of large rivers.

At the date the image was acquired (June 2002), between the eastern and western slope of the Cordillera Blanca and the eastern slope of the Cordillera Negra, the cropland class comprised cereals (several varieties of wheat). At the low altitude of the Callejón de Huaylas valley, between 2200 - 2800 m, market gardening and fruit trees dominate [4]. However, in the satellite imagery, it is very difficult to differentiate the types of cultivation.

The cropland class is very well correlated with the distribution of the villages [4]. Indeed, in the study area, the presence of villages means the presence of cultures, generally up to 3650 m altitude and in certain cases up to 3950 m. However, between 3650 and 3950 m, the isolated parcels of cultures merge with the other types of vegetation.

#### 6.4 Possible uses of the land-cover map

The land-cover map produced in this work represents the first attempt at mapping the Huascaran Biosphere Reserve. As such, it is a prototype illustrating the state of the land in 2002, at a nominal resolution of 25 meters, and with an overall thematic accuracy of 90 % (expressed as *Kappa* coefficient; table 5).

The information content of the 21 classes (Table 4) varies. A subset of them could, in our opinion, be used to compute future land cover difference maps (or land cover flows [37]) in the following areas: (a) Inside the Huascaran National Park, where are located 98% of the glaciers of the Cordillera Blanca [10]: mapping of the evolution of water reserves, represented by the glaciated surface; (b) In the Buffer and Transition zones: mapping of the urban growth and impacts of mining and tourist activities [4].

#### 6.5 Further improvements of the map

Building on the results of the present prototype, future land-cover maps could be improved in several ways. First, keeping a Landsat-type 25 m resolution, the identification of several themes, especially those pertaining to vegetation, could gain in accuracy by using multi-temporal imagery (2-3 images per year). A second improvement could stem from the enhanced use of any pertinent and up-to-date vector data together with the imagery, particularly in the mapping of anthropic features, such as villages. This could be done following a multi-source, object-oriented approach, such as previously applied with success in the mapping of the Iraqi Marshlands [38]. Thirdly, any ground-truthing campaign should match as closely as possible the date of the imagery, even though this may be difficult to achieve in the Peruvian context. Finally, there remains a question of methodology: we have opted for the use of indices in order to alleviate the effects of the strong relief on the imagery. In the event a DEM with an appropriate resolution (5 m) would become available in the future, a formal correction could be applied and spectral signatures more extensively used.

## **7 CONCLUSION**

The land-cover map presented in this work is the first of the kind established for the Huascarán Biosphere Reserve. The absence of an adequate digital elevation model did not allow a formal correction of the strong relief effects on the satellite imagery. We thus had recourse to the NDSI and NDVI indices within a procedure of segmentation. NDSI was used to map the glaciated areas, whereas NDVI was combined with the DEM to define the highlands and lowlands, as well as the various vegetation and cropland themes.

According to the first field checks, the overall map accuracy is fair (Kappa around 90%). The cartographic representation can be regarded as good for the glaciers, the debris-covered glaciers, rock outcrops and the lakes, and as satisfactory to poor for the various individual vegetation classes. This land-cover map represents a basic information layer which could be incorporated in a Geographical Information System. It would thus help establish a regional planning policy and the elaboration of a natural risk map, which is missing in the region. It could also be used as a basis for future diachronic comparisons, particularly in the fields of the evolution of glacial cover and its related natural hazards, as well as mining activity and urbanization.

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