Post-glacial chronosequence of the Pastoruri snow-capped and modeling of pioneer plant species

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Abstract*– The study was about the pioneer plant species which arise from the glacial retreat of the Pastoruri snow-capped as a result of the thaw that fluctuates between 10 and 12 meters per year. The studied area was the periglacial zone of the snow-capped, the retreat of this glacier is adduced to the climatic variability in the last years. Two families of plants - the Asteraceae and the Poaceae- were found in the area. In the first family, the existing species are: Senecio sublutescens Cuatrec., Baccharis tricuneata (L.f) Pers., Novenia acaulis Cuatrec., Xenophyllum dactylophyllum, V.A. Funk digitatum Funk., Senecio adenophyllus, and in the second family the species identified was the Calamagrostis ef. In order to evaluate the retreat of the Pastoruri glacier, the ice-covered area in the year 2001 was taken as the base point, and it was evaluated up to April 15, 2017, in which it was noticed that the retreat reached 20.95 %, this calculation was made using historical data from the National Service of Meteorology and Hydrology of Peru (SENAMHI), and the use of MAXENT software and Geographic Information System (GIS). It is concluded that the glaciers in the Cordillera Blanca are important indicators of the climate change; and that after these changes it is begun an altitudinal migration of the autochthonous plant species of the Andes taking up the spaces left by the retreat, and that sometimes these species do not adapt to the changes and disappear. This process affects the biodiversity of the flora.

Keywords: Pastoruri snow-capped, chronosequence, glacier retreat, pioneer plant.

I. INTRODUCTION

Since the end of the 20th century, the temperature of the planet has increased significantly, mainly due to greenhouse gases, and these accelerated changes are attributed to anthropogenic activity [1]. In view of this problem, the Intergovernmental Panel on Climate Change (IPCC) [2] mentions that in recent years the most representative ice sheets of the planet, such as Antarctica and Greenland, have been losing glacier mass. Similarly, glaciers around the world, including Gangotri, one of the glaciers in the longest valley of the Garhwal Himalayas, has attracted attention for having had a retreat rate of 38 m/year in the 1970s and maintained in recent decades at that average, but in 2015 it has been reduced to 10 m/year [3]. In addition, the IPCC mentions that the global mean surface temperature in 2090-2099 is likely to be 1.7-4.4 °C higher than in 1980-1999 under its A1B emissions scenario, while it is likely to be 2.0-5.4 °C higher under the A2 emissions scenario. The A1B emissions scenario describes a future world of very rapid economic growth with a balance among all energy sources, while the A2 emissions scenario describes a very heterogeneous world with self-sufficient nations and fragmented economic development [4].

According to Glaciology and water resources unit (UGRH) [5], in the Cordillera Blanca, which is located in the Andes of the North of Peru, there are a total of 755 glaciers with a total area of 527.62 Km^2. Specifically, a glacier named the Pastoruri snow-capped in the Cordillera Blanca - Ancash, which according to research, between the years 1999 to 2011, the glacier has moved 140 meters away, predicting that by the year 2050, only 500 hectares of glacier would be counted and by the year 2064 probably there will not exist glacial area [6]. Other study states that the average fluctuation of the glacial retreat of the Pastoturi snow-capped is between 10 to 12 meters per year [7]. These retreats have caused changes in the presence and possible extinctions of plant species in alpine areas hypothetically influenced by the time lag between the speed of global warming and the slowness of primary succession. This hypothesis was tested in tropical alpine environments gradually thawed at more than 4,700 meters above sea level (Central Andes) since the acceleration of global warming in the late 1970s [8]. It is necessary to investigate the consequences on biodiversity and ecosystems by successional changes, including the direct effects of the retreat of glaciers [9].

A post-glacial chronosequence, constitutes the deglaciation bands that rise in the environment, which is studied and represents a plant succession [10]. Therefore, the study was focused on modeling the presence of pioneer plant species after the retreat of the Pastoturi glacier; and the predominantly highland vegetation type, the type of plant succession that is found after the Pastoruri glacial retreat, and the abiotic and biotic factors that favor the appearance of pioneer species after the retreat of the glacier in question were determined. One study found models of geographic distribution patterns of the grass species (Poaceae) that occur in high Andean areas of Bolivia and indicate the importance of their conservation [11]. Another investigation showed the migrations presence of species to different altitudinal floors [8]. Likewise, one study mentions that the diversity of plants depends on the great variety of factors, which include groups of species, evolutionary history and abiotic and biotic restrictions. The species that coexist within a competitive dominant species are known as buffer plants [12].

For the objective set out in the research to identify pioneer plant species and model their distribution after the retreat of the Pastorui glacier, MAXENT and GIS softwares were used as supporting tools in order to understand the possible changes in the following years of plant species components of the ecosystem in the surrounding area which is part of a National

Protected Area (ANP); the result found may help to improve the management of the biodiversity conservation existing in area [13].

II. MATERIALS AND METHODS

The study was applied, descriptive and non-experimental design, as the data collected were not manipulated, and the data was collected as the observed phenomena occurred in their natural context to be analysed later [14]. The population includes the entire post-glacial area of the Pastoturi snow-capped, from 2001 to 2017, with a total of 49.14 hectares. The sample taken was objective and direct for the research of highland plant cover, selecting 10 plots of an area of 1 m^2, this quadrant is considered as a representative area of the diversity of the herbaceous communities [15]. Furthermore, under intentional criteria, it was searched for accessible areas of the north periglacial area of Pastoruri within an approximate area of 3 hectares. The research was carried out in three phases:

Phase 1: Collection of meteorological data from the database of National Meteorology and Hydrology Service (SENAMHI)[16] are monitored by three stations closest to the studied area, which are located in Chiquian, Chavin and Recuay. For the analysis of the glacial retreat of the post-glacial chronosequence, satellite images were acquired for the years: 2001, 2003, 2005, 2005, 2007, 2007, 2009, 2011, 2013, 2015 and 2017. Meteorological factors of precipitation and temperature were also considered.

Phase 2: Fieldwork, it was established a quadrant of 1m x 1m, at the same time divided into sub-quadrants of 10 cm^2, where it was identified the plant cover in terms of the pioneer species that are populating the areas left uncovered by deglaciation of the perennial ice. The quadrant was given an encoding “i-j”, (i = from 1 ... 10 for rows and j = from A ... J for columns), as shown in the Table I.

TABLE I
CODING OF SUBQUADRANTS

1-A	1-B	1-C	1-D	1-E	1-F	1-G	1-H	1-I	1-J
2-A	2-B	2-C	2-D	2-E	2-F	2-G	2-H	2-I	2-J
3-A	3-B	3-C	3-D	3-E	3-F	3-G	3-H	3-I	3-J
4-A	4-B	4-C	4-D	4-E	4-F	4-G	4-H	4-I	4-J
5-A	5-B	5-C	5-D	5-E	5-F	5-G	5-H	5-I	5-J
6-A	6-B	6-C	6-D	6-E	6-F	6-G	6-H	6-I	6-J
7-A	7-B	7-C	7-D	7-E	7-F	7-G	7-H	7-I	7-J
8-A	8-B	8-C	8-D	8-E	8-F	8-G	8-H	8-I	8-J
9-A	9-B	9-C	9-D	9-E	9-F	9-G	9-H	9-I	9-J
10-A	10-B	10-C	10-D	10-E	10-F	10-G	10-H	10-I	10-J

Fuente: Adaptado de ZIMMER *et al.* (2015)

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Phase 3: Uploading of data, the field data obtained (coordinates) were digitized in Excel 2013, which was saved in a CSV format to be processed by the MAXENT (based on maximum entropy) and the ArcGIS 10.3 software’s. Files for each of the species found in the area of the Pastoruri glacier retreat were created, subsequently the modeling of the geographical distribution of the species was carried out, considering the maximum and minimum temperature, and precipitation as base layer.

Software used:

Maxent: In the generation of predictions based on data, this software is very advantageous for ecological niche issues both for its extended graphical interface and ease of use, providing good results. It maximizes (as its name says) the entropy under constraints to be considered looking for the most uniform distribution possible especially when there are few records [16] algorithms following a logistic regression based on presence/pseudo-absence of a Poisson point process and therefore cannot determine probability of presence [17]. It allows the processing of large databases that complemented with ArcGIS allowed the processing of research data.

III. RESULTS

A. *Predominant Species*

The pioneer species of predominant vegetation found in the place of study were the Asteraceae and Poaceae families, comprising a total of 8 species. Table II shows the following findings.

TABLE II
PIONEER SPECIES AFTER THE RETREAT OF THE PASTORURI GLACIER

Field Code	Scientific Name	Family
PA-01 (Sample 1)	*Senecio sublutescens Cuatrec.*	Asteraceae
PA-01 (Sample 2)	*Senecio adenophyllus Meyen & Walp.*	Asteraceae
PA-04 (Sample 1)	*Baccharis tricuneata (L.f) Pers.*	Asteraceae
PA-04 (Sample 2)	*Calamagrostis nitidula Pilg.*	Poaceae
PA-04 (Sample 3)	*Novenia acaulis (Benth & Hook. F. ex B.D. Jacks) S.E. Freire & F.H. Hellw*	Asteraceae
PA-04 (Sample 4)	*Senecio evacoides Sch. Bip.*	Asteraceae
PA-06	*Senecio serratifolius (Meyen & Walp.) Cuatrec.*	Asteraceae
PA-O7	*Xenophyllum dactylophyllum (Sch. Bip.) V.A. Funk digitatum (Wendd.) V.A. Funk.*	Asteraceae

B. Retreat Area of the Pastoruri Glacier

Table III shows the trend of the retreat area of the Pastoruri glacier from 2001 to 2017, finding that by the year 2017 the retreat reached 29.8%, according to the base year 2001. These new areas left by the glacier after its retreat are subsequently populated by vegetation species called pioneer species.

The data was worked up to the year 2017 only in view that for the following years the information was not complete in the meteorological stations; however, this work will be monitored again after a period of 5 years (2022) to verify the status of glacial retreat and the conditioning factors to this phenomenon

TABLE III
PERCENTAGE OF RETREAT OF THE PASTORURI GLACIER

Year	Area (ha)	Glacier area (%)	Retreat (%)
2001	234.495989	0.00	0.00
2003	202.961126	86.55	13.45
2005	18.687663	79.69	20.31
2007	180.845061	77.12	22.88
2009	186.934676	79.72	20.28
2011	18.372265	78.35	21.65
2013	17.428255	74.32	25.68
2015	152.888207	65.20	34,80
2017	185.363122	79.05	20.95

C. Meteorological Factors Favoring the Emergence of Pioneer Species After the Retreat of the Pastoruri Glacier

Table IV shows the average, maximum and minimum rainfall from 2001 to 2017, considered in the investigation as well as the temperature; the data were obtained from SENAMHI stations. The maximum temperature was 23ºC and the minimum temperature was -3.90ºC recorded in 2016 and 2015, respectively.

TABLE IV
ANNUAL TEMPERATURE AND PRECIPITATION AT THE PASTORURI GLACIER

Year	Temperature (ºC)			Precipitation (mm/year)		
	MAX	MIN	Average	MAX	MIN	Average
2001	20.25	-2.00	12.28	29.40	0.00	2.95
2003	21.11	-0.80	12.73	19.40	0.00	1.88
2005	21.08	-2.80	12.34	32.40	0.00	1.95
2007	20.86	-1.80	12.54	33.00	0.00	2.59
2009	20.10	-0.80	12.69	44.00	0.00	3.60
2011	20.60	-3.00	12.38	29.50	0.00	2.25
2013	20.88	-1.40	12.76	31.40	0.00	2.33
2015	21.79	-3.90	12.59	22.60	0.00	1.76
2016	23.00	-1.40	13.82	25.70	0.00	1.71

The scenarios presented by the IPCC indicating that the average global temperature from 2090-2099 will be 1.7-4.4 °C higher than the 1980-1999 period due to the impact of emissions is worrying, because it will simultaneously affect runoff in river basins due to melting ice and also affect agriculture. For all these reasons, studies are required to be used to improve management in the conservation of glaciers and biodiversity in the area

D. Vegetal cover in Wet and Dry Season in the Pastoruri Glacier

Table V shows the sampling points, each one with its coordinates and respective altitudes of the monitoring points as well as the result of the percentage of plant cover in wet season and dry season.

TABLE V
VEGETAL COVER IN THE WET AND DRY SEASON.

SUB-PLOT	COORDINATES		Altitude (m.a.s.l)	Vegetation cover (wet season) (%)	Vegetation cover (dry season) (%)
	EAST	NORTH			
PA-01	260583	8903233	4997	1.58	1.30
PA-02	260572	8903276	5002	0.36	0.25
PA-03	260440	8903226	4988	0.00	0.00
PA-04	260506	8903519	4473	10.48	10.10
PA-05	260260	8903360	4985	0.95	0.82
PA-06	260164	8903417	4979	3.90	3.60
PA-07	260787	8903473	4993	0.62	0.56
PA-08	260777	8903579	4979	0.40	0.35
PA-09	261070	8903597	4980	2.32	2.16
PA-10	261015	8903820	4956	4.05	3.70

E. Modeling of Pioneer Species

The modeling of the distribution of pioneer species after the retreat of the Pastoruri glacier through the post-glacial chronosequence using Maxent and geographic information system is shown in Fig. 1. The Fig. 1-a shows the range of oscillation of the presence of the distribution of the pioneer species after the retreat of the Pastoruri glacier, the blue color values denote an absence of the species and the coloration of orange-reddish degradation a probability of 0.85 to find the species in that area. Fig. 1-b shows an orange-yellowish coloration that indicates the probability of finding the pioneer species between a range of 0.77 to 0.85 (1 is ideal).

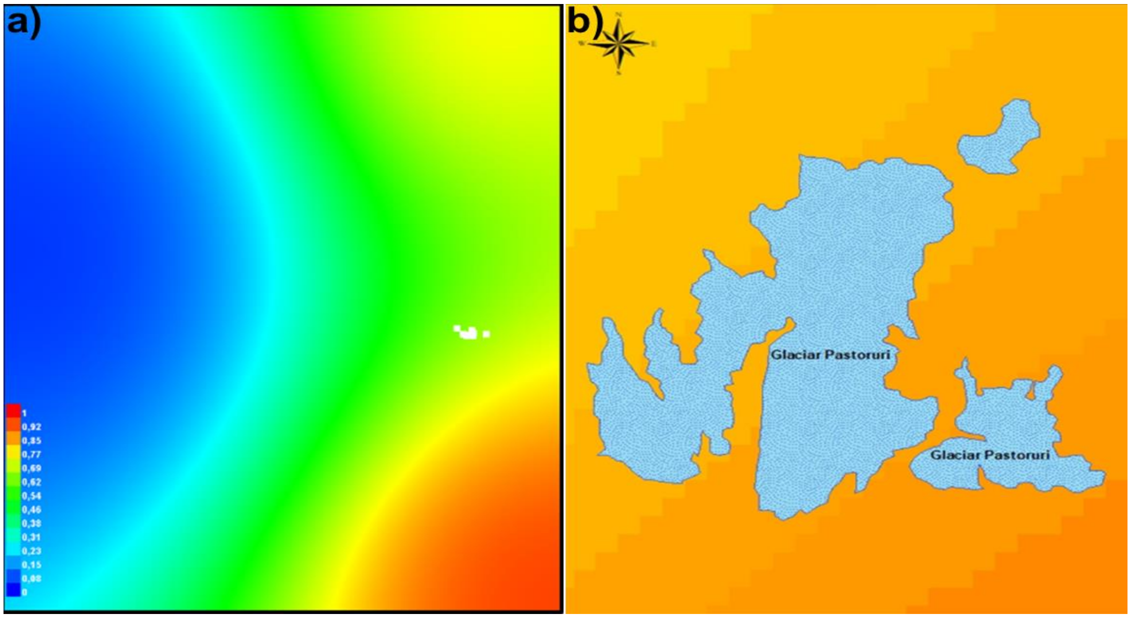

Fig. 1 Distribution of the pioneer species in the periglacial area of the Pastoruri: a) Distribution probability (0 to 1) and b) Location on degradation scale of the coloration

The reliability of the distribution model for the species *Baccharis tricuneata (L.f)* Pers and *Calamagrostis nitidula Pilg*, is shown in Fig. 2a and Fig. 2b, where the ROC curve (area under the curve) presents an AUC of 0.724 and 0.96 respectively. The values are acceptable, as they are next to 1

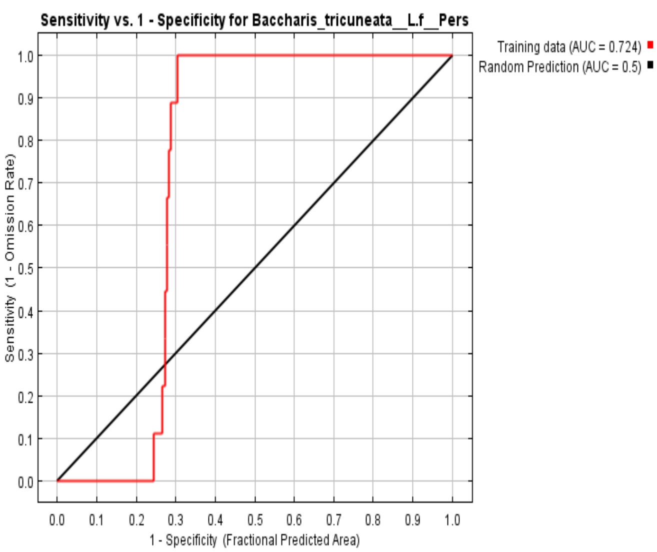

Fig. 2a Reliability of the model for the species *Baccharis tricuneata (L.f)*

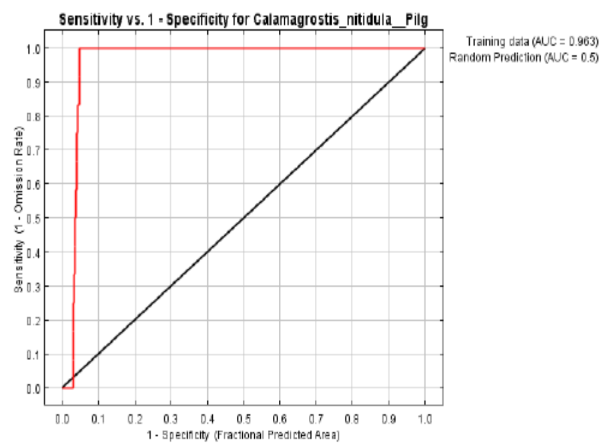

Fig. 2b Fig. 2a Reliability of the model for the specie *Calamagrostis nitidula Pilg*

F. Biotic Factors Favoring the Emergence of Pioneer Species After the Retreat of the Pastoruri Glacier

Fig. 3 shows the study area after the retreat of the Pastoruri glacier. It has been observed that in the glacier retreat zone (Fig. 3-a), the plant-plant facilitation biotic factor only occurs in the parts already covered by pioneer species (Fig. 3-b). Also, it should be noted that the species of *Pycnophyllium brioides* (yareta), family of *juncaceae*, is conditioned in areas where water has contact with them because they are like sponges and can store water and nutrients. Pioneer species are very close to the ice masses, and these are conditioned to extreme climates and the geography of the periglacial area (Fig. 3-c).

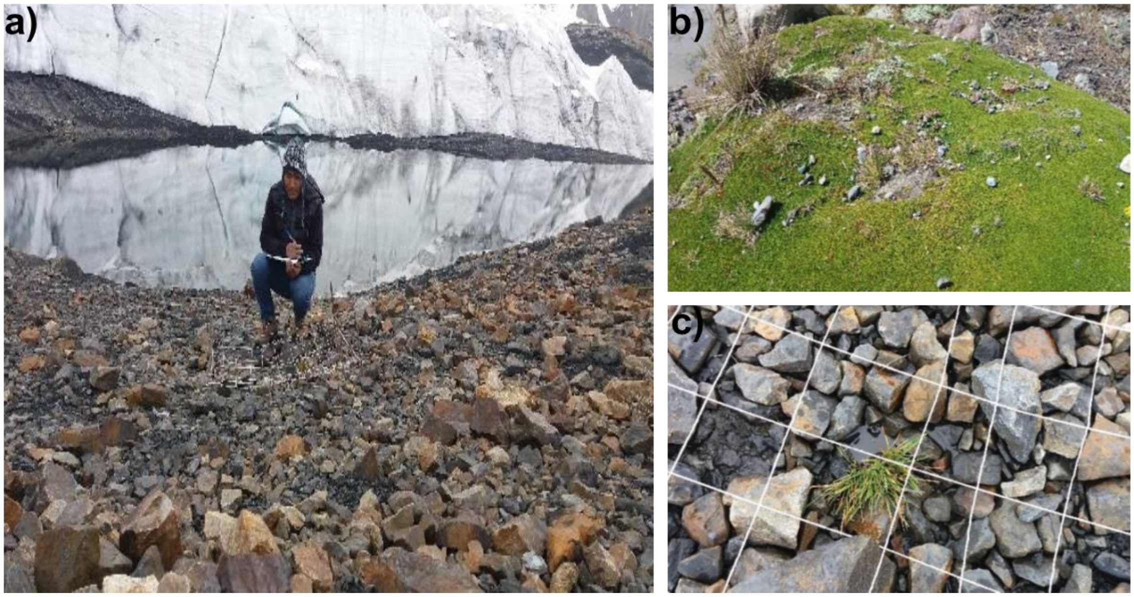

Fig. 3 Observation in field of the plant-plant facilitation biotic factor: a) Area of retreat of Pastoruri glacier, b) Area covered by pioneer species and c) Pioneer species in extreme geographic conditions

IV. DISCUSSION

In the retreat zone of the Pastoruri glacier, predominant species belonging to the *Astaraceae* and *Poaceae* families were found. This vegetation is typical of high altitude zones (4000 to 4800 m.a.s.l.) and, in addition, plant families such as *Alstroemeriaceae*, *Apiaceae*, *Aspleniaceae*, *Asteraceae*, *Brassicaceae*, *Cactaceae* and *Poaceae* are found in the Peruvian Andes [18]. In the research of [19], [20] and [21] also found similar species, and *Krapfia grace-servatiae* was reported as a species living at 4900 masl [22]. On the other hand, [23] found in the high Andean regions of northern, central and southern Peru (3900 - 5700 masl) twelve taxa belonging to the genus of *Jalcophila*, *Senecio*, *Werneria*, *Xenophyllum (Asteraceae)*, *Draba*, *Petroravenia*, *Rorippa*, *Weberbauera (Brassicaceae) and Stellaria (Caryophyllaceae*). Similarly, a research [24] report on these species considers high-altitude habitat. Other research such as that conducted by [25] indicated that climatic and physiographic conditions lead to a diversity of ecosystems and natural life zones occurring from 2700 to 4900 masl (ice zone), or are very relevant for changes in vegetation and for the development of different plant species [26]. The species of the Asteraceae family is the second most important after *Juncacea* present in high Andean wetlands [27]. Likewise, [28] also confirmed that the highest number of species present in high Andean wetlands were conformed by the Asteraceae and *Poaceae* families representing 40.63%. Transitions in plant composition are more evident when an area is affected by a natural phenomenon that eliminates the existing vegetation, and these phenomena are originated by floods, fires, forestry, glacial retreat, etc., first colonizing the so-called pioneer species that give rise to primary succession [1].

Differences in vegetation cover were observed in the wet and dry seasons. This difference is associated with rainfall that helps the species to populate more easily the glacial retreat areas, however, in the dry season there is a noticeable variation of this population due to the high mortality rate due to the increase in temperature and low soil moisture as a result of low precipitation. This effect was confirmed by [29, indicating that the tolerance of the species to heat during and after germination is not sufficient to withstand the temperatures that can occur in the summer.

It was found that at lower altitudes, competition and facilitation of species becomes more noticeable, thus at the monitoring point PA-01 with an altitude of 4997 m.a.s.l. the presence of only one species was found, unlike the monitoring point PA-04 with an altitude of 4473 m.a.s.l. where the presence of the family of juncaceae of the genus Distichia was observed. This species is peculiar to bofedales that provides plant-plant facilitation and acts as a nurse plant [30]. These pioneer species exist by overcoming many factors as well as adverse biotic and abiotic activities [12].

The periglacial area increases every year, in 2001 there was a glacier area of 234.495989 hectares and for 2017 it was 185 363 122 hectares, which meant a 20.95 % glacial retreat. [7], in his research also reported deglaciation, indicating that this is 10 to 12 meters per year. Other studies such as [3], [8] and [6] pointed out that the deglaciation problem occurs in all glaciers on the planet and that it is a consequence of global warming.

The modeling of the distribution of pioneer species after the retreat of the Pastoruri glacier showed a confidence range of finding plant species of 0.77 to 0.85 (according to the area under the ROC curve (Receiver operating characteristic curve) in the analysis performed with the MAXENT software) due to the maximum entropy of the area. The type of high Andean succession reflected in the Pastoruri periglacial area is primary succession because glacial retreat leaves free areas to colonize, and the species that colonize first are called pioneer species.

V. Conclusions

The pioneer species identified in the areas of primary succession after the retreat of the Pastoruri glacier belong to two families of species, including Asteraceae and *Poaceae*. The most influential meteorological factor for vegetation cover is precipitation, indicating that precipitation and soil moisture favor the appearance of pioneer species that are conditioned to the extreme climatic factors. At lower altitudes, plant facilitation was observed, mainly in the *juncaceae* families, which are representative species of the bofedales of mountain ecosystems, also known as "sponges" because they store water and nutrients. The modeling using Maxent and GIS allowed the identification of areas with pioneer plant species and also provided a reference of the behavior of the flora that may exist when glacial retreats occur in order to implement management and conservation programs.

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