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RESEARCH ARTICLE

Analysis of the geographic distribution and relationships among Peruvian wild species of *Arracacia*

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Abstract Relationships between *Arracacia* species were studied according to 28 morphological discriminant characters, in 90 accessions: 83 *Arracacia* (*Arracacia elata*, *A. incisa* and *A. xanthorrhiza*), and seven accessions of *Neonelsonia acuminata*, which has been confused with *A. elata.* The geographic distribution of the *Arracacia* species was determined from the passport data of the 90 accessions. *A. elata* was clearly differentiated from *N. acuminata* according to morphological characteristics. The species *A. incisa* was more closely related to *A. xanthorrhiza*. Within *A. xanthorrhiza* two forms, monocarpic, and polycarpic, were identified. The distribution of wild *Arracacia* species in Peru is characterized by two main ecological zones: (1) a dry zone, like the western Yunga and western and inter-Andean valleys of the Quechua region (with seasonal rain from November to March), where the species *A. incisa* and *A. xanthorrhiza* are present, and (2) a humid zone, like the Eastern Quechua where *A. elata* is adapted. These informations could be useful to establish strategies for *in situ* and *ex situ* conservation and management of germplasm.

Keywords *Arracacia* · Ecology · Geographic distribution · *Neonelsonia acuminata* · Peru · Plant genetic resources · Taxonomy

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Introduction

The species of *Arracacia* Bancroft are either perennial or biannual plants, characterized by the presence or absence of storage roots. They grow from Mexico to Bolivia and are adapted to altitudes ranging from 600 to 3,600 m (Hodge 1954; National Research Council 1989; Constance 1997; Hermann 1997). According to Knudsen (2003), about 30 species of *Arracacia* are presently recognized, and ten are distributed in the mountainous Andean region of South America (Venezuela, Colombia, Ecuador, Peru, and Bolivia).

Over the last 50 years, six species were reported from Peru: *A. xanthorrhiza* Bancroft, *A. peruviana* (Wolff) Const., *A. andina* Britt, *A. equatorialis* Const., *A. incisa* Wolff, and *A. elata* Wolff (Constance 1949; Brako and Zarucchi 1993). The last analysis of Peruvian species conducted by Blas (2005) reported only three species: *A. elata*, *A. incisa*, and *A. xanthorrhiza*. However, there are no reliable data about their geographic distribution and relationships, which set a problem for future collecting missions and *in situ* and *ex situ* germplasm conservation.

This study of the *Arracacia* genus in Peru was conducted with two goals: first, to formulate more precise hypotheses about the relationships among Peruvian *Arracacia* species and, second, to identify the distribution and ecology of *Arracacia* in Peru. These two goals are necessary to develop strategies for germplasm management of *Arracacia* spp. in the Andean region.

Materials and methods

Plant material

Plant material from 90 accessions of Peruvian arracacha was collected from 15 Peruvian Departments (Table 1). This collection included: 83 accessions of *Arracacia* wild species (*A. elata, A. incisa*, and *A. xanthorrhiza*) and seven accessions of *Neonelsonia acuminata* (Benth.) Coulter et Rose, often confused with *A. elata* or classified as *A. acuminata* Benth.

Morphological analysis

Wild forms were evaluated in the field at the time of collection and/or in the laboratory from herbarium material. Morphological characteristics from five wild plants per accession were recorded using the 28 descriptors previously selected (Table 2) (Blas 2005), from which 17 are double state and multistate qualitative variables and 11 are quantitative variables. These descriptors include characteristics of the storage roots, cormels, leaves, flowers, and fruits. Characters of the above-ground plant parts were recorded at flowering time, and characters of the underground parts were recorded immediately after uprooting the samples. The color of some plant organs was described according to the color chart of the Royal Horticultural Society (1995). States of shape characters were identified according to the plant identification terminology (Lindley 1951; Harris and Harris 2001). To analyze statistically each accession, we used the mode for qualitative characters and the mean for the quantitative characters.

Geographic distribution

Passport data (latitude, longitude, and altitude) were recorded for the 90 accessions of wild *Arracacia* species (Table 1). In addition, for each collection site, climate data (temperature and precipitation) were obtained from DIVA-GIS data base (Hijmans et al. 2002).

Data analysis

Data were compiled in a matrix of 90 accessions (or considered as the Operational Taxonomic Unit—OTU) × 28 descriptors. Each descriptor was analyzed using basic descriptive statistics with the help of Minitab 13.1 software. For multivariate analysis, the matrix data were standardized. The average taxonomic distances were then computed with NTSYS-pc 2.1 software (Rohlf 1994, 2000). With this matrix dendrograms were generated using "Unweighted Pair-group Method using Arithmetic Averages (UPGMA)" according to the Sequential Agglomerative Hierarchical Nested cluster analysis (SAHN) clustering program included in NTSYS-pc 2.1 (Rohlf 2000).

For the analysis of geographic distributions of species, all coordinate data (latitude and longitude) in the sexagesimal system were transformed to the decimal system. Data were analyzed and visualized by the geographic information system (DIVA-GIS 2.4: http://gis.cip.org/gis/tools/diva.htm) software (Hijmans et al. 2002). This software is aimed specifically at the analysis of biodiversity data, and allows the mapping of species and extraction of climate data for collecting sites.

Results and discussion

Genetic relationships of Peruvian wild species of *Arracacia*

The 90 analyzed accessions were classified according to the 28 selected descriptors, indicating two main

Table 1 Passport data of Peruvian *Arracacia* species (*A. elata*, *A. incisa*, and wild form of *A. xanthorrhiza*), including accessions of *Neonelsonia acuminata*

Numbers	Accession	Species	Departments	Province	Districts	Latitude (S)	Longitude (W)	Altitude (m)
1	RBS-19	*A. xanthorrhiza*	Cajamarca	Santa Cruz	Ninabamba	06°38′45.0″	78°47′05.0″	2,175
2	RBS-20	A. xanthorrhiza	Cajamarca	Santa Cruz	Ninabamba	06°38′45.0″	78°47′05.0″	2,175
3	RBS-30	*A. xanthorrhiza*	Ayacucho	Vilcashuaman	Huambalpa	13°45′05.3″	73°52′07.6″	3,876
4	RBS-31	*A. xanthorrhiza*	Ayacucho	Vilcashuaman	Huambalpa	13°45′54.4″	73°50′34.5″	3,364
5	RBS-32	*A. xanthorrhiza*	Ayacucho	Vilcashuaman	Huambalpa	13°46′28.5″	73°50′14.7″	2,948
6	RBS-33	*A. xanthorrhiza*	Junin	Huancayo	Huancayo	12°00′31.4″	75°10′10.4″	3,580
7	RBS-36	*A. xanthorrhiza*	Cusco	Cusco	Pisaq	13°27′20.7″	71°52′50.6″	3,450
8	RBS-38	*A. xanthorrhiza*	Cusco	Urubamba	Urubamba	13°18′38.0″	72°07′02.0″	2,900
9	RBS-39	*A. xanthorrhiza*	Cusco	Paruro	Paruro	13°47′01.6″	71°50′19.4″	3,041
10	RBS-40	*A. xanthorrhiza*	Cusco	Paruro	Paruro	13°43′43.07″	71°51′36.8″	3,374
11	RBS-42	*A. xanthorrhiza*	Cusco	Acomayo	Pillpinto	13°55′48.4″	71°46′37.5″	2,909
12	RBS-43	*A. xanthorrhiza*	Cusco	Acomayo	Acomayo	13°56′25.1″	71°43′33.9″	2,910
13	RBS-44	*A. xanthorrhiza*	Cusco	Acomayo	Acomayo	13°56′06.4″	71°41′08.9″	3,467
14	RBS-45	*A. xanthorrhiza*	Cusco	Acomayo	Acomayo	13°56′18.5″	71°38′31.1″	3,788
15	RBS-46	*A. xanthorrhiza*	Cusco	Paucartambo	Paucartambo	13°15′33.3″	71°36′49.5″	3,025
16	RBS-47	*A. xanthorrhiza*	Cusco	Paucartambo	Colquipata	13°22′03.7″	71°36′03.8″	3,467
17	RBS-48	*A. xanthorrhiza*	Cusco	Paucartambo	Caicay	13°32′34.3″	71°42′02.7″	3,550
18	RBS-49	*A. xanthorrhiza*	Cusco	Quispicanchis Concepcion	Quiquijana	13°47′52.1″	71°32′45.1″	3,254
19	RBS-59	*A. xanthorrhiza*	Junin	Tarma	Ingenio	11°52′43.2″	75°15′25.1″	3,555
20	RBS-61	*A. xanthorrhiza*	Junin	Morropon	Acobamba	11°20′59.0″	75°39′25.0″	2,940
21	RBS-62	*A. xanthorrhiza*	Piura	Ayabaca	Chalaco	05°02′15.0″	79°47′39.0″	2,400
22	RBS-63	*A. xanthorrhiza*	Piura	Huancabamba	Ayabaca	04°38′12.0″	79°42′51.0″	2,700
23	RBS-64	*A. xanthorrhiza*	Piura	Huancabamba	Sondor	05°19′54.5″	79°25′00.2″	2,865
24	RBS-65	*A. xanthorrhiza*	Piura	Chachapoyas	Sondor	05°17′12.0″	79°36′11.0″	2,920
25	RBS-78	*A. xanthorrhiza*	Amazonas	Huancayo	Longitad	06°23′40.4″	77°58′21.4″	2,464
26	RBS-96	*A. xanthorrhiza*	Junin		Huancayo	12°00′31.4″	75°10′10.4″	3,550
27	RBS-103	*A. xanthorrhiza*	Cusco	Cusco	Calca	13°18′29.9″	71°56′41.5″	3,120
28	RBS-107	*A. xanthorrhiza*	Cusco	Urubamba	Machupicchu	13°11′26.9″	72°27′36.5″	2,300
29	RBS-109	*A. xanthorrhiza*	Cusco	Urubamba	Machupicchu	13°12′05.5″	72°27′00.0″	2,460
30	RBS-110	*A. xanthorrhiza*	Cusco	Urubamba	Machupicchu	13°09′35.5″	72°32′08.0″	2,350
31	RBS-111	*A. xanthorrhiza*	Cusco	Urubamba	Machupicchu	13°15′16.0″	72°27′40.0″	2,800
32	RBS-118	*A. xanthorrhiza*	Cusco	Anta	Zurite	13°26′18.2″	72°13′59.1″	3,405
33	RBS-121	*A. xanthorrhiza*	Apurimac	Abancay	Tamburco	13°37′02.9″	72°51′40.1″	2,870

Table 1 continued

Numbers	Accession	Species	Departments	Province	Districts	Latitude (S)	Longitude (W)	Altitude (m)
34	RBS-122	*A. xanthorrhiza*	Apurimac	Andahuaylas	Talavera	13°40′16.1″	73°25′38.3″	2,721
35	RBS-124	*A. xanthorrhiza*	Huánuco	Huánuco	Cayran	09°59′45.0″	76°26′28.5″	2,750
36	RBS-125	*A. xanthorrhiza*	Huanuco	Pachitea	Chaglla	09°50′12.4″	75°53′49.3″	2,967
37	RBS-138	*A. xanthorrhiza*	Piura	Huancabamba	Huancabamba	05°18′54.5″	79°29′00.2″	2,863
38	RBS-146	*A. xanthorrhiza*	Piura	Ayabaca	Ayabaca	04°38′12″	79°42′32.5″	2,750
39	RBS-18	*A. xanthorrhiza*	Cajamarca	Santa Cruz	Santa Cruz	06°37′21.0″	78°56′34.0″	2,035
40	RBS-21	*A. xanthorrhiza*	Cajamarca	Santa Cruz	Ninabamba	06°38′45.0″	78°47′05.0″	2,175
41	RBS-37	*A. xanthorrhiza*	Cusco	Urubamba	Ollantaytambo	13°15′10.5″	72°15′26.6″	3,144
42	RBS-41	*A. xanthorrhiza*	Cusco	Paruro	Paruro	13°43′22.1″	71°51′48.1″	3,374
43	RBS-70	*A. xanthorrhiza*	Amazonas	Chachapoyas	Chachapoyas	06°14′59.7″	77°50′36.1″	2,408
44	RBS-71	*A. xanthorrhiza*	Amazonas	Chachapoyas	Chachapoyas	06°14′59.7″	77°50′36.1″	2,408
45	RBS-77	*A. xanthorrhiza*	Amazonas	Chachapoyas	Chachapoyas	06°14′31.5″	77°50′32.4″	2,323
46	RBS-90	*A. xanthorrhiza*	Ancash	Chiquian	Chiquian	10°09′24.4″	77°09′22.4″	3,700
47	RBS-93	*A. xanthorrhiza*	Ancash	Chiquian	Chiquian	10°09′24.4″	77°09′22.4″	3,690
48	RBS-97	*A. xanthorrhiza*	Ancash	Mcal Luzuriaga	Llama	08°53′10.7″	77°15′12.8″	3,150
49	RBS-98	*A. xanthorrhiza*	Ancash	Mcal Luzuriaga	Pampa Chacra	08°53′10.7″	77°15′11.8″	3,200
50	RBS-99	*A. xanthorrhiza*	Ancash	Mcal Luzuriaga	Pampa Chacra	08°53′28.2″	77°12′44.0″	3,450
51	RBS-123	*A. xanthorrhiza*	Cajamarca	Jaen	Jaen	05°42′15.0″	78°48′29.0″	2,035
52	RBS-131	*A. xanthorrhiza*	Cajamarca	Cajamarca	Encañada	07°03′09.8″	78°19′02.1″	3,477
53	RBS-132	*A. xanthorrhiza*	Cajamarca	Cajamarca	Encañada	07°06′26.5″	78°19′46.5″	3,040
54	RBS-133	*A. xanthorrhiza*	Cajamarca	Cajamarca	Baños del Inca	07°06′24.0″	78°25′22.5″	3,039
55	RBS-140	*A. xanthorrhiza*	Ayacucho	La Mar	San Miguel	13°05′04.3″	73°53′49.3″	2,750
56	RBS-141	*A. xanthorrhiza*	Ayacucho	Huamanga	Chiara	13°14′19.6″	74°14′25.1″	2,700
57	RBS-143	*A. xanthorrhiza*	Lima	Yauyos	Yauyos	12°27′23.0″	75°54′41.5″	2,948
58	RBS-144	*A. xanthorrhiza*	Lima	Yauyos	Yauyos	12°26′35.8″	75°55′58.5″	3,200
59	RBS-145	*A. xanthorrhiza*	Lima	Yauyos	Yauyos	12°27′19.8″	75°55′38.7″	3,032
60	RBS-147	*A. xanthorrhiza*	Cajamarca	Jaen	Huabal	05°41′30.3″	78°52′43.8″	2,100
61	RBS-148	*A. xanthorrhiza*	Cajamarca	Cajamarca	San Pablo	07°06′54″	78°49′15.5″	2,450
62	RBS-34	*A. incisa*	Lima	Canta	Canta	11°27′21.5″	76°36′28.2″	2,820
63	RBS-35	*A. incisa*	Lima	Canta	Canta	11°27′21.5″	76°36′28.2″	2,820
64	RBS-94	*A. incisa*	Lima	Huarochirí	San mateo	11°48′01.5″	76°19′54.7″	3,044
65	RBS-95	*A. incisa*	Lima	Canta	Canta	11°27′39.6″	76°36′55.5″	2,904
66	RBS-100	*A. incisa*	Ancash	Huaylas	Huaylas	08°52′04.0″	77°53′28.0″	2,600

Table 1 continued

Numbers	Accession	Species	Departments	Province	Districts	Latitude (S)	Longitude (W)	Altitude (m)
67	RBS-102	*A. incisa*	Lima	Huarochirí	Langa	12°06′54.4″	76°24′43.4″	3,177
68	RBS-120	*A. incisa*	Ancash	Bolognesi	Ocros	10°13′00.0″	77°23′46.0″	3,230
69	RBS-126	*A. incisa*	La Libertad	Otuzco	Salpo	08°00′07.2″	78°33′26.6″	2,983
70	RBS-127	*A. incisa*	La Libertad	Otuzco	Salpo	08°00′05.6″	78°33′30.5″	2,984
71	RBS-128	*A. incisa*	La Libertad	Otuzco	Salpo	08°00′08.6″	78°33′26.6″	2,985
72	RBS-129	*A. incisa*	La Libertad	Otuzco	Salpo	07°59′28.6″	78°33′21.4″	2,978
73	RBS-139	*A. incisa*	Ayacucho	Huamanga	Quinua	13°02′40″	74°28′57″	3,540
74	RBS-149	*A. incisa*	Lima	Huarochiri	San Mateo	11°46′43.7″	76°17′52.6″	3,443
75	RBS-150	*A. incisa*	Lima	Huarochiri	San Mateo	11°46′02.1″	76°18′04.8″	3,410
76	RBS-60	*A. elata*	Junin	Concepcion	Mariscal Castilla	11°34′35.2″	75°06′18.4″	3,089
77	RBS-112	*A. elata*	Cusco	Urubamba	Machupicchu	13°15′17.4″	72°27′43.7″	3,100
78	RBS-130	*A. elata*	Cajamarca	Cajamarca	Encañada	07°02′05.5″	78°12′39.0″	3,500
79	RBS-134	*A. elata*	Piura	Huancabamba	Canchaque	05°19′01.6″	79°30′48.8″	3,132
80	RBS-135	*A. elata*	Piura	Huancabamba	Sondorillo	05°19′13.3″	79°30′35.7″	3,146
81	RBS-136	*A. elata*	Piura	Huancabamba	Sondorillo	05°19′18.6″	79°30′16.1″	3,140
82	RBS-137	*A. elata*	Piura	Huancabamba	Huancabamba	05°19′12.0″	79°30′03.9″	3,112
83	RBS-151	*A. elata*?	Pasco	Pasco	Paucartambo	10°48′52.4″	75°50′50.2″	3,496
84	RBS-72	*N. acuminata*	Amazonas	Chachapoyas	Chachapoyas	06°15′37.8″	77°49′37.9″	2,524
85	RBS-73	*N. acuminata*	Amazonas	Chachapoyas	Chachapoyas	06°15′07.6″	77°50′40.4″	2,407
86	RBS-76	*N. acuminata*	Amazonas	Chachapoyas	Chachapoyas	06°14′31.5″	77°50′32.4″	2,323
87	RBS-104	*N. acuminata*	Cusco	Urubamba	Machupicchu	13°10′53.9″	72°30′37.3″	2,190
88	RBS-105	*N. acuminata*	Cusco	Urubamba	Machupicchu	13°10′06.1″	72°30′06.2″	2,250
89	RBS-108	*N. acuminata*	Cusco	Urubamba	Machupicchu	13°11′40.4″	72°26′49.1″	2,622
90	RBS-117	*N. acuminata*	Cusco	Urubamba	Machupicchu	13°10′07.0″	72°30′10.0″	2,450

Table 2 The 28 selected morphological descriptors used in the wild *Arracacia* analysis

Descriptors
Cormels and rootstock
Life form: 1 monocarpic, 2 polycarpic
Cormels or branches presence: 0 absent, 1 present (1or 2 cormels), 2 (>2 cormels) (determined in the field at sampling time)
Cormels shape: 1 hole long tube, 2 conic, 3 ovoid, 4 oblong, 5 oblong long, 6 oblong divided
Rootstock shape: 1 hole long tube (root-stock absent), 2 conic 3 oblong-divided, 4 oblong long divided, 5 oblong with few cormels, 6 oblong with many cormels
Leaves
Acumen leaflet shape: 1subacute, 2 acute, 3 largely acute
Leaflet adaxial surface (hairs presence):1 glabra, 2 only in veins, 3 squamose
Leaflet shape: 1 triangular-ovate, 2 ovate-oblong, 3 ovate-lanceolate, 4 lanceolate
Leaflet division (incision of terminal leaflet or lobule): 1 superficial, 2 medium 3 deeply incised
Leaflet margin: 1 mucronate-serrate, 2 serrate, 3 serrate-spinulose
Inflorescence and fruit
Involucel form: 1 entire conic, 2 oblong-linear 3 ovate-acuminate, 4 ovate with wing sheathing, 5 oblong-lanceolate, 6 ovate-lanceolate, 7 long linear
Involucel length (mm)
Involucel width (mm)
Number of rays/umbels
Ray length (cm)
Umbel form: 1 elongated flat, 2 flat, 3 conic flat
Generative shoot (GS) length (cm)
GS number/plant
Petal color: 1 greenish, 2 reddish brown, 3 dark-purple
Stylopodium shape: 1 pyramidal, 2 depressed
Number of umbels/GS
Pedicel length (mm)
Number of grains/GS
Carpophore: 1 bi-parted at 1/4, 2 bi-parted to base
Seed length (mm)
Seed width (mm)
Mericarp transection: 1 semi-rounded, 2 pentagon
Fruit shape: 1 rounded, 2 conic, 3 ovoid, 4 ovoid-oblong, 5 cordate
Storage root
Predominant storage root flesh color: 1 white, 2 yellow, 3 purple

Source: adapted from Blas (2005)

groups at 2.0 taxonomic distance (Fig. 1). The first group includes the species without storage roots, corresponding to *A. elata* and *N. acuminata*, and the second group includes species with storage roots, corresponding to *A. xanthorrhiza* and *A. incisa*.

States of qualitative characters are shown in Table 3, while basic descriptive statistics of quantitative characters are shown in Table 4. High-variation coefficients of the quantitative traits are expected due to their measurement directly *in situ*.

Species without storage roots

The first group of species was divided into two subgroups: *N. acuminata* and *A. elata*. *N. acuminata* was isolated from all *Arracacia* species. This taxon is often confused with *A. elata* and also classified as *A. acuminata* Benth (Knudsen 2003). Except for *A. elata, N. acuminata* is unlikely to be confused with any other Peruvian *Arracacia* species. Both species share similar leaf and leaflet forms, incision and size of leaflet, greenish and white flowers, and sprawling habit. However, the filiform involucel and broad cordate fruit of *N. acuminata* are two characters which separate the taxon from *A. elata* (Fig. 2a, b). *N. acuminata* was first described as *A. acuminata* Benth, but later transferred to the genus *Neonelsonia* J.M. Coulter et Rose. Constance (1949) and Mathias and Constance (1962) maintained this view, whereas Knudsen (2003) included the genus in *Arracacia*. We agree with the maintenance of *Neonelsonia*, since the two characters – cordate fruit and long filiform involucel – are not considered in the taxonomical key of *Arracacia* (Mathias and Constance 1962).

Arracacia elata is not likely to be confused with any of the Peruvian *Arracacia* species. In general, *A. elata* displays spinulose-serrate leaflet margin, ovoid fruit with acute apex, and ovate-lanceolate involucel.

In *A. elata*, there is one accession, RBS-151, showing differences from the other populations, i.e., serrate and revolute leaflet margin, white adaxial leaflet, and plant size (1.5–2 m); nevertheless this accession shares the same habitat as the other populations of *A. elata* (e.g., they prefer the eastern humid highland, especially in permanently humid riparian vegetation).

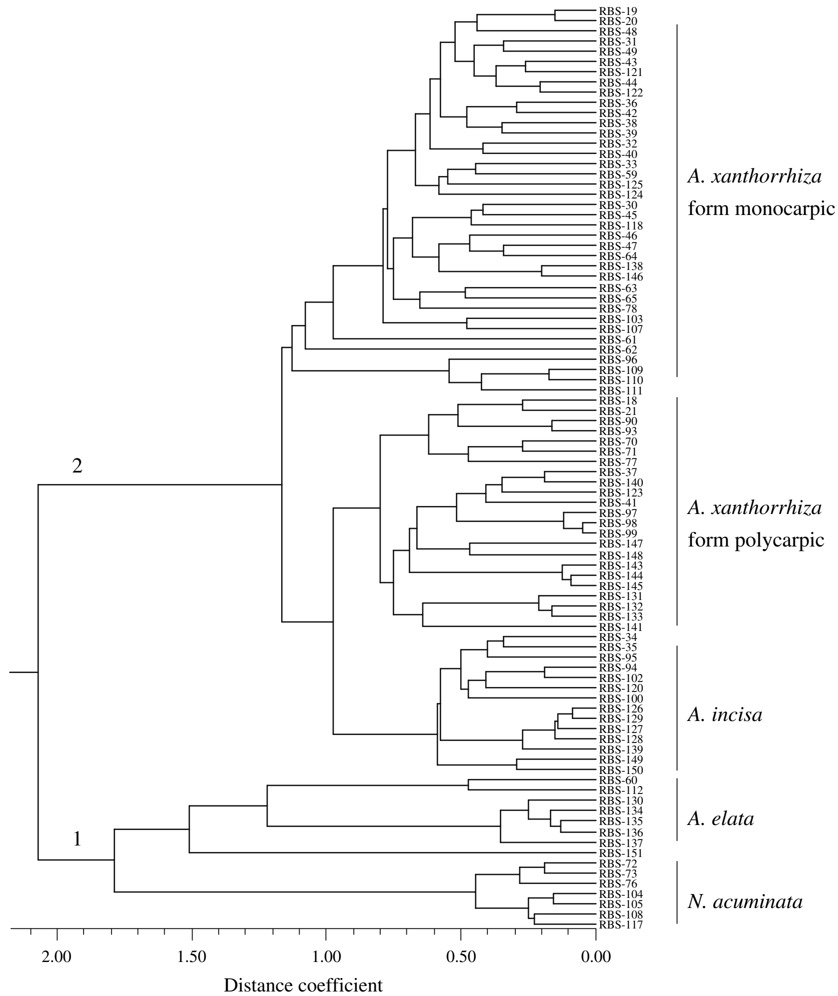


Fig. 1 Dendrogram elaborated from 83 *Arracacia* and seven *Neonelsonia acuminata* accessions, and 28 morphological descriptors

Species with tuberous roots

In species with tuberous roots (*A. incisa* and *A. xanthorrhiza*), two sub-groups were found: monocarpic and polycarpic forms. Monocarpic plants die once they have flowered and produced fruits, although it may take several years before they develop the first generative shoots. In contrast, polycarpic plants of *Arracacia* are perennials. They flower and fruit many times (Hermann 1997). Cultivated arracacha genotypes from inter-Andean valleys have been observed to grow during 4–5 years in backyard gardens (Blas 2005). According to the same author, monocarpic wild *Arracacia* plants produce a large amount of seeds (394 ± 265/generative shoot), one or two cormels, and size of the generative shoot is tall (140 ± 40 cm). In contrast, the polycarpic plants produce a moderate to low amount of seeds (101 ± 55/generative shoot), have well developed cormels and rootstocks, and medium size of generative shoot (101 ± 36 cm) (Tables 3, 4). This type of classification should be analyzed further in the same ecological conditions, in order to evaluate the expression and behavior of these characters within and between Peruvian *Arracacia* species.

Within the polycarpic form, two groups were found: a first group corresponding to 14 accessions of *A. incisa*, and a second group corresponding to 23 accessions of the *A. xanthorrhiza* wild form. The presence of *A. incisa* within the polycarpic form supports the view that it is closely related to *A. xanthorrhiza* through the shared compressed basal stem structures (cormels), the ramification of the flowering stem and the perennial growth habit

Table 3 States of 17 qualitative characters in each analyzed *Arracacia* species and *Neonelsonia acuminata*

Species	Qualitative characters[a]																
	1	2	3	4	5	6	7	8	9	10	15	18	19	23	26	27	28
A. xanthorrhiza monocarpic form	1	1	2, 3	2	2, 3	2	2, 3, 4	2, 3	2	1, 2	3	2, 3	2	2	2	3	1, 2
A. xanthorrhiza polycarpic form	2	2	5, 6	4, 5	2, 3	2	1, 2, 3, 4	2, 3	2	1, 2, 3	2, 3	1, 2, 3	2	2	2	3, 4	1
A. incisa	2	2	4, 5	3, 4	1, 2	2	1, 2	2, 1	2	3, 4	2	2, 3	2	2	2	1	1
A. elata	2	0	1	1	3	1	4	3	3	5	1	1	1	1	1	2	1
N. acuminata	2	0	1	1	2	1	2	2	1	7	1	5, 6	1	1	1	5	1

[a] Character numbers and their state according to Table 2 (see Materials and methods)

(Table 3). *A. incisa* can be distinguished by the length of the involucel which exceeds the flower, the conspicuously scarious margins, and the semi-rounded seeds. In addition, *A. incisa* is characterized by a short plant size, combining short petioles and small and incised leaflets (Fig. 2c). Additionally, the taxon is geographically isolated, being present in hilly and dry areas of the Peruvian eastern and central highlands of Quechua region, while *A. xanthorrhiza* is growing along the eastern, inter-Andean valleys and western Peruvian highlands.

Within the monocarpic form, 38 accessions are very close together and form a cluster in the dendrogram (Fig. 1). The *A. xanthorrhiza* monocarpic form differs from the *A. xanthorrhiza* polycarpic form by the root dying away after the end of flowering, the presence of one (rarely 2) cormel and one (rarely 2) reproductive shoot per plant. In addition, the reproductive shoot is very vigorous and shows many ramifications that carry up to 1,000 seeds (Table 4).

Arracacia xanthorrhiza polycarpic form is related to *A. xanthorrhiza* monocarpic form, but differs in some characters: the presence of cormels with several shoots, the few umbels or low amount of seeds/generative shoot, the short plant size, and the perennial behavior (Fig. 2d, e).

Also, *A. xanthorrhiza* polycarpic form appears to be the most closely related to *A. xanthorrhiza* cultivated form, sharing a perennial habit and similar ramifications of the flowering shoot, leaves, involucel, and fruit shape (Blas 2005; Blas et al. 2007). But, *A. xanthorrhiza* polycarpic form differs from *A. xanthorrhiza* cultivated form, in having few and small cormels, and often a splitting fibrous root (Fig. 2e, f).

According to this analysis, three species from Peru were clearly identified inside the *Arracacia* genus: *A. elata*, *A. incisa*, and *A. xanthorrhiza* (including: monocarpic and polycarpic wild forms).

Geographic distribution of *Arracacia* genus in Peru

The geographic distribution of the four species *A. elata*, *A. incisa*, *A. xanthorrhiza*, and *N. acuminata* according to latitude, longitude, and altitude data is indicated in Figs. 3 and 4. Collections of the *Arracacia* genus in Peru cover an altitudinal range from 2,035 to 4,050 m, from the Department of Piura (04°38′12.0″S) to Cuzco (13°56′25.1″S). This extensive altitudinal distribution involves four natural regions classified by Pulgar (1987) as: Yunga (500–2,300 m), Quechua (2,300–3,500 m), Suni (3,500–4,000 m), and Jalca (4,000–4,800 m). The most favorable environment for arracacha growth is between the Yunga and Quechua regions, mainly in the Eastern and Western side of the Andes and in the inter-Andean valleys.

The higher percentage of the *Arracacia* accessions come from the Quechua region, representing 81% of the total number of analyzed accessions, while the regions Suni, Yunga, and Puna represent 10, 8, and 1%, respectively (Fig. 4). This is in agreement with Pulgar's observation (1987), who considered arracacha as an indicator plant for the Quechua region. In general, in this region the predominant climate is temperate, with significant differences between day and night temperatures. The annual average temperature fluctuates between 11 and 16°C, the maximum temperature between 22 and 29°C, and the minimum

Table 4 Basic descriptive statistics of 11 quantitative characters analyzed in *Arracacia* species and *Neonelsonia acuminata*

Ch number	*A. xanthorrhiza*						*A. incisa*			*A. elata*			*N. acuminata*		
	monocarpic form (*n* = 38)			polycarpic form (*n* = 23)			(*n* = 14)			(*n* = 8)			(*n* = 7)		
	Mean ± SD	CV	Range	Mean ± SD	CV	Range	Mean ± SD	CV	Range	Mean ± SD	CV	Range	Mean ± SD	CV	Range
11	4.9 ± 0.6	11.8	3.8–6.2	5.3 ± 1.0	18.4	3.5–8.4	8.4 ± 1.5	17.9	5.2–10.3	13.7 ± 2.3	17.0	10.4–16.2	16.6 ± 1.1	6.5	15.6–18.4
12	0.6 ± 0.5	78.4	0.3–2.8	1.1 ± 0.9	85.0	0.4–3.1	1.6 ± 0.7	45.4	0.9–3.0	3.3 ± 1.6	47.6	0.8–4.8	0.3 ± 0.1	26.2	0.3–0.5
13	14.3 ± 2.4	17.1	8.4–20.0	10.5 ± 2.6	25.3	7.2–15.6	11.1 ± 1.5	13.8	8.6–13.8	29.5 ± 14.2	48.1	10.4–42.0	14.7 ± 0.6	4.1	14.0–15.4
14	4.0 ± 0.7	16.3	2.6–5.4	3.4 ± 0.6	16.6	2.4–4.5	3.2 ± 0.5	14.2	2.4–3.8	7.5 ± 1.3	17.0	4.9–8.7	5.4 ± 0.2	4.3	5.1–5.7
16	139.6 ± 39.7	28.4	60.0–206.5	101.3 ± 36.1	35.6	46.0–160.5	72.4 ± 17.5	24.2	45.0–95.8	385.8 ± 127.8	33.1	81.0–460.5	487.2 ± 101.3	20.8	350.6–655.4
17	1.1 ± 0.3	29.9	1.0–2.0	2.2 ± 0.7	32.7	1.0–4.2	3.4 ± 0.8	23.1	2.3–5.0	5.6 ± 0.5	8.2	5.0–6.2	5.6 ± 0.5	9.6	5.0–6.0
20	27.6 ± 12.6	45.6	10.5–70.2	13.7 ± 5.5	40.6	5.0–27.6	12.9 ± 6.7	52.2	5.4–25.2	5.7 ± 0.7	11.7	5.2–7.2	7.7 ± 1.7	22.2	5.8–10.8
21	4.8 ± 1.2	25.5	2.5–7.2	4.0 ± 0.5	13.8	2.9–5.0	3.3 ± 0.4	13.0	2.8–4.1	8.6 ± 1.5	16.8	5.4–10.2	6.0 ± 1.7	28.1	3.9–8.0
22	394.4 ± 264.9	67.2	62.6–1037.4	100.7 ± 55.4	55.0	30.0–310.0	115.5 ± 60.9	52.7	32.0–235.8	140.3 ± 87.1	62.1	29.0–230.2	100.9 ± 44.2	43.8	50.0–163.2
24	7.8 ± 1.3	17.1	5.8–11.2	7.1 ± 0.8	11.7	5.2–8.2	6.9 ± 0.5	7.3	6.2–8.2	7.4 ± 1.8	23.8	4.6–9.2	5.1 ± 0.5	9.4	4.4–5.7
25	2.3 ± 0.2	10.6	1.9–3.0	2.3 ± 0.2	10.1	1.8–2.7	2.6 ± 0.1	4.2	2.4–2.8	1.9 ± 0.1	7.7	1.7–2.2	2.0 ± 0.1	4.3	1.9–2.2

Ch # character numbers according to Table 2 (see Materials and methods), *SD* standard deviation, *CV* coefficient of variation, *n* number of accessions per taxon

temperature during the winter between -4 and 7°C. The latter occurs between May and August. During the sunny days, the temperature is high under shade conditions, with temperatures higher than 20°C; but the nights are fresh, with temperature lower than 10°C. Elevations over 3,200 m are known as the limit of the winter frosts, which take place by the alteration of days with strong solar radiation and calm nights of transparent sky with temperatures below 0°C (Pulgar 1987). The region Quechua offers some advantages for the life development, such as: good climate, better soils for cultivation, water for irrigation, and great amounts of firewood.

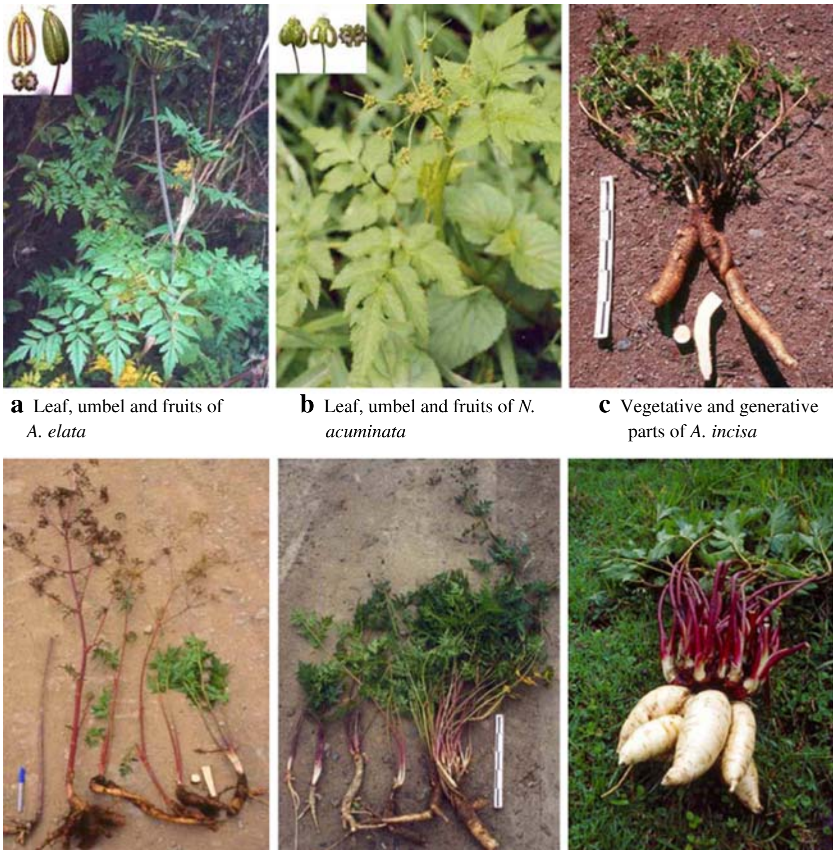
Altitudinal distribution patterns of wild arracacha are very variable (Fig. 4). *A. xanthorrhiza*, with both monocarpic and polycarpic forms, is mainly found between 2,000 and 4,000 m, *A. incisa* is also found between 2,000 and 4,000 m, *A. elata* is present between 3,000 and 4,000 m, and *N. acuminata* is present between 2,000 and 3,000 m. Considering the different altitudinal adaptation of the various collected materials and the very wide ecological conditions prevailing in their distribution areas, it will be possible to identify genotypes characterized by a high level of tolerance to frost and drought conditions.

Climatic characteristics

Two different ecological niches are found for wild *Arracacia* in Peru. The first ecological niche concerns the dry areas of Western Yunga and Western and inter-Andean valleys of the Quechua region where rainfalls occur from November to March. The second ecological niche concerns the permanent humid regions of the Eastern Quechua and upper forest where *A. elata* is particularly well adapted.

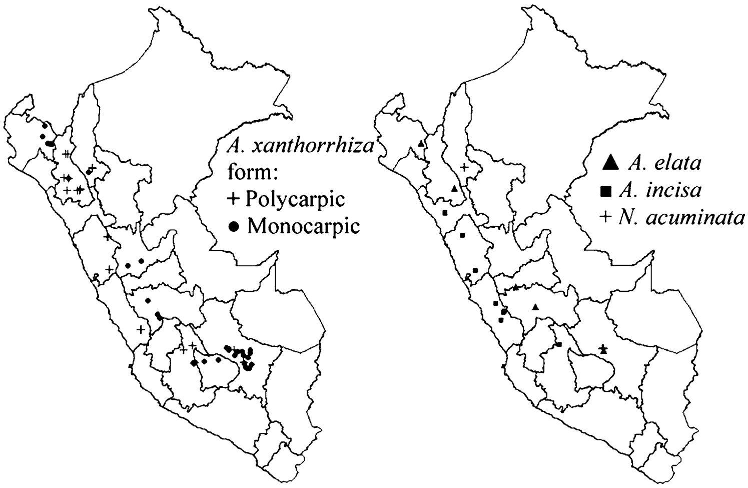
In the first niche, some wild species, such as *A. incisa* and *A. xanthorrhiza*, are present. Apparently, the *Arracacia* specimens growing in this region are characterized by some dormancy type: during the seven dry months prevailing in this region, plants remain dormant until the next rainy season. The large storage root, rootstock, and cormels may help explain this survival ability. In addition, the floral biology is affected by the environmental factors such as water, nutrients, temperature, and light. Under some stress of these factors (e.g., poor soil fertility, drought, and

Fig. 2 Vegetative and generative structures of *Arracacia elata* (**a**), *Neonelsonia acuminata* (**b**) *Arracacia incisa* (**c**), and *Arracacia xanthorrhiza* [wild forms: monocarpic form (**d**) and polycarpic form (**e**) and cultivated form (**f**)]



a Leaf, umbel and fruits of *A. elata*
b Leaf, umbel and fruits of *N. acuminata*
c Vegetative and generative parts of *A. incisa*
d Monocarpic form **e** Polycarpic form
Vegetative and generative parts of *A. xanthorrhiza* wild forms
f Storage root, cormels and leaves of *A. xanthorrhiza* cultivated form

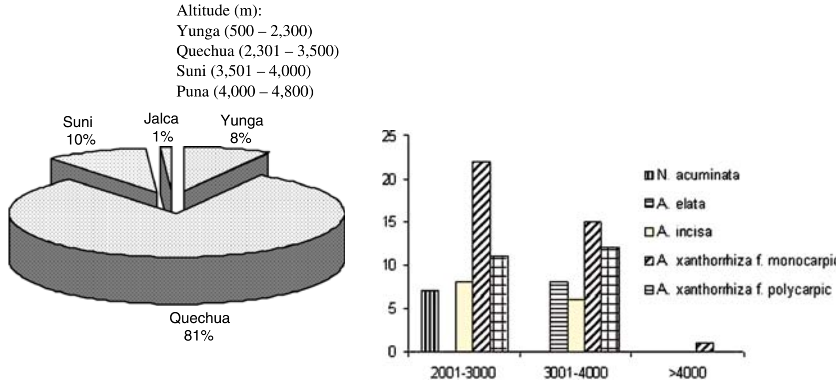
Fig. 3 Geographic distribution of *Arracacia* wild species in Peru



frost), the plants produce a greater proportion of male flowers and fewer hermaphrodite flowers (Salick and Merrick 1990). This could explain presence of andromonoecious plants in *Arracacia* specimens.

In our main collection of wild arracacha specimens with storage roots, we found a large amount of seeds. Propagation of these species was mainly sexual, and many seedlings were observed during our field survey.

Fig. 4 Altitudinal distribution of the *Arracacia* species and *Neonelsonia acuminata* according to the Peruvian natural regions

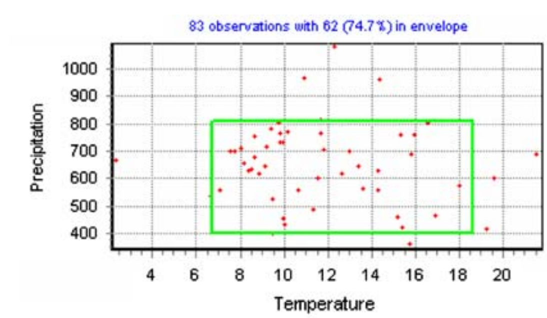


Distribution by regions　　Distribution by species

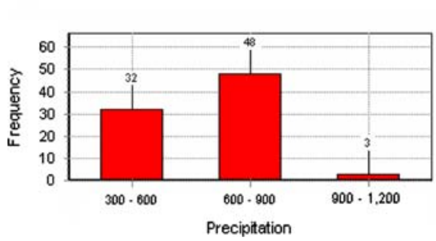
The areas of wild population distribution are characterized by open fields with or without moderately compact vegetation of shrubs and/or herbaceous plants. Generally, wild arracacha is growing among other shrub plants, like “kishuar” (*Buddleja incana* Ruiz et Pav.) “chamana” (*Dodonaea viscosa* Jacq.), and “chilca” (*Baccharis lanceolata* Kunth); succulent plants from the Bromeliaceae [*Aechmea fernandae* (E. Morren) Baker, *Guzmania claviformis* H. Luther, and *Tillandsia complanata* Bentham], Cactaceae families [*Neoraimondia arequipensis* (Meyen) Backeb, *Opuntia ficus-indica* (L.) Mill., and *Weberbauerocereus rauhii* Backeb.]; and herbaceous plants from: Basellaceae (*Ollucus tuberosus* Caldas), Oxalidaceae [*Oxalis dombeii* St. Hil., *O. herrerae* (L.) Waterman, *O. tuberosa* Molina, and *O. weberbaueri* Diels], *Poaceae* [*Stipa ichu* (Ruiz et Pav.) Kunth.], *Solanaceae* [*Lycopersicon peruvianum* (L.) Mill., *Nicotiana undulata* Ruiz et Pav., *Solanum nitidum* Ruiz et Pav., *S. acaule* Bitter, and *S. albicans* Ochoa], and *Tropaeolaceae* (*Tropaeolum bicolor* Ruiz et Pav., *T. cochabambae* Buchenau, *T. minus* L., and *T. tuberosum* Ruiz et Pav.).

The second ecological niche concerns the permanent humid regions of the Eastern Quechua and upper forest where *A. elata* is particularly well adapted. Specimens of this species do not have tuberous storage roots and the aerial parts are vigorous and tall

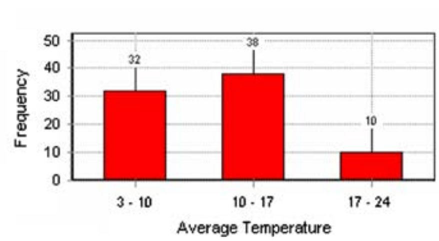
Fig. 5 Climatic data corresponding to the regions of *Arracacia* accessions distribution. **a** Distribution of *Arracacia* accessions according to temperature and rainfall. **b** Distribution frequencies of *Arracacia* accessions according to rainfall. **c** Distribution frequencies of *Arracacia* accessions according to temperature



a Distribution of *Arracacia* accessions according to temperature and rainfall



b Distribution frequencies of *Arracacia* accessions according to rainfall



c Distribution frequencies of *Arracacia* accessions according to temperature

(4 ± 1 m). *A. elata* genotypes are setting many seeds (140 ± 87 seeds/generative shoot according to Table 4), but vegetative propagation through adventitious root formation of the creeping stem is also observed. So, in *A. elata* there is both sexual and asexual propagation, although the seed dispersal seems to be more important. Specimens were usually found along the riverbanks in the cloudy Eastern highlands, alongside compact vegetation.

According to our field surveys, wild arracacha is mainly distributed in rural communities and near small villages in the mountainous Quechua and Suni regions. In some places, the wild arracacha is considered as a weed, e.g., in Apurimac, Cajamarca, and Cusco Departments. But in general, the wild forms are not considered as invasive. According to our observations, wild arracacha is not presently threatened directly by human activities. Indeed, in this region, agricultural activities are characterized by traditional and subsistence farming, with very little or no connection to markets.

According to the climatic data, 75% of the evaluated accessions come from regions where the average temperature ranges from 7 to 19°C and the rainfall varies from 400 to 810 mm (Fig. 5a). While 39% of the accessions grow between 300 and 600 mm, more than 57% of the accessions grow between 600 and 900 mm and <4% are present between 900 and 1,200 mm (Fig. 5b). Concerning the temperature range, 39% of the accessions are present in areas where average temperature varies between 2 and 10°C, 46% in areas where average temperature varies between 10 and 17°C, and 12% in areas where average temperature varies between 17 and 24°C (Fig. 5c). Such data could also be useful to establish strategies for *in situ* and *ex situ* germplasm management in Peru. Up to now, data on the precise distribution of *Arracacia* in the Andean region were lacking. No accurate distribution map of *Arracacia* species has been published.

Conclusions

Clustering 90 accessions (including wild *Arracacia* spp. and *N. acuminata*) with the 28 selected descriptors, showed two main groups. The first group includes the species without storage roots, corresponding to *A. elata* and *N. acuminata*, and the second group includes the species with storage roots, corresponding to *A. xanthorrhiza*, and *A. incisa*.

The filiform involucel that extends from the flowers and the broad cordate fruit of *N. acuminata* are two characters which clearly separate this taxon from *A. elata*. In addition, *A. elata* shows spinulose-serrate leaflet margin, ovoid fruit, and ovate-lanceolate involucel.

Species with tuberous roots are divided into monocarpic and polycarpic plants. In the polycarpic plants two species are found: *A. incisa* and the wild form of *A. xanthorrhiza*, showing the close relationship between the two taxa. In addition, they share the following characteristics: compressed basal stem structures (cormels), the ramification of the flowering stem and the perennial growth habit. On the other hand, *A. incisa* can be distinguished from *A. xanthorrhiza* by the length of the involucel which exceeds the flower, the conspicuously scarious margins, and the semi-rounded fruits.

Arracacia xanthorrhiza polycarpic form differs from *A. xanthorrhiza* monocarpic form by the presence of cormels with several shoots, the limited number of umbels or the low amount of seeds/generative shoot, the short plant size, and the perennial behavior. From these results, three species from Peru are clearly identified inside the *Arracacia* genus: *A. elata*, *A. incisa*, and *A. xanthorrhiza* (including: monocarpic and polycarpic wild forms). In order to identify the most discriminating characters among the Peruvian accessions collected and measured *in situ*, it is suggested to compare a representative sample of them together in the same geographical stations.

The most favorable environment for wild arracacha growth is between the Quechua and Suni regions, mainly in the Eastern and Western side of the Andes and in the inter-Andean valleys. However, wild specimens are more frequently found in the Quechua region (81% of accessions). Consequently, the distribution of wild *Arracacia* species in Peru is characterized by two main ecological zones: (1) a drier zone, like western Yunga and western and inter-Andean valleys of the Quechua region (with seasonal rain from November to March), where the species *A. incisa* and *A. xanthorrhiza* are present, and (2) a permanent humid zone, like the Eastern Quechua where *A. elata* is adapted. Due to this wide distribution, it is expected to identify genotypes more adapted or tolerant to drought, humid, and frost conditions. This information could be useful to establish strategies for *in situ* and *ex situ* conservation and management of germplasm in the Andean region.

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