Promoting the conservation and use of underutilized and neglected crops. 21.

Andean roots and tubers: Ahipa, arracacha, maca and yacon

M. Hermann and J. Heller, editors

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Foreword

Humanity relies on a diverse range of cultivated species; at least 6000 such species are used for a variety of purposes. It is often stated that only a few staple crops produce the majority of the food supply. This might be correct but the important contribution of many minor species should not be underestimated. Agricultural research has traditionally focused on these staples, while relatively little attention has been given to minor (or underutilized or neglected) crops, particularly by scientists in developed countries. Such crops have, therefore, generally failed to attract significant research funding. Unlike most staples, many of these neglected species are adapted to various marginal growing conditions such as those of the Andean and Himalayan highlands, arid areas, salt-affected soils, etc. Furthermore, many crops considered neglected at a global level are staples at a national or regional level (e.g. tef, fonio, Andean roots and tubers, etc.), contribute considerably to food supply in certain periods (e.g. indigenous fruit trees) or are important for a nutritionally well-balanced diet (e.g. indigenous vegetables). The limited information available on many important and frequently basic aspects of neglected and underutilized crops hinders their development and their sustainable conservation. One major factor hampering this development is that the information available on germplasm is scattered and not readily accessible, i.e. only found in 'grey literature' or written in little-known languages. Moreover, existing knowledge on the genetic potential of neglected crops is limited. This has resulted, frequently, in uncoordinated research efforts for most neglected crops, as well as in inefficient approaches to the conservation of these genetic resources.

This series of monographs intends to draw attention to a number of species which have been neglected in a varying degree by researchers or have been underutilized economically. It is hoped that the information compiled will contribute to: (1) identifying constraints in and possible solutions to the use of the crops, (2) identifying possible untapped genetic diversity for breeding and crop improvement programmes and (3) detecting existing gaps in available conservation and use approaches. This series intends to contribute to improvement of the potential value of these crops through increased use of the available genetic diversity. In addition, it is hoped that the monographs in the series will form a valuable reference source for all those scientists involved in conservation, research, improvement and promotion of these crops.

This series is the result of a joint project between the International Plant Genetic Resources Institute (IPGRI) and the Institute of Plant Genetics and Crop Plant Research (IPK). Financial support provided by the Federal Ministry of Economic Cooperation and Development (BMZ) of Germany through the German Agency for Technical Cooperation (GTZ) is duly acknowledged.

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Andean roots and tubers at the crossroads

At least 25 species of root and tuber crops are native to South America. They belong to 16 botanical genera and 15 families including mono- and dicotyledons. This represents a greater range of root and tuber crop diversity in terms of taxonomic affiliation and ecological adaptation than occurs anywhere else in the world (Hawkes 1989). New World root and tuber crop diversity is particularly high-in the Northern and Central Andes, a mountainous area north of the Tropic of Capricorn, which makes up only a minor fraction of the continent's land mass, but is of great altitudinal and climatic variation. The resulting floristic richness and ancient cultural diversity led to the Andes' abundance in domesticates.

Apart from the seven species of cultivated (Solanum) potatoes, of which only the Irish potato (Solanum tuberosum) is known worldwide, there are another nine lesser-known species native to the Andes (Table l), commonly referred to as Andean Root and Tuber Crops (ARTC). ARTC are mainly grown for their edible underground organs and are traditionally, but not exclusively, associated with indigenous people, who use them for subsistence or as cash crops. From a classification point of view, ARTC would be considered a fairly inappropriate assemblage of very dissimilar things. Not only does each of them belong to a distinct botanical family, they differ considerably in life form, propagation method, chemical composition, utilization, storage behaviour as well as economic scope.

With the exception of biennial maca (which can assume an annual habit under certain conditions; see chapter on maca), ARTC are perennial plants. Although most ARTC have retained sexual fertility, they are mostly propagated vegetatively. Interestingly, this also applies to arracacha, which belongs to the umbellifer family with numerous Old World representatives usually grown from seed. Ahipa and maca are exclusively grown from sexually obtained seed (Table 1).

As seen in Table 1, ARTC occur in three altitudinally determined phytogeographic zones: the cool-temperate highlands from about 2500 to 4000 m altitude, the subtropical zone in inter-Andean valleys and on both slopes of the Andes (1000-2500 m altitude) and the inhospitably cold subarctic puna (4000-4500 m).

The highland tubers oca, ulluco and mashua share many similarities with potatoes in terms of ecological requirements, cropping systems and uses (Table 1). Their phenologies are also very much alike. Each cropping cycle starts with a sprouting tuber which is planted at the onset of the rainy season and ends with a senescent plant that, on underground stolons, has produced dormant tubers with the dual purpose of food and seed. Although clearly perennials, these crops show a determinate growth habit and true senescence, that is, aerial plant parts die after tuber bulking is completed, even if favourable growing conditions persist. Tuber formation in these species occurs only in days shorter than 13-14 hours. This, in combination with long crop duration (6-9 months), is a serious constraint to the cultivation at extra-tropical latitudes. The three tubers are moderately frost-resistant and occur with their wild relatives at high altitudes, often near the altitudinal limit of agriculture. Owing to their cold-tolerance, they represent one of the few cropping

Table 1. Attributes of Andean root and tuber crops

Common name [†]	Botanical name and authority	Family	Life form [‡]	Edible part [§]	Propagule[§,¶]	Starch content [††] (%)	Undesirable compounds	Yield (t/ha)	Crop duration (months)
Cool-temperate (2500-4000 m altitude)									
Oca	*Oxalis tuberosa* Molina	Oxalidaceae	p	T	T	10-15	Soluble oxalate	10-40	6-9
Ulluco	*Ullucus tuberosus* Caldas	Basellaceae	p	T	T	<10	Mucilage	5-20	6-9
Mashua	*Tropaeolum tuberosum* R. & P.	Tropaeolaceae	p	T	T	<10	Isothiocyanates	30-60	6-9
Subtropical (1000-2500 m altitude)									
Arracacha	*Arracacia xanthorrhiza* Bancroft	Umbelliferae	p	R	St	12-20	None	12-16	10-14
Yacón	*Smallanthus sonchifolius* (Poepp. & Endl.) H. Robinson	Compositae	p	R	St	0 [‡‡]	None	40-60	10-12
Achira	*Canna edulis* Ker-Gawler	Cannaceae	p	Rh	Rh	12-18	None	30-80	10-12
Mauka	*Mirabilis expansa* R. & P.	Nyctaginaceae	p	R	St	18-25	Raphids [§§]	20-50	12-18
Ahipa	*Pachyrhizus ahipa* (Weddell) Parodi	Fabaceae	p	R	S	9-14	None	30-50	5-10
Puna or cold steppe (4000-4500 m altitude)									
Maca	*Lepidium meyenii* Walpers	Cruciferae	b	Hyp	S	n.d.	?	10-15	8-9

[†] Only the most widely used common names are given here.
[‡] p=perennial, b=biennial.
[§] Only principal edible parts are indicated. Hyp=hypocotyl/root, R=root, Rh=rhizome, St=basal stem; T=tuber.
[¶] Only the agriculturally used propagules are indicated, S=sexual seed.
[††] In % of edible fresh matter.
[‡‡] Yacon dry matter is mostly oligo-fructans.
[§§] Raphids are needle-shaped oxalate crystals causing astringency.
n.d. = no data.

options at high altitudes and complement a diet based on potatoes, barley, faba beans and chenopod grains. Because of their high starch content, the highland tubers are always cooked for consumption.

With regard to propagation mode, chemical composition and economic scope, the subtropical ARTC are a much more heterogeneous group (Table 1). In the vegetatively propagated achira, the edible part also serves as the propagule. By contrast, arracacha, yacon and mauka cannot be propagated from the edible root. These plants develop very peculiar rootstocks with fleshy offshoots that serve as propagules. Propagation of ahipa, as mentioned above, is through sexual seed. High starch contents in some species - notably arracacha, achira and mauka - require cooking of the edible parts for better digestion and palatability On the other hand, the sweet-tasting yacon and ahipa, with their elevated oligo-saccharide contents, are eaten raw and function as 'fruits' in rural diets.

As a rule, plant development in these species is indeterminate to the extent to which nutrient supply, space, temperatures and photosynthetically active radiation permit continually renewed shoot growth. Crop duration as well as the matter accumulated by single roots (or rhizomes) are therefore much more variable and are heavily influenced by cropping practices. To realize the high yield potential, these species are mostly cultivated for one year.

The ecological requirements of subtropical ARTC are not well understood. However, from the analysis of their present distribution and sporadic reports of cultivation at high latitudes, we can conclude that they are frost-sensitive and for the most part daylength-neutral with regard to the production of the underground organs. Although currently restricted to mid-elevations in tropical highlands, these species have potential for wider distribution and use than the high-altitude tubers.

Maca is a very peculiar root crop. The storage structure is partly made up from hypocotyl and taproot tissue. Maca is the only Cruciferae known to have been domesticated in the Americas. It is cultivated only in Peru. An extremely hardy crop, maca is grown in the puna, a montane steppe at 4000-4400 m altitude which is characterized by regular frosts and mean monthly maximum temperatures under 12°C during the growing season.

Circumstantial evidence suggests that, in general, ARTC are eminently nutrient-efficient crops. For example, the tubers oca, ulluco and mashua are grown as the last crops before fallow and are generally not fertilized. Other ARTC thrive on residual nutrients, yet, under such conditions, they can yield well (Table 1). Some crops, notably achira, have extensive and deep root systems which effectively take up nutrients from deep soil layers.

Pests and diseases have been known to cause serious losses in oca (weevil) and arracacha production (fungi, nematodes, acari). However, as a rule of thumb, the production of ARTC does not appear to be constrained significantly by antagonistic organisms. Various viruses infecting ARTC have been described, but again, the available evidence suggests that their presence is 'benign' and host plants display few if any symptoms of viral pathogenesis.

In rural communities and urban areas, ARTC account for only a minor fraction of caloric intake, but this alone would be a poor indicator of their role in diets. Although often and mistakenly referred to as ‘staples’, ARTC add diversity to local cuisines, especially to the diets of the rural poor who take part only marginally in the market economy. They also provide significant amounts of minerals and other essential nutrients, such as vitamins, which are in short supply to poor people in the developing world.

Are ARTC underutilized? A first approach to answer this question would be to look at production figures. Unfortunately, official statistics are for the most part not available or are notoriously unreliable. However, by making a few assumptions on the proportion of rural populations and the degree of urban consumption, as well as from our knowledge of the distribution and presence of ARTC in markets, we can ‘guesstimate’ the number of people that frequently or occasionally use ARTC, either for direct consumption or for processing (Table 2). Although these figures represent an approximation only, they provide an idea of the scale of production.

Table 2. Estimated number of users and extra-Andean distribution of ARTC

	Users (in millions)		
Common Andean name	In Andes	Outside Andes	Distribution outside Andes
Arracacha	30	>30	Brazil, Caribbean, Central America
Achira	<1	>50†	Vietnam, China, Indonesia, Papua New Guinea
Oca	15	<2	Mexico, New Zealand
Ulluco	30	–	–
Mashua	<10	–	–
Yacon	<1	n.d.	Japan, Brazil
Mauka	<<1	–	–
Ahipa	<<1	–	–
Maca	<1	–	–

† Used mostly for starch extraction.
n.d. = no data.

As seen in Table 2, five of the nine crops are known and consumed by less than one million people in the Andes. In fact, these crops are unknown to the vast majority of the Andean people, and rarely reach the marketplace. The number of ahipa and mauka producers is perhaps no more than a few thousand at best. Moreover, these are concentrated in a handful of districts widely scattered in the Andes. Both crops are about to disappear and might well become extinct in a generation or two if present trends of rural migration and abandonment of these crops persist. The situation of achira, maca and yacon is less severe for different reasons. Achira is widely employed

and grown in backyard gardens as a source of 'leaf wrappers' (many people are actually unaware of the edibility of the rhizome). Achira is also increasingly exploited for starch in Asia. Yacon is becoming popular as an 'exotic' food outside the Andes, notably in Hokkaido, Japan. In recent years maca has seen a renaissance as a medicinal plant and is becoming an attractive raw material for the pharmaceutical industry.

Although sporadically consumed across the Andean highlands, especially in Native American communities, the use of oca and mashua tubers and their market presence are in decline (Table 2). There is also evidence for ongoing genetic erosion. Although oca has spread to New Zealand and Mexico as an 'exotic crop', this seems to be commercially insignificant.

Arracacha and ulluco users, by contrast, number several tens of millions. Both crops occupy established market niches and their consumption appears to be stable, if not slightly rising, as in the case of arracacha, which is also grown in southern Brazil and to a minor extent in Central America and the Caribbean.

In conclusion, ARTC use is, with the exception of arracacha and ulluco, largely restricted to a minor (and frequently disadvantaged) sector of the Andean population. Is this deservedly so, because of some intrinsic limitations of these crops? If ARTC are robust, nutrient-efficient and nutritious as stated above, why then is their use so marginal? Why have some never spread beyond the Andes, and those which did, only to a limited number of countries, although the ecological requirements to grow them successfully are met in many more?

A widely held belief suggests that European prejudice toward 'Indian food' on the part of ruling elites has hindered the appropriate use of ARTC. In another stereotype, it is often lamented that the introduction of Old World crops and their presumedly enforced production 'wiped out' ancient American cultigens. Both arguments seem to ignore the fact that the exchange of food crops in the wake of the Spanish conquest benefited both the Old and New Worlds. It enriched cropping systems and triggered an unprecedented culinary revolution in both hemispheres. The Spanish embraced enthusiastically many Andean crops — in particular potatoes, fruits and vegetables — as novel sources of food. Today, their presence on any fruit or vegetable market in the Andes demonstrates that the same 'Indian foods' are as highly valued as in ancient days.

We cannot dismiss the role that cultural change and social factors have played in pushing some ARTC 'to the edge'. Tasty and sophisticated meals can be prepared using them, and there are, for example, no obvious reasons for their total absence from the menus of fine restaurants in the Andes. In rural Ecuador, it is considered inelegant, if not offensive, to offer a meal of oca or ulluco to visitors, although such meals are enjoyed in the privacy of the family. In racially and socially divided mestizo societies, ARTC seem to symbolize 'rural backwardness', 'Indianness' or poor nutrition. While such attributes may do no good to the marketing of ARTC, it would be too simplistic to suggest they are the sole cause of neglect.

Rather, we must seek to understand what factors limit the production and use of ARTC. Some production-related constraints have been briefly addressed above:

long crop duration, narrow ecological requirements, etc. In the Andes, however, the robustness of ARTC and the ease of cultivation suggest that the lack of demand rather than production-related constraints are at the heart of problem. Post-harvest procedures need to be applied to reduce oxalates in oca and to leach out mucilage from ulluco. This undoubtedly discourages urban consumption. Shelf-life and market quality are often poor. Preliminary findings suggest that palatability may also constrain the use of certain species. Finally, simple ignorance about their existence and culinary uses limits demand.

The present book is the first of two volumes to deal in depth with the biology and genetic resources of ARTC. Apart from Leon's classic (Leon 1964a), no comprehensive monograph of these crops has been attempted. Obviously, this more than anything bespeaks the scientific neglect of ARTC.

Of the four species selected for this volume, ahipa is perhaps the least known, and yet one that deserves more attention by researchers, as the authors convincingly argue. In multilocational trials, ahipa has been shown to yield heavily. Not only has this crop potential for raw consumption, but its crispy texture lends itself for use in stir-fried dishes where water chestnuts and bamboo sprouts are not available. For a crop of such limited geographical distribution (its cultivation is known from Bolivia and northern Argentina only), ahipa is astonishingly variable in terms of chemical composition, morphology and growth habit. Both determinate and indeterminate forms are described here for the first time. This monograph and a previous one on genus *Pachyrhizus* published in this series (Sørensen 1996) are the first to deal extensively with this crop.

Our chapter on arracacha shows that the importance of this crop extends well beyond the Andes, especially into Brazil. Since Hodge's paper on the economic botany of arracacha in Colombia (Hodge 1954), most of the literature on this crop has appeared in Portuguese. Arracacha use also provides interesting examples for the potential of processing to make ARTC more attractive to urban consumption. Novel data on arracacha's breeding system and closely related wild species are also given here.

The chapter on maca adds new findings to a very limited body of international literature on this crop. Since Leon introduced an international audience to it (Leon 1964b), more than 30 years have passed in which maca has seen its fortunes change from precipitous decline (during the tumultuous 1980s in Peru) to an export earner advertised on the Internet. Type *'Lepidium meyenii'* or 'Andean Ginseng' in any of the search machines and numerous advertisements will pop up to praise the "invigorating" effects of a drug made from the pounded dry root. Processing of maca into 500-mg gelatine capsules may add several hundred US dollars of value to a kilogram of dry root.

Another 'fruit' crop dealt with in this monograph is the yacon root, which, as the authors reveal, is increasingly grown in Brazil, Japan, Korea and New Zealand for sale in niche markets. Yacon products range from sirups and pickles to dried flakes and leaves. Interest in yacon has been stimulated by the discovery of dietary sugars

in the roots (mostly fructans) and putative medicinal compounds in the leaves. Entrepreneurial farmers have seized upon market opportunities and demonstrated that product development, rather than lament over changing food patterns, is a way to give perspective to seemingly 'obsolete' crops. Unfortunately, this has happened mostly outside the Andes. Modern taxonomic concepts place yacon, hitherto known in the scientific literature as *Polymnia sonchifolia,* in genus *Smallanthus,* a nomenclatural change that is explained and justified in this section. The authors also present cytological and morphological evidence pointing to several wild *Smallanthus* species that could have been involved in the ancestry of the cultigen.

We hope this book will stimulate interest in, and experimentation with, ARTC. Some of these crops may still have their apogee ahead.

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Ahipa

(*Pachyrhizusahipa* (Wedd.) Parodi)

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Introduction

The Neotropical genus *Pachyrhizus* DC. (the yam beans) is one of the few legume genera with edible tuberous roots. The so-called Mexican yam bean (or jícama, = *P. erosus* (L.) Urban) is the only species cultivated on a larger scale for the domestic as well as the export market and which has been successfully introduced to various regions pantropically and with remarkable success in Southeast Asia. However, of the five species within the genus, two additional species are cultivated: *P. ahipa* (Wedd.) Parodi and *P. tuberosus,* both of South American origin.

At present *P. ahipa* is only recorded in cultivation practised by small communities situated in the subtropical east Andean valleys of Bolivia and northern Argentina at higher altitudes than the other two cultivated species (Ørting 1996b; Ørting *et al.* 1996).

The variation available within this little known species was until recently poorly recorded as only five accessions were available to morphological and physiological studies. Not until additional germplasm, representing Bolivian landraces of known origin, was included in the studies could a fair estimation of the specific variation be completed. It was previously accepted that all *P. ahipa* landraces were of a determinate growth habit, i.e. small erect bushes, with a short growth season of 6 to less than 5 months, but now landraces with indeterminate growth and a longer growth season have become known. The species is so far only known in cultivation and only genotypes producing a single, vertical tuberous root have been seen. The tuberous root is characterized by having a higher dry matter content (more than 10%) than recorded in *P. erosus* and the Ashipa cultivar group within the *P. tuberosus* complex. The tubers are, as a rule, consumed fresh almost like a fruit.

The Yam Bean Project - a multidisciplinary research project aimed at elucidating the agronomic potential of the genus and initiated in 1985 - has succeeded in the collecting and evaluation of the widest range of extant genotypes of both the wild and the cultivated species.

It is the hope of the authors that the great potential and attractiveness of this species as an alternative tuber crop for subtropical regions will be clearly demonstrated.

1 Taxonomy

1.1 Generic

The first botanical references to the species, presently known as *P. erosus,* is a plant from Mexico described and depicted by Plukenet (1696) under the name *'Phaseolus Nevisensis'.* Linnaeus (1753) used the description by Plukenet as the basis for his *Dolichos erosus.*

The now valid generic name *Pachyrhizus (pachy* = thick, *rhizus* = root) was originally used by L.C.M. Richard in the illegitimate species name *Pachyrhizus angulatus* on a herbarium specimen. This name was used by De Candolle spelled in the original way, i.e. with a single 'r' when first published in 1825. Sprengel(1827) was the first to introduce the incorrect spelling of *'Pachyrrhizus'*. Later, when conserving the generic name *Pachyrhizus* against what was considered a barbaric(!) name: *'Cacara'* (Briquet 1906), the erroneous spelling of *'Pachyrrhizus'* was retained. However, according to the present botanical code the spelling used by L.C.M. Richard is the valid one. Further details concerning the origin of the name of the genus and the species are given in Sørensen (1988).

1.2 Nomenclature

Genus: *Pachyrhizus* Rich. ex DC. (1825: 402 nom. cons.); type species: *P. angulatus* L.C.M. Richard ex DC. (nom. illeg. = *P. erosus* (L.) Urban)

Generic synonyms:

Cacara Rumph. ex Du Petit-Thouars (1806: 35 nom. rej.); Type species: *C. bulbosa* Rumph. ex Du Petit-Thouars (= *P. erosus* (L.) Urban).

Taeniocarpum Desvaux (1826:421); type species: *T. articulatum* (Lam.) Desv. (= *P. erosus* (L.) Urban).

Robynsia Martens & Galeotti (1843:193); type species *R. macrophylla* Mart. et Gal. (= *P. erosus* (L.) Urban).

1.3 The genus

The yam bean, i.e. the Neotropical genus *Pachyrhizus* Rich. ex DC., is placed taxonomically in the subtribe Diocleinae, tribe Phaseoleae within the legume family (Fabaceae), according to Lackey (1977). The genus currently comprises five species (Sørensen 1988). Three of the five species are cultivated for their edible tubers and the remaining two are only to be found in the wild.

The fact that among the cultivated species only the Mexican yam bean has been spread more or less pantropically cannot be explained by the lack of agriculturally attractive characteristics in the remaining two cultivated species. This situation must be interpreted as either solely due to their specific climatic adaptation and/or possibly combined with the historical progress of the Spanish and Portuguese conquest of Latin America and the general policy of destroying the traditional Andean agricultural systems.

Although the genus had been the subject of a previous taxonomic revision by Clausen (1945), the taxonomy of the genus remained somewhat diffuse, especially for the South American species. This was mainly due to the limitation of available herbarium material caused by World War II. Also, the narrow species concept held by the author of this first revision contributed to the considerable complexity of this work, e.g. made obvious by the great number of infraspecific taxa included. Hence, as the herbarium material available for a new taxonomic revision included material from all relevant European herbaria as well as the material collected during the 40 years elapsed since the work by Clausen (1945), it appeared that the completion of a new revision was justified, see Sorensen (1988).

The genus *Pachyrhizus* is morphologically delimited by the presence of the following characteristics. Vines or semi-erect herbaceous to somewhat lignified perennial plants. All species have more or less prominently tuberous roots, one or more per plant. Trifoliolate leaves with stipules, pinnately arranged leaflets with caducous stipels. The inflorescence is a complex to simple raceme and the flowers have a tubular calyx and a papilionaceous corolla. The ovary has a basal crenate disc-formed nectarium, the recurving style is ciliated forming a 'false beard' of short hairs along the dorsal (= adaxial) side of ovary practically continuing to the base of the stigma along the incurved side of the style and the vertical, subglobose surface of the stigma is placed in the middle or almost terminally. The straight legume is septate between the seeds and the seeds are square, more or less flattened or rounded, kidney-shaped with colours ranging from olive green, deep maroon, lilac, to black or black and white/cream mottled.

Chemosystematic examinations of the phylogeny and interrelationships of *Pachyrhizus* on the generic as well as on the subtribal level have so far been limited to the studies of canavanine by Lackey (1977) and of isoflavonoid phytoalexins by Ingham (1979). [Lackey (1977) placed *Pachyrhizus* in the subtribe Diocleinae; Ingham (1979,1990) suggested a close affinity between *Pachyrhizus* (subtribe Diocleinae) and the Palaeotropical genus *Neorautanenia* (subtribe Glycininae, according to Ingham (1979) and subtribe Phaseolinae (Ingham 1990)), a relationship that according to Ingham (1979) could justify the transfer *of Pachyrhizus* to the subtribe Glycininae. Ingham (1990) suggests that the genera *Pachyrhizus* and *Calopogonium* (both Diocleinae) may bridge the gap between the genera *Neorautanenia* (Phaseolinae) and *Pueraria* (Glycininae).]

Molecular analyses by Bruneau *et al.* (1990) studied the significance of a chloroplast DNA inversion as a subtribal character in the Phaseoleae and demonstrated the presence of the inversion in 11 of the 23 genera included in the subtribe Phaseolinae. All six genera (including *Pachyrhizus)* examined within the subtribe Diocleinae lacked the inversion. The result is thus in agreement with the subtribal classification as suggested by Lackey (1981). A new research project involving the study of isozymes, chloroplast DNA and ribosomal DNA has recently been initiated between the School of Biological and Medical Sciences, Plant Sciences Laboratory, University of St. Andrews, Scotland (Dr R.J. Abbott and Ing. Agr. J.E.

Estrella E.) and the Botanical Section, Department of Botany, Dendrology and Forest Genetics, Royal Veterinary and Agricultural University, Copenhagen, Denmark (Estrella E. *et al.* 1997). The results of these studies have revealed considerable agreement between molecular systematic affinities and the numerical taxonomy based on morphological characters. Two main groups/branches have been identified — one containing the species *P. tuberosus, P. ahipa* and *P. panamensis* (the species of South American origin) and the second with the Central American and Mexican species of *P. erosus* and *P. ferrugineus.* When looking at the species level and below, these examinations indicate that molecular methods of analysis can serve to demonstrate differences, not only between the species, but of even greater interest between different genotypes within a single species — see discussion below on the *P. tuberosus* complex in Sørensen *et al.* (1997).

A palynological study of the genus (Sørensen 1989) revealed that the interspecific variation was sufficient to allow unequivocal identification of the single species. The greatest infraspecific variation was, not surprisingly, observed in the pollen grains from the cultivated species.

1.3.1 The species: *Pachyrhizus ahipa* (Wedd.) Parodi (Fig. 1)

Pachyrhizus ahipa (Weddell) Parodi (1935: 137).
Basionym: *Dolichos ahipa* Weddell (1857: 113).
Type: Mandon, G. 747, Boliviense, prov. á Laracaja, Sorata ad rivum (P. holo).
Heterotypic synonyms: *Pachyrhizus ahipa* (Wedd.) Parodi var. *violacea* Parodi (1935: 138).
Type: Parodi, L.R. 12145, ex cult. in Hort. Bot. Fac. Agr. B. Aires (BAA, holo).
Pachyrhizus ahipa (Wedd.) Parodi var. *albiflora* Parodi (1935: 138).
Type: Parodi, L.R. 12146, ex cult. in Hort. Bot. Fac. Agr. B. Aires (BAA, holo).

Vernacular names: *ajipa (ahipa)* (Spanish); Andean yam bean (English); *Andine Knollenbohne* or *Andine Jamsbohne* (German); *l'ahipa* or *dolique tubereux d'Ande* (French).

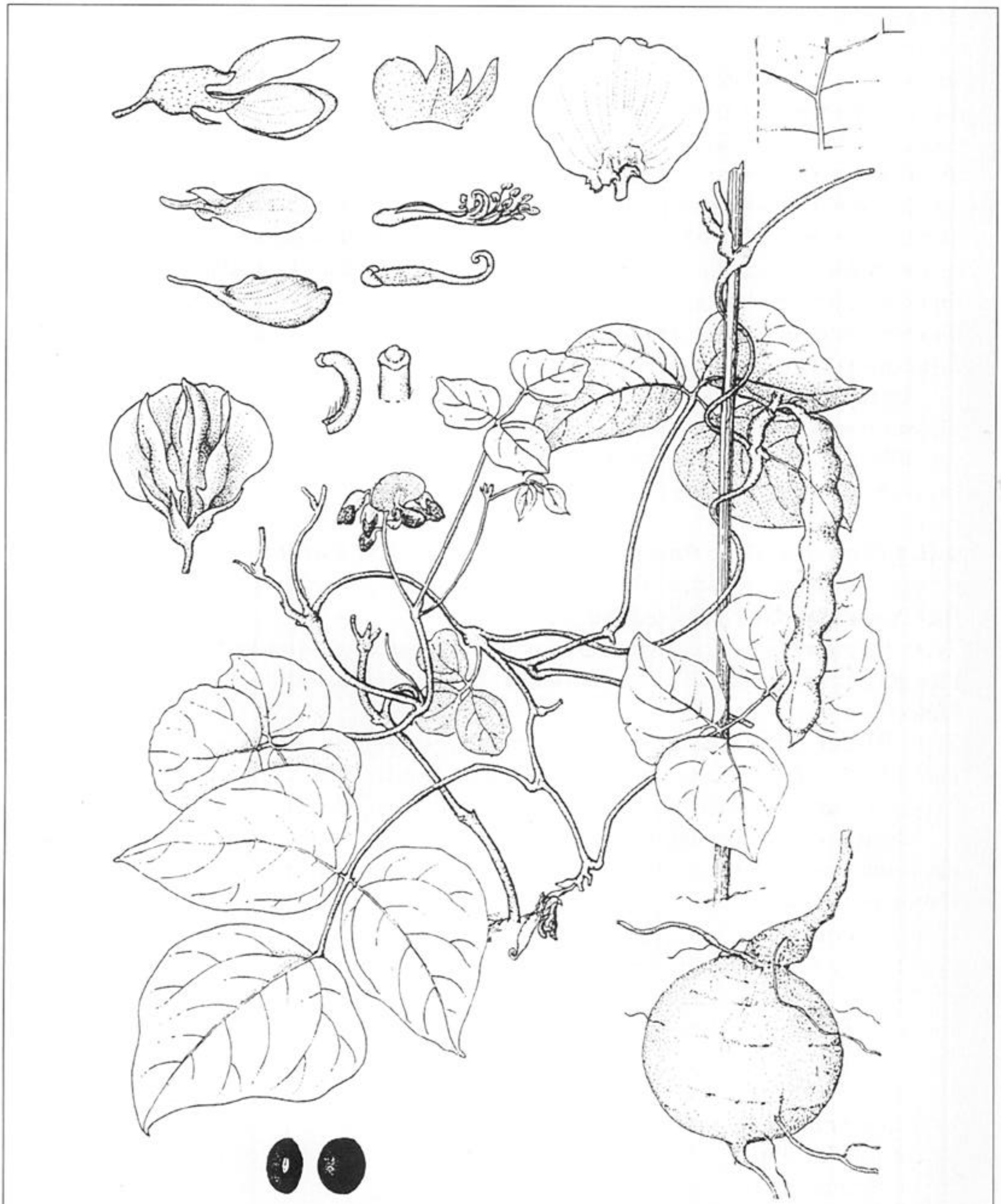


Fig. 1. *Pachyrhizus ahipa.* Habit, 2/3 of natural size. B. Flower, side view. C. Flower, seen from underneath. E. Calyx, opened. F. Standard. G. Wing. H. Keel. J. Stamens. K. Pistil with basal disc. L. Side view and front view of style and globose stigma. M. Side and top view of seed. N. Section of abaxial surface of leaf. O. Tuberous root. (All parts from AC102, originally from the Province of Tarija, Bolivia).

2 Description of *P. ahipa*

2.1 Botanical/morphological description of the species

Pachyrhizus ahipa is morphologically distinguished by being a herbaceous plant with entire leaflets (a few individual plants possessing dentate leaflets have been recorded), with short racemes (48-92 mm) and the general absence of lateral axes, i.e. simple racemes. The number of flowers per lateral raceme is, if present, as low as 2-6. The wing and keel petals are usually glabrous, but slightly ciliolate specimens have been seen. The wings curl outward following anthesis and this is a feature within the genus seen only in *P. ahipa.* The pod is 13-17 cm long and 11-16 mm wide, almost circular in cross-section when immature, i.e. only slightly dorsiventrally compressed (Fig. 1). Seeds are black, lilac, maroon or black and white (cream) mottled, never olive-green or red; rounded kidney-shaped, never flattened and square, 9 x 10 mm. The 100-seed weight is (17.3-) 29.2 (-41.2) g.

This species is furthermore unique in that both twining/trailing and semi-erect to short bushy erect growth habits are found, i.e. both determinate and indeterminate genotypes exist. Erect genotypes are 15-40 cm tall, semi-erect 30-60 cm and twining types 60 cm to several metres long.

2.2 Reproductive biology

Like all *Pachyrhizus* species, *P. ahipa* is a perennial (although cultivated as an annual crop), and may be multiplied vegetatively by cuttings (or in the case of multituberous genotypes, also from tubers). But in contrast to the majority of the tropical root crops all species in the genus are mainly reproduced generatively. Thus all cultivated species, including *P. ahipa,* are replanted by seed annually.

Flowering: both short- and long-day plants exist in the genus. Even though *P. ahipa* in its area of origin is grown under a short-day photoperiod, all accessions are short-day insensitive. On the other hand the entire germplasm of *P. erosus* and *P. tuberous* must be regarded as short-day sensitive and reproductive development does not normally occur under greenhouse conditions at high latitudes.

Usually sown in August-October (Bolivia), with reproductive pruning (manual removal of flowers) starting 4-7 months after sowing in November-March and with mature pods in April-June. The planting date is mainly determined by the rainy season. During the flowering period the labour-intensive reproductive pruning is conducted once or twice. The flower pruning is only necessary to a certain extent, as the tuber formation is mainly affected by the number of pods produced per plant with fully developed seeds and not by the amount of flowers per plant. Hence, good tuber formation also takes place in profusely flowering plants, but with a high abscission rate. The seeds are easy to harvest owing to the non-dehiscent pods and they generally have high 1000-seed weights.

In the landraces two seed multiplication strategies in this predominantly self-pollinating species were reported (Ørting *et al.* 1996). (While *P. erosus* and *P. tuberous* may be regarded as mainly being self-pollinators, *P. ahipa* must be regarded as a

partial self-pollinator.) The common strategy is to select the most vigorous plant within a field for seed production and reproductively prune the remaining plants in order to increase tuber growth/yield. The second strategy involves leaving the initially produced legume on each plant for seed production, followed by the removal of all subsequently produced flowers. In both practices an indirect selection was said to be implemented when harvesting the seeds by selection on the basis of largest size (Ørting *et al.* 1996). It is to be expected that these two seed multiplication strategies, practised in the area of origin, have a high impact on the variation within each individual accession. In greenhouse experiments a lower variation was detected within accessions multiplied by the first strategy with respect to a much higher variation recorded in those accessions multiplied by the second multiplication strategy.

This pollination behaviour cannot be considered as a result of the flower morphology only, i.e. with an internally curved stigma in close contact with the anthers. It is also determined by the low pollen fertility and the presence or absence of pollinating insects, i.e. the only natural method of cross-pollination. With respect to pollen fertility and number of flowers produced, highly significant differences between the accessions - and therefore tuber formation - could be detected under greenhouse conditions. In spite of the low pollen fertility, both infra- and interspecific crosses may be carried out successfully. Fertile interspecific hybrids from all combinations (including reciprocal crosses) involving the three cultivated species were obtained with the exception of the cross between *P. ahipa* (female) x *P. tuberous* (male) where seeds were produced but were not capable of germinating. The pollen fertility of the hybrids was in general reduced by 10-20% compared with the parental species. Hybridization experiments involving the wild species *P. panamensis,* conducted in Benin and Tonga, have demonstrated this species to be fully compatible with the three cultivated species (Grum 1994; Prof. D.F. Adjahossou, pers. comm. and Dr P.E. Nielsen, pers. comm.).

In terms of plant breeding it should be stressed at this point that the combination of vegetative and generative reproduction by selfing is unique to the cultivated species. This combination may be advantageously integrated into a breeding programme. Thus in breeding strategies the species may be treated as a cloneable, annual self-pollinator.

2.3 History

Ahipa or ajipa is, as mentioned, probably the most interesting of all the cultivated yam bean species: (1) from the systematic view because of the absence of known wild ancestral material, (2) from the morphological view because of the presence of genotypes with an erect, short growth habit, and (3) from the agronomic view because of the daylength neutrality, short growth season (5 months) and its considerable adaptability to climatic variation. The distribution is limited to Andean valleys in Bolivia and possibly Peru. There is no definite evidence of the presence of the crop in Peru, but owing to the proximity of the northern Bolivian landraces it may be

assumed that Peruvian material exists. The recorded history of *P. ahipa* in cultivation indicates that in contrast to the other two cultivated species this species has never been associated with shifting cultivation. The earliest indications of a *Pachyrhizus* species used as a crop in South America are remains of tuberous roots found among the plant residues in the 'mummy bundles' of the Paracas Necropolis, the southern coast of Peru, belonging to the Nasca culture (Yacovleff 1933; Towle 1952; Ugent *et al.* 1986). Evidence also appears on the ceramics and embroideries of Mochica (Brücher 1989) as well as the Nasca culture (Yacovleff 1933; Yacovleff and Muelle 1934; Herrera 1942a, 1942b; Mangelsdorf 1942; O'Neale and Whitaker 1947). Accordingly, substantial evidence exists that a plant resembling *P. ahipa* or a plant belonging to the Jíquima cultivar group (a morphologically distinct group from coastal Ecuador within the *P. tuberosus* complex, Sørensen *et al.* (1997)) was known and cultivated by at least one of the Indian cultures of pre-Columbian South America. Information in the manuscripts of Oviedo (1535) also confirms the existence of pre-Columbian cultivation. Although some authors, e.g. Yacovleff and Muelle (1934) and Hawkes (1989), have identified these remains and depictions as belonging to *P. tuberosus,* the typical growth habit and morphology of the inflorescences and the legumes allow for a positive determination as *P. ahipa* or the Jíquima in agreement with Ugent *et al.* (1986). Sauer (1950) mentions the crop as one of the common elements in the cropping systems of the terraced Andean fields of Peru, i.e. none of the three cultivar groups belonging to the *P. tuberosus* are cultivated at altitudes above 1800 m asl; the Jíquima is a lowland cultivar, whereas the main cultivation of *P. ahipa* takes place above 2000 m asl.

3 Origin of the cultivated species and geographical distribution

The distribution area of the three cultivated species within *Pachyrhizus* extends from 21° N in Mexico to 25° S in Bolivia/northern Argentina.

Pachyrhizus ahipa is found sporadically in cultivation in Bolivia and in a few localities in the provinces of Jujuy and Salta in Argentina in subtropical Andean valleys along the eastern side of the range. The latter genotypes probably originate from seeds introduced from the southern part of Bolivia. Bolivian farm labourers working in Argentina recall importing seed material from Bolivia when visiting relatives and the genotypes are of the erect bushy type found in the Bolivian province of Tarija (Parodi 1935; Burkart 1952; Sørensen 1990; Ørting 1996b; Ørting *et al.* 1996; Ing. Agr. R. Neuman pers. comm. and pers. observ.). Altitudinal range: fertile subtropical valleys between 1000 and 3000 m asl (Fig. 2).

The only herbarium specimens known to the authors are from the provinces of Sorata and Tarija in Bolivia and Jujuy Argentina. No herbarium specimen of Peruvian origin has been seen nor has any reference to such material been found by the authors.

Today the cultivation of *P. ahipa* in Peru is either extinct or possibly restricted to a few valleys in the area around Tarapoto (Dr C. Arbizu, pers. comm.); hence, the locating and conserving of any remaining Peruvian germplasm is urgently needed.

There are no records of plants undoubtedly wild, a wild progenitor of *P. ahipa* has yet to be identified and the geographical origin is still obscure. Brücher (1977, 1989) states that the likely location must have been in the 'ceja de montañas' in the Andean region; however, recently Ing. Agr. J. Rea (pers. comm.) has claimed to have found a wild *P. ahipa* near Sorata, Bolivia, i.e. the locality where the type specimen was collected by G. Mandon (no. 747, 1856). Nevertheless, until material of this genotype becomes available for morphological and molecular analyses the phylogeny of this species cannot be finally determined. Another possible location where a wild progenitor may be found is the Peruvian valleys of Apurimac, Ene and Mantaro owing to the climatic and edaphic conditions according to Dr D. Debouck (pers. comm.)

Not surprisingly the germplasm of Bolivian origin — representing 26 of the 31 available accessions — has been found to have the greatest diversity seen. Even the 13 landraces/primitive cultivars from the two departments of La Paz and Cochabamba possess a remarkable degree of genetic/morphological variation in earliness, growth rate of both vegetative and reproductive shoots and internodal lengths. The single Argentinean landrace/cultivar seen from the northern province of Salta has several distinguishing traits: very short, erect bushy growth and reduced seed set and good tuber growth. The landraces/cultivars of known origin most strongly resembling the Salta cultivar have been collected in the southern Bolivian departments of Tarija (in the village of Carapari) and Chuquisaca (along the Pilaya and Pilcomayo rivers). A thorough survey of the southern Bolivian/northern Argentinean germplasm conducted in 1996 revealed that all germplasm of this area

has determinate growth habit, i.e. *P. ahipa* landraces with indeterminate growth habit have only been observed in the northern parts of Bolivia (Fig. 2).

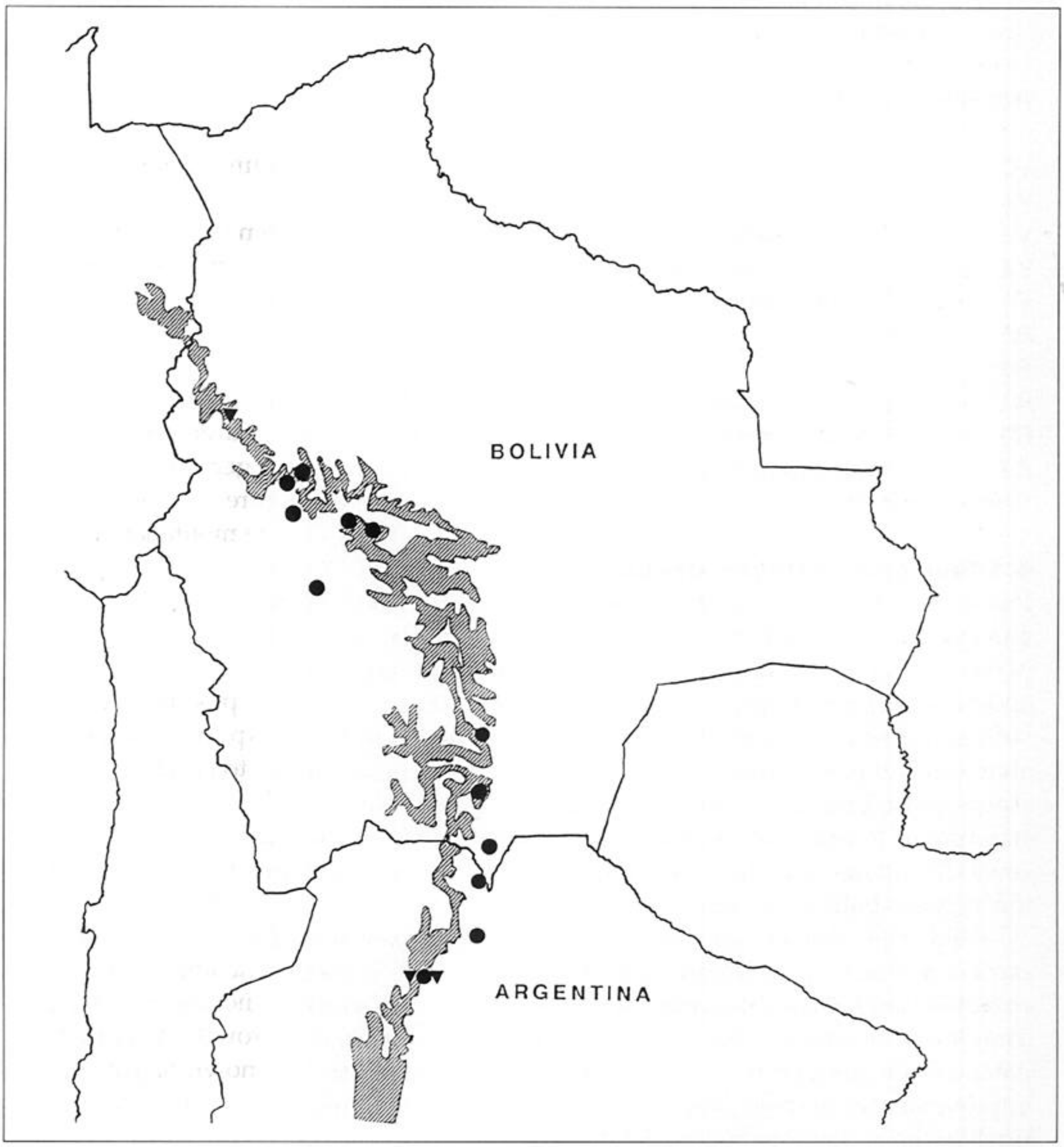


Fig. 2. Distribution of *Pachyrhizus ahipa;* dots = field collections; triangles = herbarium specimen; the hatched area is above 2500 m asl.

4 Properties of the species

The developmental stages (V0-R9) of the genus - also applicable to the species *P. ahipa* (see Fig. 6) - according to Grum (1990) and Sørensen *et al.* (1993) are presented in Table 1.

Table 1. The developmental stages of *Pachyrhizus,* based on morphology and physiological changes according to Grum (1990) and Sørensen *et al.* (1993)

Reference	Stage	Description
V0	Germination	Appearance of the primary root
V1	Emergence	Primary leaves and epicotyl emerge
V2	Primary leaves totally opened	Primary leaves fully unfolded
V3	First trifoliate leaf opens	Second trifoliate leaf appears
V4	Third trifoliate leaf opens	Buds at lower nodes produce branches
R5	Pre-flowering	First flower bud or reproductive shoot appears
R6	Flowering	First flower opens
R7	Pod formation and filling	At the end of this stage the pods feel firm
R8	Post-pod growth	Pods filled and are hard
R9	Physiological maturity	Leaves senesce and defoliation starts

4.1 Biological nitrogen fixation

Like other members of the legume family, *Pachyrhizus* has an efficient symbiosis with nitrogen-fixing *Rhizobium* and *Bradyrhizobium* bacteria. These bacteria provide the plants with a source of nitrogen and, as a result, there is no requirement for an additional supply of nitrogen fertilizer. In contrast to many of the grain legumes, a substantial amount of the fixed nitrogen is returned to the soil if the vegetative aboveground parts are left in the field. The crop therefore forms an integral part of a sustainable land-use system, both in an ecological sense and from a socioeconomic standpoint. Recent studies (Kjær 1992; Halafihi 1994; Halafihi *et al.* 1994) have been conducted under both greenhouse and field conditions to examine the efficiency of the biological nitrogen fixation

Field collecting of indigenous strains of *Rhizobium* and *Bradyrhizobium* was carried out in 1993 in Central and South America. Subsequent isolation of the collected material and evaluation in 1993-94 under greenhouse conditions have been completed in order to select *Pachyrhizus* genotypes and bacteria strains with high potential for nitrogen fixation (Grum 1997). The emphasis of this research is the improvement of the host plant range, thus providing a simple technology within the reach of the agriculture in developing countries.

Castellanos *et al.* (1997) conducted the first field test quantifying the actual amount of nitrogen fixed by two accessions of *P. ahipa* (reproductively pruned and

harvested after 154 days): 58-80 kg N/ha (or 60-76 g N/t biomass per day), and three cultivars of *P. erosus* (reproductively pruned harvested after 154-168 days): 162-215 kg N/ha (or 84-107 g N/t biomass per day). Approximately 50% of the harvested N, i.e. ±130 kg/ha or close to 800 kg protein/ha (N x 6.25), accumulated in the tuberous root in *P. erosus,* i.e. a value which equals or outyields the amount of protein harvested in grain legumes. The amount of N in the residue, i.e. hay; of *P. erosus* was 120-150 kg/ha, twice the amount recorded in the *P. ahipa* residue. The N amounts recorded in the residue of *P. erosus* are higher than the quantity recorded in practically all grain legumes (the plant population of both species in the trials was 110 000 plants/ha and the plants were reproductively pruned).

4.2 Chemical composition of the used parts

The tuberous root of the Andean yam bean is the only part used. The seeds are not used because of their rotenone/rotenoid content (neither as food nor as insecticide). The possibility of using the insecticidal compounds will be treated later in this subsection. Here it is enough to mention that the rotenone (and rotenoids) ingredient is not found in toxic amounts in the tuber or in any other part of the plant except for the seeds. Other ingredients of the seed, e.g. protein, starch and fatty acids, have yet to be analyzed.

The current knowledge of the chemical composition of the tuber is based on the analyses of 19 different non-reproductively pruned accessions (6 plants per accession) grown in a trial under greenhouse conditions in Denmark (Ørting 1996a). The dry matter content ranged from 15% (minimum) to 20% (average) to 30%. In the subsequent analyses the tubers were freeze-dried and ground to meal. From this material 25 samples were selected and analyzed by the reference method for protein (Smith *et al.* 1985), starch (Krisman 1962; Shannon 1968) and sugar (Dubois *et al.* 1956). Additional calibration was carried out by Dr W.J. Grüneberg. The estimation of the amylose, i.e. the amylopectin fraction of the starch, was conducted according to Somogyi (1945) and Nelson (1944) (see Table 2). The analyses repeatedly demonstrated that the starch consists of nearly pure amylopectin (96 to >99.9%). Initially, saccharose, glucose, fructose, mannose, arabinose, xylose, maltose and several malto-oligosaccharides were analyzed separately. Later the analyses of the sugars were reduced to the determination of the total sugar content, saccharose and reducing sugars, in agreement with Somogyi (1945) and Nelson (1944). A determination of the lipid content and composition was not conducted for the abovementioned material, as in preliminary investigations on both protein and lipid the lipid content was found to be below 1% (Dr A. Borcherding, pers. comm.)

The tuber flour of all 120 plants (material from the greenhouse trial in Denmark, Ørting 1996a) was screened by using Near-Infrared Analysis (NIRS) (Burns and Ciurczak 1992). The principles of calibration of NIRS-equipment with regard to rapid screening of plant material were described in detail by Tillmann (1996). The *P. ahipa* NIRS calibration was based on the reference analysis of the abovementioned 25 samples and on available reference calibrations for *Vicia faba* L. material. The results

Table 2. Protein, starch and sugar content (on a dry matter basis) in tuberous roots of 19 *P. ahipa* and 2 *P. tuberosus* (Chuin cultivar group) accessions

Species/ accession	Protein†	Soluble sugars†	Saccharose†	Reducing sugars†	Starch†	Amylo-pectin‡
P. ahipa						
AC102	10.66 ±0.73	16.48 ±1.69	7.00 ±0.71	4.74 ±0.54	47.02 ±1.23	97.52
AC201	15.17 ±1.24	22.35 ±1.17	7.94 ±0.75	7.31 ±0.64	44.66 ±1.35	97.55
AC202	20.18 ±3.14	22.71 ±3.20	4.60 ±0.36	13.47 ±3.05	44.42 ±2.84	99.31
AC203	14.75 ±1.18	24.46 ±2.08	8.44 ±1.09	8.16 ±1.08	45.25 ±1.92	95.78
AC204	11.52 ±0.55	21.23 ±2.63	7.98 ±1.33	6.32 ±0.74	46.71 ±l.77	95.97
AC205	8.88 ±1.58	18.78 ±2.41	7.58 ±1.52	4.06 ±1.48	49.89 ±3.03	96.02
AC206	12.03 ±2.20	16.06 ±2.65	4.89 ±0.49	8.45 ±1.81	51.52 ±0.65	≥ 99.99
AC207	13.20 ±1.59	23.94 ±3.22	5.45 ±0.39	15.51 ±4.17	43.09 ±5.27	≥ 99.99
AC208	17.49 ±4.60	19.58 ±5.32	4.73 ±0.67	11.78 ±4.08	48.30 ±4.24	≥ 99.99
AC209	10.55 ±2.12	15.92 ±2.87	5.87 ±0.91	5.47 ±1.66	50.62 ±2.75	96.95
AC213	13.78 ±1.05	13.87 ±2.14	3.80 ±0.76	6.49 ±1.08	51.94 ±0.97	98.18
AC214	15.18 ±2.34	14.48 ±2.93	3.82 ±1.40	7.63 ±1.26	51.24 ±2.17	99.76
AC215	8.49 ±0.74	11.98 ±1.57	3.98 ±0.71	5.11 ±0.50	55.57 ±1.28	99.68
AC216	8.13 ±1.41	12.54 ±2.80	3.83 ±1.61	6.11 ±0.64	55.93 ±0.63	99.24
AC217	–§	11.37±–	2.91 ±–	7.28 ± –	57.00 ±–	≥ 99.99
AC521	9.31 ±1.19	17.51 ±3.48	7.70 ±1.33	4.24 ±1.09	47.71 ±1.66	99.23
AC524	11.64 ±1.48	13.52 ±1.01	4.47 ±0.87	5.25 ±1.29	52.05 ±1.88	≥ 99.99
AC525	13.31 ± 0.84	20.30 ±1.82	6.90 ±0.99	7.59 ±0.79	47.65 ±2.07	96.36
AC526	11.07 ±1.61	13.57 ±1.66	5.03 ±0.44	4.67 ±1.31	50.94 ±1.63	98.69
P. tuberosus						
TC353	6.64 ±0.72	9.60 ±0.98	4.82 ±0.53	1.50 ±0.42	51.83 ±0.95	≥ 99.99
TC354	5.16 ±1.08	9.56 ±1.24	4.61 ±0.79	1.25 ±0.97	55.30 ±0.82	99.87

† Mean ±SE, as percentage (%) of dry matter.
‡ Percentage (%) of the total starch content.
§ Not analyzed.

of these analyses demonstrating the level and the variation in the nutritional composition of Andean yam bean tuber are presented in Table 2. Whether the resulting yam bean calibration may also be used to evaluate large progenies in breeding programmes has yet to be verified in future experiments.

An additional common generic characteristic of *Pachyrhizus* is the presence of an insecticidal compound called rotenone ($C_{23}H_{22}O_6$). This ingredient is to be found in the mature seeds, but not in toxic amounts in the tuber itself or in any other part of the plant. As is clearly demonstrated in Sørensen (1990,Table 2) practically all studies of the insecticidal compounds and their properties have been conducted on one

species only, *P. erosus* (until the recent examinations by Lackhan (1994) and Scramin (1994)). Few analyses evaluating the compounds with insecticidal or fungicidal properties in *P. ahipa* have been conducted so far. The examinations published by Hansberry *et al.* (1947) included the species *P. erosus, 'P. strigosus'* Clausen (considered conspecific with *P. erosus* according to Sørensen (1988), *P. ahipa* and *P. tuberosus.* This extension of the material analyzed did increase the knowledge of the properties of the genus in general; however, the differences between the species identified by Hansberry and his associates were remarkably few. The recent analyses carried out in Brazil (Scramin 1994) and in Trinidad (Lackhan 1994) both included *P. ahipa.* These analyses are therefore valuable and will possibly lead to renewed commercial interest in the exploitation of the insecticidal properties of the Andean yam bean.

4.3 Nutritional

In the areas of origin the Andean yam bean tuber is regarded as both healthy and nutritious. The brown skin may easily be peeled away, leaving a white (often with purple subepidermal stripes), juicy and crisp flesh. The tuber is always eaten raw and there are no reports on antinutritional factors in the Andean yam bean tuber.

The tubers have a protein content of 8-18% (dry weight) based on recent analysis of 19 accessions, i.e. a high content in comparison with that of traditional root crops (pers. observ.). About 80% of the protein is water-soluble (Dr A. Borcherding, pers. comm.). No information on the amino acid composition is currently available for the Andean yam bean tuber. However, an amino acid composition similar to that of the Mexican yam bean (= *P. erosus)* (investigated by Evans *et al.* (1977)) is to be expected. The amounts of essential amino acids in extracted (crude) protein the Mexican yam bean according to Evans *et al.* (1977) are listed in Table 3 in relation to the recommended values of the FAO/WHO (1989). As may be seen from the essential amino acid index (EAA) the chemical score of all amino acids exceeds the recommended values with the exception of the two amino acids, methionine and cysteine, where the EAA index is 1. These two amino acid contents are generally regarded as being limited in legumes. Nevertheless, more precise information about the EAA values and range for the Andean yam bean is important. In particular, further evaluations of the ratio between crude protein and small peptides with different genotypes are urgently needed, especially as this ratio is presently regarded as poor (Evans *et al.* 1977).

In addition to the interesting and valuable protein content, the tuber is very rich in carbohydrates, which provides energy. The range of the starch content is between 45 and 55% and of the sugar between 8 and 24% (pers. observ.), whereas the lipid content is below 1% (Dr A. Borcherding, pers. comm.). Despite the lack of digestibility experiments it appears from the biochemical composition that the *P. ahipa* tubers have a very good nutritional composition. Nevertheless, the protein and energy concentration may be classified as being medium because of the high moisture content in the tuber — the major constraint of *P. ahipa,* if the crop is to be readily accepted by consumers used to the traditional starchy root crops outside its present distribution.

Table 3. Amino acid composition of Mexican Yam Bean *(P. erosus)* according to Evans *et al.* (1977) in comparison with the recommended FAO/WHO values (FAO/WHO 1989)

Amino acid	Extracted protein (mg/g protein)	Recommended value (mg/g protein)	EAA value+
Histidine	32	19	1.68
Isoleucine	48	28	1.71
Leucine	79	66	1.19
Lysine	78	58	1.34
Methionine +Cysteine	25	25	1.00
Phenylalanine +Tyrosine	98	63	1.55
Threonine	50	34	1.47
Tryptophan	–[‡]	11	–[‡]
Valline	82	35	2.34

[†] EAA = Essential Amino Acid index (although *P. ahipa* is a separate species from *P. erosus,* the amino acid composition can be expected to be similar).
[‡] Not recorded.
Calculation based on protein; free and small-peptide amino acids not included.

4.4 Industrial and other aspects

In addition to the recent advances in the evaluation of the Andean yam bean as a new vegetable crop in Europe, the evaluation of the *P. ahipa* tuber as a renewable resource crop has become of interest. This is mainly because of the high starch content and the high proportional amount of amylopectin (see above). Therefore, the Andean yam bean starch would represent a nearly perfect raw material for the starch industry. However, the suitability of the *P. ahipa* starch for the industry will depend on several additional factors such as the extractability of the starch, the diameter of the starch particles/grains and their distribution. Examinations of these starch characteristics are in progress at the Georg-August University Göttingen.

The industrial use of the protein content of the tubers may also be of commercial interest. The protein market is of high economic interest to the European Union as Europe has to import several million tonnes of soyabean *(Glycine max* (L.) Merr.) protein each year. Also, the total tuber protein yield per hectare of *P. ahipa* exceeds that of soyabean seed protein. However, 80% of the protein is water-soluble and not extractable within a pH range of 2-10. This characteristic may be an advantage to the food industry (Dr A. Borcherding, pers. comm.).

Of further interest is the sugar and fibre content of the *P. ahipa* tuber, although the use of either component seems only to be worthwhile provided both the starch and protein contents can be used. The potential exploitation of the saccharose content is mainly of interest as a by-product. Regarding the *P. ahipa* tuber fibre the mechanics

Table 4. Comparison of starch yields of indigenous (European) starch crops (yield potentials in classic crop areas) and *P. ahipa*

Crop	Tuber/root/ grain yields (t/ha)	Protein content (% DM)	Starch content (% DM)	Starch yield: total (t/ha)	Starch yield: net‡ (t/ha)	Amylose (crude) content (%)
Maize	7.0	12	70	4.9	4.7	28
Wheat	6.0	12	65	3.9	2.7	26
Barley	5.5	12	60	3.3	-	22
Pea	3.5	35	40	1.4	-	35
Potato	40.0	2	70	7.2	6.6	20§
P. ahipa	45.0†	12	50	6.0	-	<5§

† Yield figures are from plants which have been reproductively pruned; average from three field experiments (1992-95) in Portugal using three landraces (Vieira da Silva, pers. comm.).
‡ Net = extractable.
§ In addition to the amylose, potatoes contain approximately 30% amylopectin and *P. ahipa* approximately 95% amylopectin.

of the fibre within a thermoplastic matrix were compared in a preliminary survey with flax *(Linum usitatissimum L.)* and ramie *(Boehmeria nivea* (L.) Gaudich.). Even though the results were unclear, it will be worthwhile to investigate this possibility in the future (Dr Bader, pers. comm.)

To demonstrate the attractive possible uses of the Andean yam bean in the non-food sector the authors have calculated the starch yield per hectare in comparison with the yields of other starch-producing crops on the basis of *P. ahipa* field experiments in Portugal (Table 4).

5 Uses

The tuber is used as a vegetable, as mentioned earlier. It is locally considered as being a fruit rather than a vegetable, hence it is marketed by the street or market vendors selling fruits and not vendors of vegetables, according to Ørting *et al.* (1996). It is consumed raw like an apple, in various dishes or as juice.

No records on the use of the insecticidal properties or ethnobotanical uses of the plant are known to the authors, but during the interviews conducted in Bolivia by Ørting *et al.* (1996) it was repeatedly stated that the consumption of *P. ahipa* tubers is considered to have a cleansing effect upon the body, that it is beneficial to the lungs, and curative to infections of the air passage, i.e. coughs, etc. Ørting *et al.* (1996) did not encounter persons confirming the report by Cárdenas (1969) that *P. ahipa* tubers are considered curative for gout in Bolivia.

The economy of *P. ahipa* production in Bolivia was also studied by Ørting *et al.* (1996). At the central markets in the major cities the price of *P. ahipa* per kilogram is comparable to the price of groundnuts *(Arachis hypogæa* L.) and potatoes *(Solanum tuberosum* L.) - 1994 prices: US$0.5-1.0. The price at the local markets is somewhat lower (US$0.25), the price obtained when selling to wholesalers varies (US$0.15-0.40/kg). The optimal price is obtained during May-June, while the lowest is from August-September, when the competition by fruits produced in Las Yungas is at its peak. Apparently the wholesalers make a gross profit of 50-100% when reselling to the retailers. The latter will then also increase the price by 50-100%. Even though the price per kilogram of *P. ahipa* tubers was higher than that of potatoes or cassava *(Manihot esculenta* Crantz), the profit per unit area for these or other tuber/root crops may exceed that of *P. ahipa,* but more importantly these other crops provide a continuous cash flow throughout the year in contrast to a short-season crop like *P. ahipa.* The market share of *P. ahipa* in both urban and rural areas is small and is steadily declining, possibly as a result of an increased demand for industrially produced soft drinks in combination with the labour-demanding practice of reproductive pruning.

The marketing of *P. ahipa* associated with the religious festival of 'Corpus Cristi' may indicate some linkage with ancient religious uses.

6 Genetic resources: range of diversity for major characteristics

In 1985, when the Yam Bean Project was initiated, few seed samples and very little information about the yam bean species were available from the worlds various genebanks. Through different contacts some 20 samples of the Mexican yam bean *(P. erosus)* and two samples of the Andean species *(P. ahipa)* were procured, but there were virtually no details concerning the exact origin of this material, the cultivation practices involved or other relevant data. Thus, in order to make a comprehensive examination of the crop's potential, a thorough recording of the natural and cultivated distribution of the genus, based on information available from herbarium specimens, had to be undertaken (Grum *et al.* 1991a; Sørensen *et al.* 1993). Subsequently, a number of field collections were carried out and today approximately 200 sample groups, covering both wild and cultivated material, are available for the hybridization and evaluation experiments currently in progress.

In *P. ahipa* the recent analysis of infraspecific variation conducted by Ørting (1996a) under greenhouse conditions has clearly succeeded in demonstrating that what was previously regarded as a quite homogeneous taxon does in fact possess a wide range of morphological and physiological diversity Figures 3-6 show the variability in stem length, number of flowers produced by individual plants, pollen fertility and development stages. Both twining vines and genotypes with very short internodes having an erect bushy growth habit exist. Furthermore, both multituberous and monotuberous lines have been identified (though the monotuberous form appears to be dominant). Sørensen (1996, Table 2) gives an overview of the morphological variation of 27 characters in the five species. Strikingly different abscission rates exist, and the number of flowers produced by the individual plant as well as the actual number of seeds produced per plant differ considerably. The yield of the 20 accessions so far analyzed also differs.

Field evaluations recently conducted in Tonga have served to further substantiate the diversity available within this species, as have the physiological drought-tolerance studies conducted by Prof. Vieira da Silva (Univ. Paris VII) and Dr D.J.M. Annerose (CERAAS, Senegal). The recent examination of photothermal sensitivity and the rotenone/rotenoid contents of the species, conducted by Prof. Válio and his associates, will certainly serve to increase the available information on the diversity of *P. ahipa.*

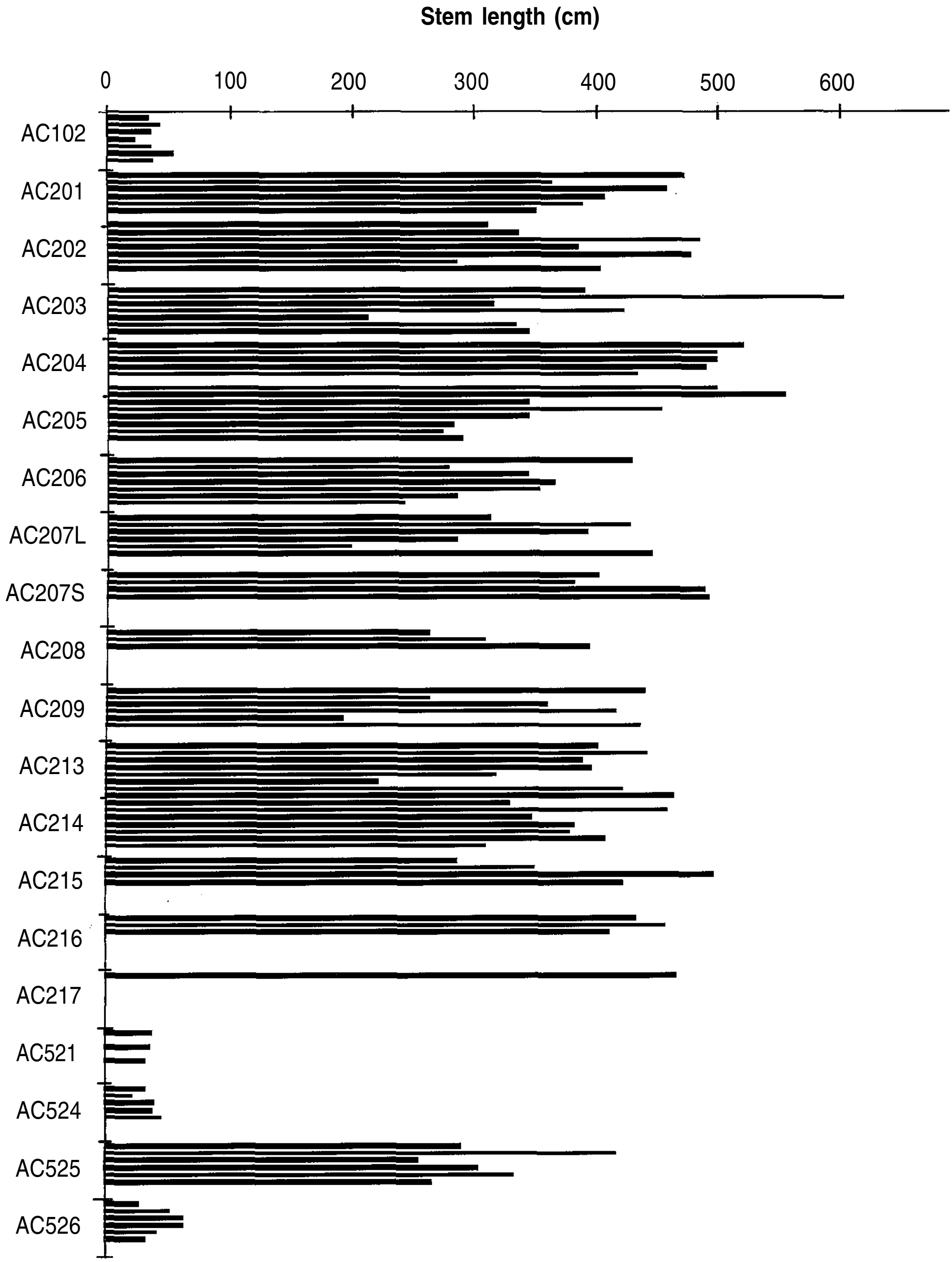


Fig. 3. Stem lengths of individual plants in 20 *P. ahipa* accessions (each bar represents one plant).

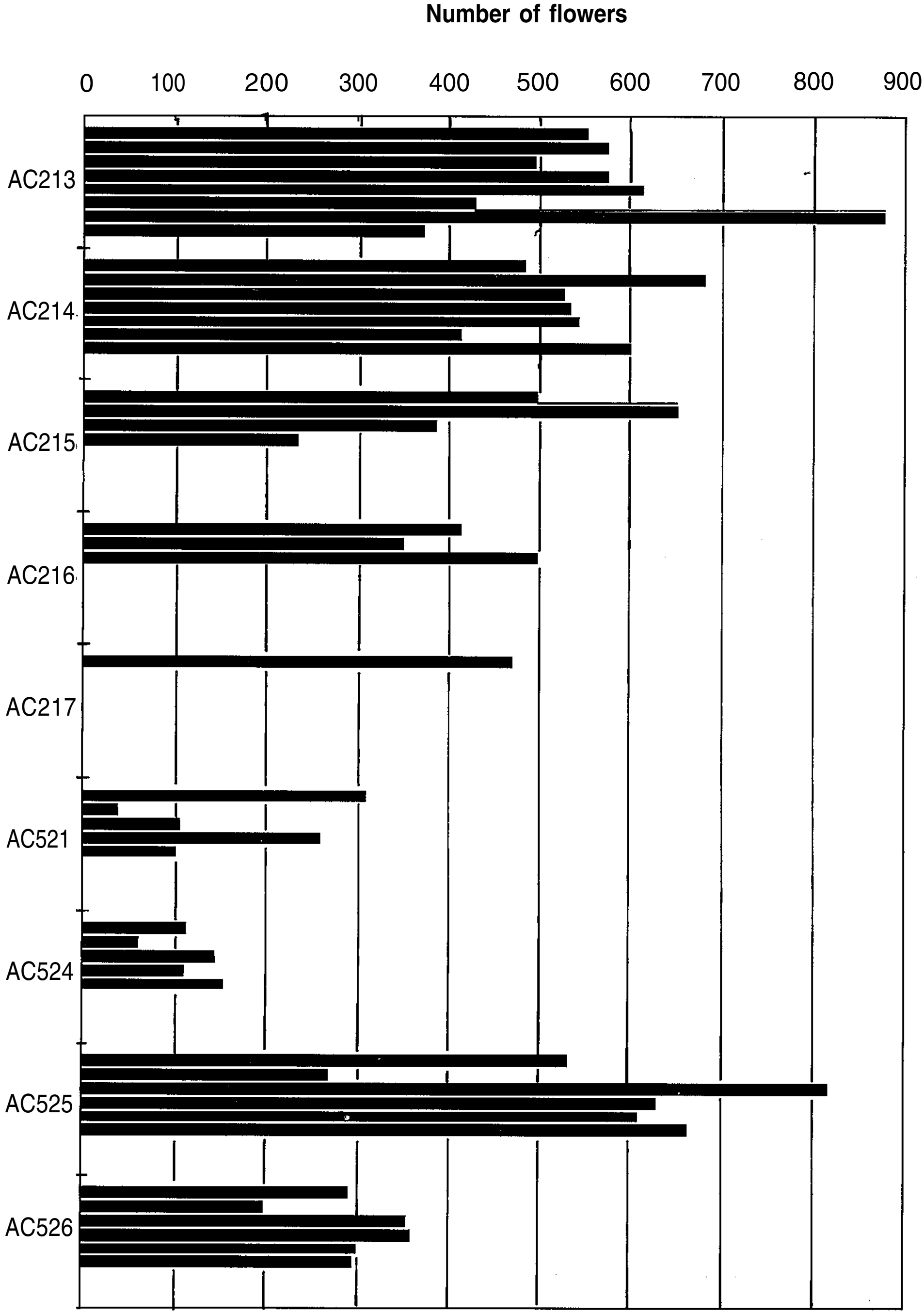


Fig. 4. Total number of flowers produced by individual plants in 20 *P. ahipa* accessions (each bar represents one plant).

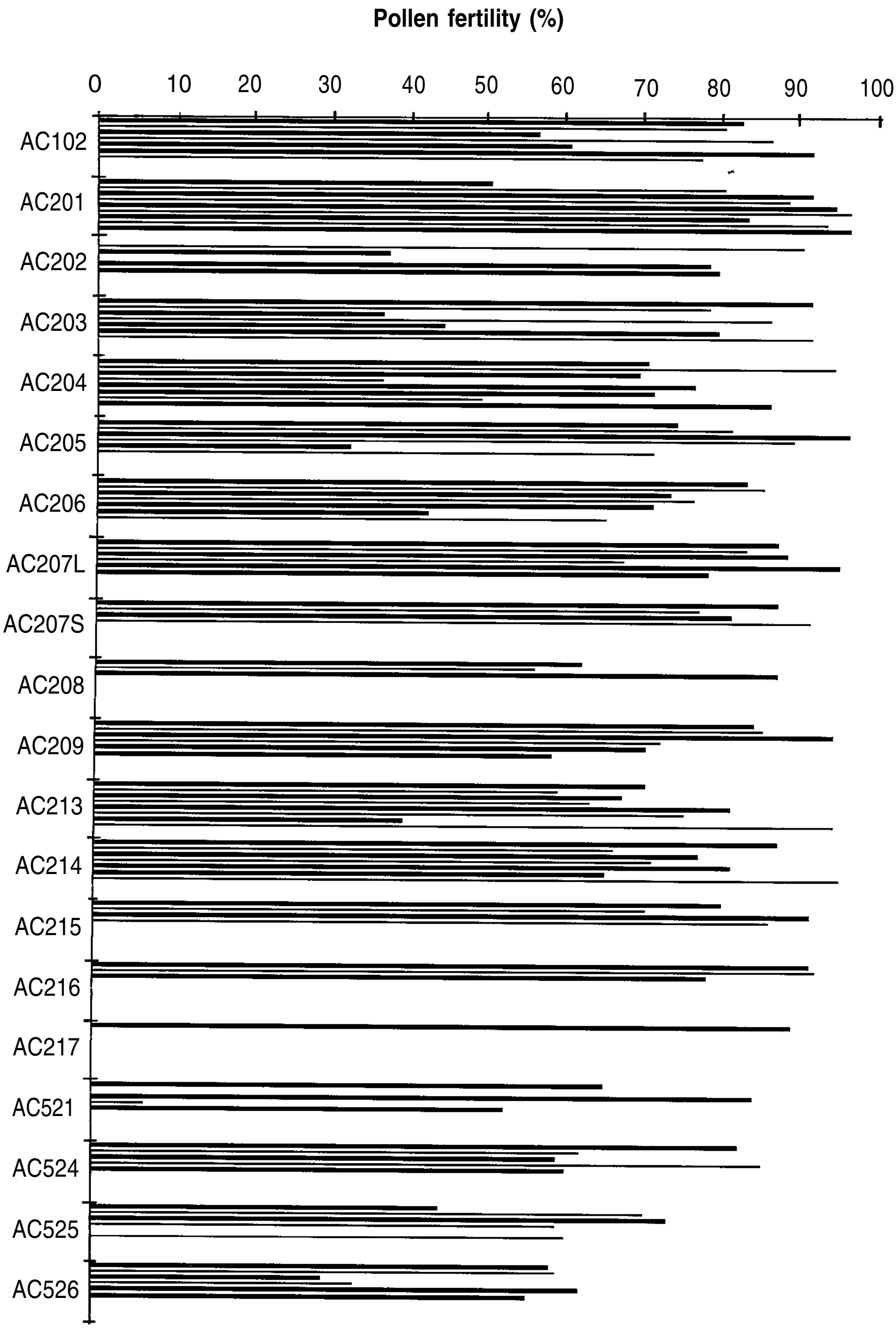


Fig. 5. Pollen fertility (%) of individual plants in 20 *P. ahipa* accessions (each bar represents one plant).

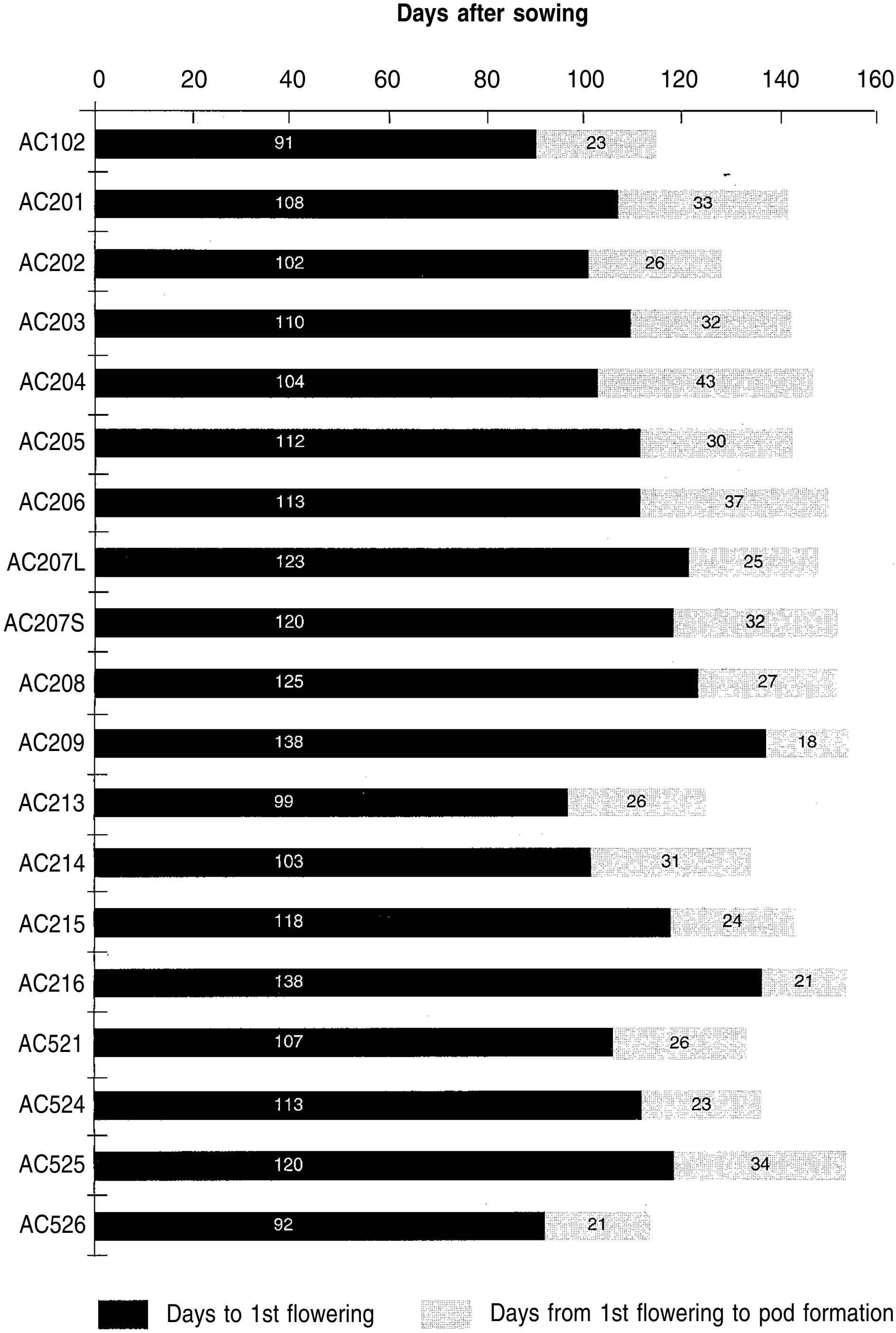


Fig. 6. Days after sowing until 1st flowering and from 1st flowering until pod formation in 19 *P. ahipa* accessions. Averages for each accession are based on 1-8 plants. Number of days shown on top of bars.

7 Geographical distribution of important traits in the entire genepool

The initial analysis of existing genetic variation within the 31 accessions available demonstrated the presence of highly significant differences in growth habit. It furthermore became apparent that this trait follows a geographical distribution from north to south with the strongest vine-like genotypes to the north near La Paz in Bolivia and the smallest, bushy landraces to the South in the provinces of Chuquisaca and Tarija, Bolivia and in the provinces of Jujuy and Salta, Argentina (Fig. 2). The considerable difference in flower/seed production recorded between the different accessions may well be the result of differences in the agronomic selection pressure, i.e. the short bushy landraces produced fewer than 100 flowers and fewer than 20 seeds per plant and had pollen fertility percentages of less than 45% whereas several accessions from the La Paz area produced more than 800 flowers and more than 100 seeds per plant and had practically 100% fertile pollen (see Figs. 4 and 5). The abscission rate also varied significantly as did the pollen fertility percentages (Ørting 1996a, Table 3).

8 Importance of wild relatives as a source of diversity

If the high disease and pest resistance observed in *P. ferrugineus,* recorded in multiplication plots in Tonga, Ecuador and Costa Rica, can be successfully transferred to the cultivars this would be of obvious agronomic interest. However, although interspecific hybridization experiments have been attempted repeatedly in both Costa Rica and Tonga, so far all combinations involving this species have been unsuccessful. The ecological association of *P. ferrugineus* with soil types low in available phosphorus may also be of potential breeding interest (see Manu *et al.* 1996), as could the evergreen habit.

The interspecific hybridization experiments have, as mentioned in Section 2.2, primarily involved cross-breeding between the three cultivated species *P. erosus, P. ahipa* and *P. tuberosus.* But the wild populations belonging to *P. erosus* from either the Department of Huehuetenango, Guatemala or from the Province of Guanacaste, Costa Rica and the wild species *P. panamensis* also have been used in interspecific crosses. The objective of the experiments is the transfer of the strigose pubescence of the vegetative parts and subcoriaceous leaf type to high-yielding genotypes that are susceptible to insect damage and/or which may need improved drought tolerance in order to increase the climatic adaptability. The strigose pubescence has been successfully transferred and, among the resulting hybrids, genotypes with high yield potential have been identified (Dr P.E. Nielsen, pers. comm.).

Until actual analyses of the variability in the rotenone content of the two wild species as well as the wild populations of the cultivated species have been concluded, it can only be theorised whether some genotypes among these groups may possess sufficiently high levels of rotenone to make the extraction of seeds from interspecific hybrids involving these genotypes and *P. ahipa* commercially interesting.

9 Institutions holding germplasm collections

A comprehensive list of the institutions holding *Pachyrhizus ahipa* germplasm (and *Pachyrhizus* germplasm in general) is given in Appendix I. Seed samples of especially *P. erosus* landraces have been made available from a large number of institutions to the partners within the Yam Bean Project. The viability of the received germplasm (all species) varied from 0 to 100%. *Pachyrhiztus* seeds lose viability within one year if insufficiently dried and not kept under cool conditions. Yam bean has orthodox seed storage behaviour. A moisture content of less than 10% (5% is preferable) if the seeds are to be stored for prolonged periods and a temperature below 5°C is recommended.

Of the *Pachyrhizus* material registered with institutions holding germplasm collections as listed by IBPGR (1981), 98% represent one species only: *P. erosus* (some accessions may have been registered as belonging to other species, and misidentifications are common).

Very few of the institutions involved have the financial means, interest and knowledge necessary to implement an efficient rejuvenation programme. Hence, a number of the recorded accessions – stored with institutions not part of the Yam Bean Project – are no longer viable and only if complete passport data have been filed will the individual records be of interest.

Today the principal germplasm collections are located with the individual partners linked within the Yam Bean Project. A complete collection is kept at Research Division, Ministry of Agriculture and Forestry, Tonga (South Pacific) where all accessions have been rejuvenated at regular intervals, and a core collection is kept at the Botanical Section, Royal Veterinary and Agricultural University, Copenhagen, Denmark. All available passport data are included in the germplasm list available from the authors. The completion of a comprehensive catalogue, which is to include experimental data on each accession from the field trials conducted pantropically, is currently in progress. This will be a valuable tool when selecting genotypes for introduction to new regions.

The largest collection kept by any institution not associated with the Yam Bean Project is kept at the Southern Regional Plant Introduction Station, USDA-ARS in Georgia, USA, although this institution does not store any *P. ahipa* accessions.

9.1 Availability of data on individual accessions

Generally the available data on individual accessions is limited to the origin (although a number of accessions kept at different institutions are of unknown origin) with little or no geographic, climatic, edaphic, ecological and agronomic data. This has been one of the major constraints when evaluating accessions obtained from existing germplasm collections. Furthermore, it is difficult to assess the influence of the multiplication, i.e. selection, method used for seed production in the place of origin when comparing the performance of different landraces, e.g. Ørting *et al.* (1996) found that Bolivian farmers use very different criteria when selecting plants for seed production (see Section 2.2). The methods used are quite unlike the method commonly used in *P. erosus* where a special plot is cultivated for seed production only.

An effort to collect as much information as possible on the cultivation practices associated with each accession has been made on the field collections conducted by colleagues within the Yam Bean Project (Ørting 1996b; Ørting *et al.* 1996; Sørensen *et al.* 1997). To facilitate the field observations, a comprehensive questionnaire was developed, targeting a uniform data-set of information that enables statistical comparisons (Ørting *et al.* 1996).

9.2 Gaps in existing collections

Among the known gaps in the existing germplasm collections the lack of any wild *P. ahipa* material is probably the most widely recognized. If the report by Ing. Agr. J. Rea from Bolivia (pers. comm.) concerning the recent collection of such material can be further substantiated, and the material be made available for taxonomic and agronomic research, this would provide valuable information on the phylogeny of this species and be of considerable interest to present and future breeding programmes.

From what little is known of the extant landraces of the Tarija Province, Bolivia as well as those from the Argentinian provinces of Salta and Jujuy (so far only two accessions known to originate in this southernmost part of the distribution area are included in the germplasm collection), these landraces are morphologically distinct in their short bushy growth habit and earliness and have been identified as being highly efficient plants when considering the three most important quantitative traits: (1) tuberous root growth – high, (2) growth of the aboveground vegetative parts – determinate and erect/bushy, and (3) reproductive shoot formation – limited. A survey of these landraces is clearly of high priority. As previously mentioned no record is known to the authors of any extant *P. ahipa* landraces in Peru. However, according to Dr C. Arbizu (pers. comm.), *P. ahipa* may still be found in cultivation in the Tarapoto area and perhaps further south in the Cuzco, Apurimac and Juni Provinces, Peru, i.e. areas where the traditional cultivation systems as well as climatic and edaphic conditions resemble the main production areas in Bolivia. Material from these regions may well be extremely attractive for breeding, because this material would fill the gap between the Bolivian *P. ahipa* genotypes and the Chuin cultivar group (*P. tuberosus*) from the Ucayali river (see Sørensen *et al.* 1997). The last group is of extreme value to the yam bean germplasm, as it is suitable for cooking (used like manioc) owing to its high dry matter/starch content. Therefore, within the regions mentioned above a high dry matter genotype of *P. ahipa* may exist.

9.3 Conservation of the species *(ex situ, in situ,* on-farm)

At present only *ex situ* conservation techniques are being used to preserve the germplasm collected. Indirectly, *in situ* conservation of wild population of *P. ferrugineus, P. panamensis* and *P. tuberosus* is used because populations belonging to these three species are located in national parks and forestry reserves and are thus in no imminent danger of becoming extinct.

Alternative *in situ* methods of conserving rare and endangered landraces are rapidly becoming apparent when surveying the status of the still extant landraces. In the case of the Andean *P. ahipa,* the two surveys of the Bolivian and Argentinean *P. ahipa* conducted in April-June 1994 and in May-June 1996 recorded the present status of *P. ahipa* in cultivation, examined the infraspecific variation and conserved as many extant local landraces as possible (Ørting 1996b; Ørting *et al.* 1996). During the 9 weeks of the first survey some 16 localities were visited, 24 farmers were interviewed and 17 new accessions (15 *P. ahipa* and 2 *P. tuberosus)* were collected. The second survey included visits to some 14 localities, 23 farmers were interviewed and 12 new accessions were collected. This proves that landraces are still to be found, but what transpired from the interviews and which calls for urgent initiatives was that only 65% of the farmers intended to continue to cultivate this crop.

When considering *in situ* /on-farm methods to conserve these endangered landraces, such efforts could well become successful for *P. ahipa,* especially if the authorities responsible for the agricultural policies were to promote the marketing of *P. ahipa* tubers. The present knowledge and interest is very limited.

9.4 Use of germplasm in research/breeding/crop improvement programmes

In principle all accessions included in the Yam Bean Project collection of germplasm have been or will be morphologically described and evaluated for agronomic and breeding potential. This process obviously depends on the seed quantity available, i.e. successful multiplication of small samples. The results from field trials using some 50 accessions including all species have been published (Grum *et al.* 1991b, 1994, 1997).

In the course of the field trials traits such as tuber shape, tuber yield, protein content of the tubers and required vegetation period have been evaluated. In addition to the field experiment conducted in several tropical countries, three series of *P. ahipa* field trials have been successfully carried out under Mediterranean conditions for three consecutive seasons in northeast Portugal (Prof. J. Vieira da Silva, pers. comm.). Special tuber quality evaluation programmes involving *P. ahipa* have been initiated in Germany, focusing on dry matter content, protein, starch and sugar contents and composition under greenhouse conditions (pers. observ.). Furthermore, initial hybridization experiments were conducted in order to examine the interspecific compatibility of the three cultivated species – *P. erosus, P. ahipa* and *P. tuberosus* (Grum 1994; Heredia G. 1994; Sørensen 1989, 1991; Sørensen *et al.* 1993). The production of fertile interspecific hybrids from all combinations (including reciprocal crosses) is possible, although patience and numerous pollinated flowers are needed for hybrid seed formation. This has been demonstrated repeatedly in hybridization experiments with all *Pachyrhizus* species (Grum 1994; Heredia G. 1994; Sørensen 1989, 1991; Sørensen *et al.* 1993). These experiments are not only of interest in phylogenetic studies, but interspecific hybrids must be regarded as being of

considerable importance in breeding, because the entire *Pachyrhizus* genepool may in this way be used in a breeding programme.

Field trials evaluating the initial interspecific hybrids have been in progress since 1989. The interspecific hybrid production has been carried out as one-way crosses, e.g. *P. erosus* x *ahipa* (Fig. 7), *P. erosus x tuberosus* and *P. tuberosus* x *ahipa,* as well as three-way crosses, e.g. *P. tuberosus* x (*P. erosus* x *ahipa*). Material of these experimental hybrids is now approaching non-segregating generations (F_6 or later). The selected lines are regarded as being extremely agronomically and commercially interesting according to information from Ing. Agr. A. Heredia Z. (pers. comm.). This material may be released to producers in 1-2 years. The new 'cultivars' of *P. erosus* x *ahipa* origin will possess several traits originating in either species, e.g. the tuber quality of *P. erosus* combined with the erect, determinate growth habit and earliness found in *P. ahipa* (Fig. 7).

In breeding research the hybrids will be of importance when estimating the range of genetic parameters and the base of negative secondary effects within wide crosses in pre-breeding material.

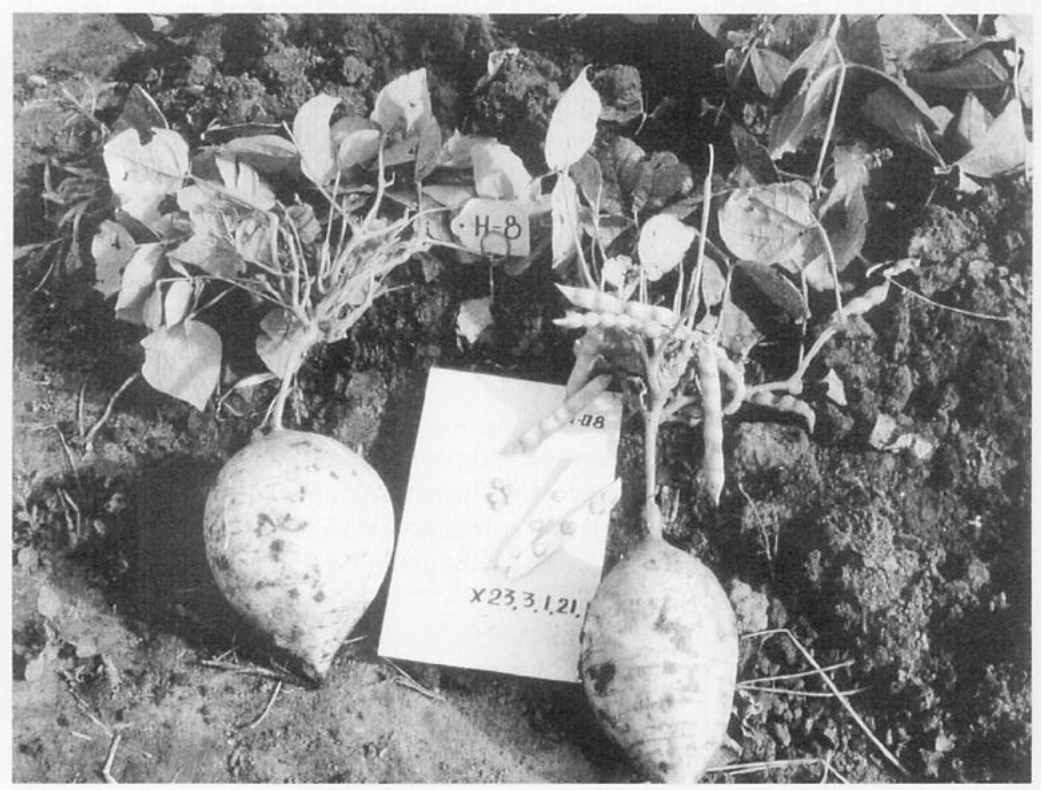


Fig. 7. Interspecific hybrid (F_4), from original cross of EC032 *(P. erosus* from Mexico, State of Yucatan, Kantunil) x AC102. Grown at the CEBAJ experimental station near Celaya, State of Guanajuato, Mexico. Photo, E. Heredia G.

10 Breeding

As mentioned above, a wider variation of *P. ahipa* material has become available for plant breeding only recently. Four accessions only were available prior to 1994, in 1994 an additional 14 accessions were added, and finally in 1996 a further 12 accessions were included (Ørting 1996b; Ørting *et al.* 1996). Nonetheless, *P. ahipa* has gained a remarkable attraction for applied and theoretical aspects in plant breeding.

10.1 Strategy for the traditional and more advanced production areas

In general a suitable breeding strategy depends mainly on the reproduction biology and the applicable sources of variation. For the reproduction biology, *P. ahipa* may be treated as a cloneable, annual self-pollinator as mentioned. However, for breeding and production it must be propagated sexually because the reproductive rate by cloning from tubers is low (1-2) compared with potatoes (10-15). Of course this rate is certainly higher if biotechnological propagation methods or cuttings are used. Nevertheless, the possibility of plant propagation by seed in *P. ahipa* and the other *Pachyrhizus* species may be regarded as an advantage, to avoid transmission of virus and to avoid costly storage of propagation material. With regard to the applicable sources of variation, in *P. ahipa* all possibilities still exist. There is considerable variation between and within landraces. Also the use of the entire *Pachyrhizus* genepool via fertile hybrid production within and between species may be considered. The work on all current breeding challenges is possible by selection between and within landraces or by selection between and within cross/hybrid progenies, apart from the fact that creation of genetic variation in *P. erosus* induced by radiation has been conducted in India (Nair 1989; Nair and Abraham 1985, 1989,1990).

The utilization of existing variation within and between landraces for selection has been carried out by positive mass selection, e.g. in Portugal and Mexico. These field experiments were conducted using the accessions AC201, AC524 and AC521. Until 1992 only this material had been sufficiently multiplied to allow mass selection to be conducted.

From breeding experiments with the Mexican yam bean (= *P. erosus*) it may be concluded that the mass selection procedure within landraces is very efficient, especially on traits like crop duration, pod-formation, tuber size and shape, yield and geographic adaptability. All known cultivars of *P. erosus* – Mexican, Indian or Far Eastern—are the result of mass selection without the induction of genetic variation via crosses.

The main emphasis is currently given to individual plant selection of landrace material by testing of single-plant progenies. These tests are carried out under greenhouse conditions and a series of field experiments, the latter coordinated by the Yam Bean Project. At present, this is undertaken with all presently available *P. ahipa* accessions, including the material collected in 1994 and 1996 (Ørting 1996b; Ørting *et al.* 1996).

In spite of the high short-term selection response expected through the selection in landrace material, the target of this procedure is not to release superior material

for agronomic production. The main target is to identify interesting parental lines for cross-breeding.

The introduction of new variation via crosses combined with selection of single-plant progenies that have been sufficiently multiplied to conduct enough pure line field tests is generally the backbone in any breeding programme in self-fertilizing species. In *P. ahipa* this has been undertaken with F_5 and F_6 derived-material of all pair crosses between accessions AC201, AC521 and AC524. This non-segregating material is currently being evaluated in field trials in Mexico and according to information by Ing. Agr. A. Heredia Z. (pers. comm.) this material may be released to producers in the near future.

The main emphasis in these experiments is given to the combination of superior characters, e.g. tuber shape and required growth period. To conduct this on a large scale, with accession material and with material that shows highly significant genetic distance, was until recently possible to a limited extent only. The limitations were (1) small botanical seed samples of two of the three accessions used as cross-breeding parents, and (2) different indications that the whole material originates from one region in south Bolivia. This situation changed owing to the mentioned Bolivian and Argentinean collecting trips, but no pure line material is presently available. Early selections within lines, derived from the F_2 and F_3 generations, have only been implemented in the form of visual selection based on plant performance toward pure line development, but not as a chance to reduce the extremely time-consuming period for recombination intervals. To use this in a rapid population improvement is currently under focus for *P. ahipa* and/or *P. tuberosus.* A selection, carried out repeatedly, and the recombination of superior F_2 or F_3 lines, would considerably enhance the probability of breaks in negative linkage groups within and between quantitative traits in connection with the opportunity of selection. Because of the special reproductive biology of *Pachyrhizus,* selected segregating cross parents may also be reproduced vegetatively and this would easily result in the development of pure lines, as suggested by Jensen (1988). From the view of selection theory this is defined as recurrent selection, targeting on the enhancement of the long-term selection response in the population (Gallais 1984). This is theoretically the most efficient method of population improvement and therefore pre-breeding. In practice the result depends on the control of the negative secondary effects (genetic drift under linkage) in other traits, i.e. a critical point in recurrent selection programmes which has yet to be solved.

The interspecific hybridization experiments – initially established to investigate the compatibility of the three cultivated species – formed the basis of the breeding programmes where *P. ahipa* is used as a donor for cultivar characteristics. The hybrids of *P. erosus* x *ahipa* origin were, as mentioned, selected to combine the tuber quality of *P. erosus* with the erect, determinate growth habit and earliness of *P. ahipa.* Similar experiments have been conducted with *P. erosus* x *tuberosus* in Mexico and triple hybrid combinations involving *P. tuberosus* x *(P. erosus* x *ahipa)* in Tonga. These are all selected according to the pedigree method (5%) with tuber shape/size,

determinate growth habit, pest resistance and seed yield as the selection criteria. Although the breeding programmes were initially set up to use *P. ahipa* as a donor parent for cultivar characteristics, amazingly good-performing hybrid lines have been found within these populations with regard to tuber yield and wide adaptability. Nevertheless, negative secondary effects in these hybrid populations have been observed, e.g. reduced seed set and germination rates (pers. observ.). The reduced seed set reached a critical level in the F_3 and F_4 generations; thus seed yield has had to be included as a selection criterion in later generations. In particular, as these wide crosses resulted in an unbalanced genome, it is probable that an increased recombination within these hybrid populations, by means of increased of cross intensities, would be very suitable. This could be achieved as described above.

10.2 Challenges for the traditional and more advanced production areas

When contemplating the breeding challenges of the Andean Yam Bean it is helpful to distinguish between breeding aims for *P. ahipa* as a vegetable crop, a basic food crop and as a possible industrial crop. However, some breeding aims are common for all usage forms, e.g. reduction of the growth period and reduced pod formation per plant to avoid reproductive pruning. In the following the common aims will be treated under the usage as a vegetable crop.

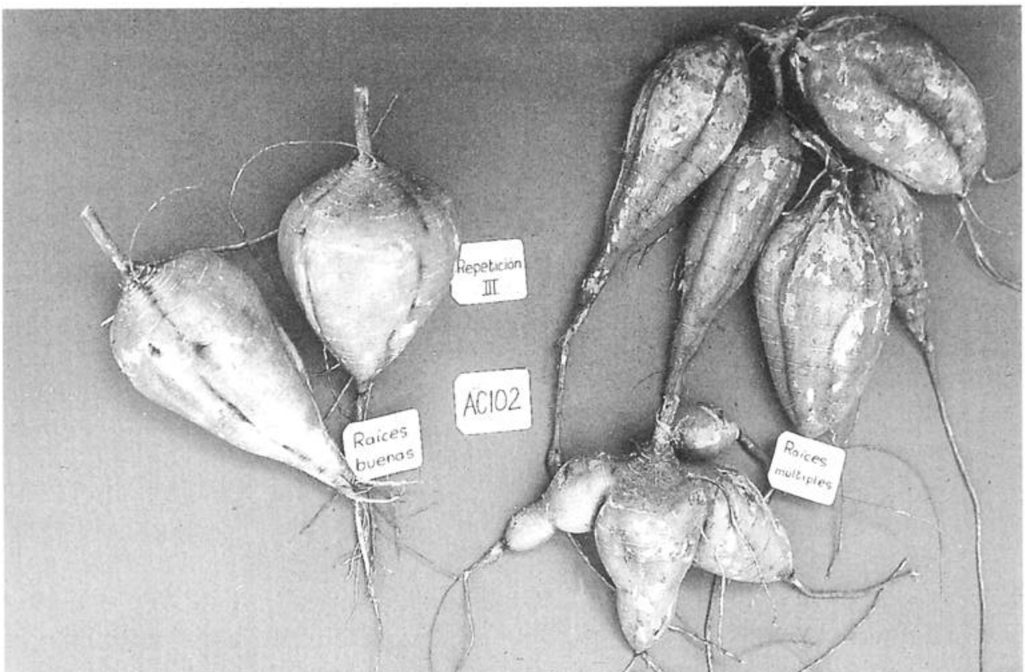


Fig. 8. *Pachyrhizus ahipa,* accession AC102. Well-shaped monotuberous root and non-marketable multituberous roots. Grown at the CEBAJ experimental station near Celaya, State of Guanajuato, Mexico. Photo, E. Heredia G.

All *Pachyrhizus* species are – in their area of origin and today also in many overseas areas—known as a vegetable/fruit crop. The tubers are eaten raw or to a lesser extent used in salads and juices. As mentioned earlier, this has reached a level of importance where *P. erosus* today is recognized as the fastest-growing speciality vegetable/fruit on the US market, mainly imported from Mexico (according to Brumback 1990). In general, the breeding challenges for the speciality vegetable like the Andean yam bean (*P. ahipa*) and/or the Mexican yam bean (*P. erosus*) are size and shape of tubers (Fig. 8). On the US market monotuberous plants with a round shape of the single tuber between 0.7 and 1.2 kg is demanded, whereas on the South American market a multituberous plant with more sugar-beet-like shape, between 1 and 2 kg, is accepted (Fig. 8). For trading and selling at the rural markets cultivars with a thicker skin are demanded. Thick skins decrease susceptibility to bruising during transport and prolong shelf-life. The improvement of both traits is named as very important by local producers in Mexico. This is especially the case when the US market is the target.

For the main, large-scale *P. erosus* production areas in Mexico the major challenge is currently the development of new early cultivars which will allow a continuous production within the country, alternating between the lowland regions (the State of Nayarit) and the areas at higher altitudes (in the States of Guanajuato and Michoacan). The new lines developed as a result of cross-breeding experiments involving *P. erosus* x *ahipa* hybrids have been shown to possess a significantly shorter crop duration and may therefore increase the total period of tuber availability.

The introduction of improved yam bean cultivars in the traditional cropping systems practised by smallholders in Mexico and Central America is presently in progress. The same situation applies to India and South East Asia where advanced Mexican cultivars will have to be evaluated extensively under field conditions. Also in a number of West African countries, where both *P. erosus* and *P. tuberosus* have recently been introduced, the crop has attained a remarkable success. In these regions the introduction of yam bean cultivars into the traditional intercropping systems is of great interest. Therefore, the evaluation of the crop itself is urgently needed, including a wide range of available genotypes and interspecific hybrids of potential in sustainable intercropping systems at various climatic locations and with a tuber quality similar to the traditional root crops. Hybrids involving *P. ahipa* may again serve to reduce the cropping period. In spite of the difficulties associated with the statistical treatment of large-scale tests in intercropping designs, such a project should be given a high priority (Federer 1979; Pearce *et al.* 1988). The first steps in this direction have been conducted within the Yam Bean Project by estimating the nitrogen input of yam beans via the difference method (Castellanos *et al.* 1997).

The evaluation of the efficiency of both improved yam bean lines and interspecific hybrid-lines in connection with the development of adapted intercropping systems would likewise have a great impact. This is true not only with reference to the introduction of the crop in more tropical and subtropical regions, but also to retain

and improve the attractiveness of *P. ahipa* and the Jíquima cultivar group (*P. tuberosus* complex) with the local farmers, thereby ensuring the conservation of these taxa.

Yam beans are not used or known as a basic food stuff in any parts of the entire distribution area, with one exception: the Chuin cultivar group within the *P. tuberosus* complex collected along the upper reaches of the Ucayali river. In this region, two *P. tuberosus* cultivar groups are found – the Ashipa and the Chuin. The last is used similar to the traditional root crops sweet potatoes and manioc. Because of their high dry matter content the tubers are prepared like the roots of the manioc. It seems probable that new cultivars involving the Chuins would have a major impact on *Pachyrhizus* tuber consumption and perhaps also on crop production systems that include this legume/root crop within intercropping systems. One way could be to include more cultivar characteristics into the Chuin type, such as high yield, determinate or semideterminate growth, shorter growth season and adaptation to a wide range of climatic environments. An alternative, and this is the current main breeding target within the Yam Bean Project, is to introduce the high dry matter character of the Chuin tuber into the high-yielding and widely adapted types of the *P. erosus* and/or *P. ahipa* genepool. Here emphasis must be given to designing a breeding strategy that will avoid genetic drift in other traits like protein, starch and sugar contents.

The successful development of the yam bean as a basic food crop will demand a widened breeding focus encompassing important nutritional characteristics such as protein quantity and quality of the tubers. It is most likely that *P. ahipa* has a composition similar to that of *P. erosus,* e.g. in *P. erosus* the amino acid composition is close to the ideal values for human nutrition formulated by FAO/WHO (1989) (see Section 4.3). Here the Mexican yam bean equals the values listed. Evaluations of the *P. ahipa* and *P. tuberosus* genepool are still needed to verify whether this also applies for these two species.

Provided the amino acid composition of *P. ahipa* and *P. tuberosus* is of the same quality as *P. erosus,* the main breeding aim for the two species, in terms of nutritional quality, must be the increase of pure protein content. That this is physiologically possible in yam beans can be concluded from the protein content of tubers from Winged Bean *(Psophocarpus tetragonolobus* (L.) DC.) and *Vigna* sp. (20-30% on dry matter basis). As suggested by Vavilov's rule of homologous lines, accessions or single genotypes with a similar high protein content may also be found within the *Pachyrhizus* genepool. This aspect has been supported in the yam bean genepool by preliminary quality evaluations involving 16 *P. ahipa* accessions and 2 *P. tuberosus* accessions (Chuin). A protein content of *P. ahipa* within the range of 8-18% was recorded, whereas the range for *P. tuberosus* was 5-8% (pers. observ.).

10.3 Opportunities for modern biotechnology

The use of *in vitro* multiplication techniques constitutes an attractive possibility when contemplating the rapid multiplication of genotypes of limited availability for conservation purposes (new material from field collections) or breeding material

possessing agronomically attractive traits (limited cross-parents). If such genotypes became available instantly in sufficient quantities they could be subjected to broad use almost immediately following their identification/selection.

Several institutions, i.e. in Costa Rica, Denmark, Ecuador and Trinidad, have initiated studies in this field (Forbes and Duncan 1994; Muñoz *et al.* 1997). The experiments have so far involved regeneration and multiplication from adventitious and axillary shoots (explants) and callus formation with subsequent organogenesis, i.e. the development of protocols for somatic embryogenic systems.

In the area of molecular taxonomy, the relationship between the different species is currently being studied at the School of Biological and Medical Sciences, Plant Sciences Laboratory, University of St Andrews (Estrella E. *et al.* 1997). The identification of molecular analyses as a new approach appears to be an obvious one as improvement in agricultural production of yam beans is ultimately dependent on the availability of appropriate germplasm for developing drought-tolerant, photothermally neutral, and pest and pathogen-resistant cultivars capable of producing high yields over a wide range of climatic and edaphic conditions. In view of the critical situation of *Pachyrhizus* germplasm in South America, widely recognized by national and international agencies, a programme of assessment of genetic resources is of the highest priority.

The research at University of St. Andrews involves the estimation of molecular genetic distances and evaluation of cross-progenies, utilizing isozyme variation over 20 enzyme systems and polymerase chain reaction (PCR) to resolve randomly amplified polymorphic DNA sequences (RAPDs) analysis to assess and resolve the level and distribution of genetic diversity within and between species of *Pachyrhizus.* The analyses are conducted on a representative sample of the existing germplasm collection of *Pachyrhizus* to include all species and a wide range of cultivars, landraces and wild material.

The survey of molecular genetic diversity in the germplasm collections of *Pachyrhizus* will enable the following to be achieved:

- analysis of phylogenetic relationships within the genus *Pachyrhizus* with particular emphasis on the origin of the cultivated species P. *ahipa, P. erosus* and *P. tuberosus*
- location of natural centres of genetic diversity for collection and conservation
- estimation of genetic diversity levels within and among species
- identification of markers associated with attractive genetic traits, e.g. earliness, protein content.

11 Major and minor production areas

There are no major production areas of *P. ahipa.* The production is restricted to a few localized villages and individual farmers; *P. ahipa* is partly cultivated for home consumption, and approximately 50% is marketed. In Bolivia the *P. ahipa* tubers are principally sold on the markets of the nearest villages which have organized vegetable markets, i.e. only a fraction of the production reaches the—markets in the larger cities.

No international trade in *P. ahipa* is known to take place.

12 Ecology

The habitat of *P. ahipa* is known from cultivation only, in cool tropical/subtropical valleys, where it appears to be well adapted to an altitudinal range of 1800-2600 m asl, though the crop was also recorded at +3000 m as1 in sloping north-facing fields (fully exposed to the sun). The region of cultivation is located along the border between the warm ('tierra templada') and cold tropics ('tierra fria'). The average temperature within the region is between 16 and 18°C where the climatic conditions are extremely dependent on the time of day. The temperature oscillates between a minimum of 0-5°C to a maximum of 30-35°C. As the average annual precipitation rate is 400-700 mm, occurring within 4-6 months, the remainder being the dry season, the climate is semi-arid. Farmers reported that the cultivation period has a duration of 5-10 months, depending on the length and intensity of the rainy season. The *P. ahipa* plant will tolerate long dry spells, but an additional water supply is essential to increase tuber yield. Cultivation is predominantly carried out along loamy riverbanks, although sloping hillsides with loamy soil may in some cases be used. A well-drained soil type with pH=6-8 will meet the edaphic requirements of the crop (Ørting *et al.* 1996).

12.1 Photothermal neutrality (daylength sensitivity)

A view generally held is that yam beans are short-day plants, i.e. that flowering and tuber production will only take place under decreasing daylength. However, field studies and observations and experiments conducted under greenhouse conditions have demonstrated the existence of genotypes with reduced or practically absent photothermal sensitivity.

Pachyrhizus ahipa has been grown continuously for a number of years in the greenhouses at RVAU, Denmark. Seeds have been planted in virtually all months of the year. During both short-day and long-day periods, the *P. ahipa* accessions have been observed to have the most rapid flower initiation among the *Pachyvhizus* species, i.e. from 87 days (in plants with determinate growth habit) to 140 (in indeterminate plants) days after sowing regardless of the season (Ørting 1996a). Furthermore, the tuber growth does not appear to be influenced by variations in daylength; hence this species may be regarded as daylength-neutral and neutral lines may be bred from interspecific hybrids involving the species.

According to Prof. I.F.M. Válio (pers. comm.), Dr M. de Fatima Ferrine has studied the daylength sensitivity in four to five accessions under different light and temperature regimes at UNICAMP, Brazil; however, the results from these experiments have yet to be published.

12.2 Climatic and edaphic requirements

Physiological studies of the response to drought in *Pachyvhizus* have been carried out under field conditions in Senegal (Annerose and Diouf 1994) and under greenhouse conditions in France (Vieira da Silva, pers. comm.).

The studies in Senegal demonstrated *P. erosus* as being a good drought-avoider, i.e. able to reduce respiration and metabolic processes during drought spells, and

P. ahipa as being a drought-tolerant species, i.e. able to continue respiration and metabolism during drought spells. The latest trials, designed as pot trials, were aimed at studying the developmental competition between the reproductive organs (flower, legume and seed) and the storage organ (tuberous root) under the influence of drought. The experiments, using *P. ahipa,* include four different treatments: (1) reproductive pruning and water stress, (2) reproductive pruning without water stress, (3) no reproductive pruning with water stress, and (4) no reproductive pruning without water stress. The results indicate that the reproductive pruning has no influence on the physiological response to drought, i.e. no influence on respiration or metabolic processes (Annerose and Diouf 1997; Diouf *et al.* 1997; Orthen and von Willert 1997).

The experiments studying the drought tolerance of the accessions of *P. ahipa* based on the correlation of leaf polar lipids and fatty acid composition on the cell membrane resistance to osmotic stress demonstrated the considerable variation in response to drought of these three accessions (AC102, AC521 and AC524) and the comparatively high drought tolerance in comparison with other tropical leguminous crops (Vieira da Silva 1995).

12.3 Impact on environment

The beneficial effects on the environment – mainly as a result of the biological nitrogen fixation (see Section 4.1) – must be considered as surpassing the negative effects. Hence, a list of the beneficial effects will include the following characteristics and their effect: highIy efficient nitrogen fixation – increased vigour among the neighbouring plants (especially so on poorer soils); good drought tolerance-provide high-protein forage for livestock and other herbivores; erosion control – though not as aggressive as the *Pueraria* spp. the *Packyrhizus* spp. will effectively reduce soil erosion. The negative effects are: seed propagated – the crop may easily (be) spread into the wild vegetation bordering fields cultivated for seed production; rotenone/rotenoid content – the poisonous seeds may cause problems in livestock foraging on escaped plants among the wild vegetation, and as the seeds may be used to poison fish this poses a risk in areas where unauthorized use of such methods may disturb the ecological balance; vigorous growth – although as mentioned, the *Packyrkizus* spp. are not as aggressive as some of the *Pueraria* spp., a few of the *P. tuberosus* genotypes are very large, strong vines and they may upset a fragile indigenous flora; legume – several of the species have been found to become infected by different viruses and escaped plants may therefore serve as hosts for such diseases; tuber/root crop – in areas suffering from heavy infestation by nematodes, escaped plants may serve to maintain a high level of infestation, also some insect pests, e.g. *Diabrotica* spp., may find refuge on escaped plants.

Careful quarantine measurements should be implemented when introducing the crop to new regions in order to minimize the risk of introducing diseases (especially those possibly seedborne) and, more importantly, bean weevils (= bruchids) specific to *Packyrkizus* which do not at present occur in any of the areas outside the Neotropics.

13 Agronomy

13.1 Propagation of the crop

Packyrhizus ahipa is always propagated by seed and seeds are sold in the markets (Fig. 9a).

Ørting *et al.* (1996) report that two different methods are used when selecting plants for seed production: (1) the grower will select the healthiest and most vigorous looking plants and leave these without reproductive pruning to produce seeds, or (2) leave the first developed legume/pods on all plants and remove all subsequently produced.

Seeding rates of 21-105 kg/ha have been recorded, but general rates are 40-65 kg/ha. Again, factors like preferred tuber size, soil fertility and obviously seed weight play a major role when determining the rates (Ørting *et al.* 1996).

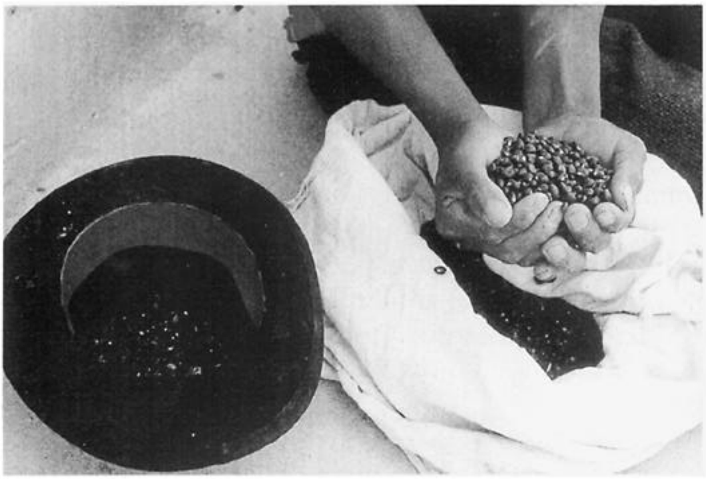
13.2 Crop husbandry

Ahipa is generally grown as a monocrop, but may in some instances be intercropped with maize *(Zen mays* L.). Crop rotation is always practised and *P. ahipa* is cultivated prior to maize/potato, maize/tomato *(Lycopersicon esculentum* Miller nom. cons.), maize/oca *(Oxalis tuberosa* Molina), groundnut or manioc. Planting distances vary from 20-60 cm between rows and 6-25 cm between plants within rows, i.e. 6-83 plants/m^2 (Fig. 9b). In areas with high precipitation rates during the growth period or when the crop is flood-irrigated, it is planted on ridges to increase the drainage, a practice which is generally necessary in the Andean region. As part of the land preparation, the soil is loosened to a depth of 15-25 cm using a hoe, and thoroughly cleaned from weeds and stones. There are no reports of later weeding, but the practice of reproductive pruning is regarded as being of considerable importance. This manual operation was reported as being conducted once or twice in order to obtain the optimal tuber size (Ørting *et al.* 1996) (Fig. 9c).

13.3 Field trials

The various experiments conducted within the Yam Bean Project have succeeded in demonstrating the potential of *P. ahipa* with regard to both its immediate utilization as a high-yielding tuber/root crop with high contents of sugar and protein for subtropical regions, and its use in interspecific hybrid combinations with the other two cultivated species in the development of early, photothermally neutral and bushy-type cultivars. In trials carried out in Portugal by the French partner in the project the astonishing potential of the Andean yam bean (= *P. ahipa)* under Mediterranean conditions was observed -yields of 54t/ha with up to 24% dry matter were achieved, and crude protein percentages of 9.6 to 11.1 (DM).

The various trials have been/are carried out at different altitudes and cover a wide range of soil and climatic conditions. Both high-rainfall and semi-arid regions are included.



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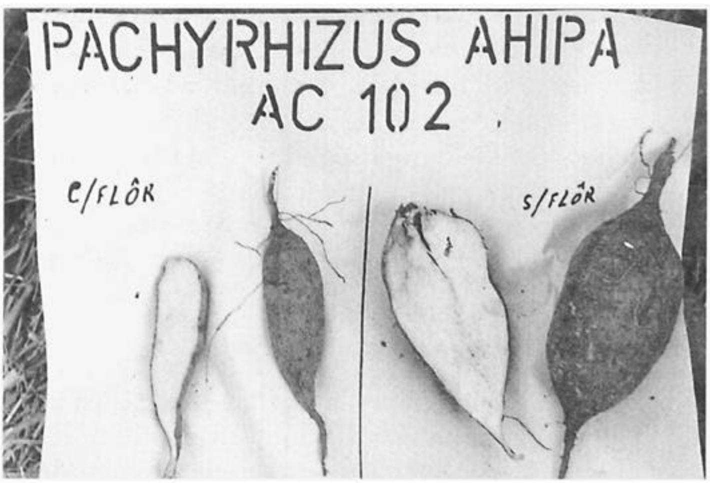

c

Fig. 9. a. Selling seeds by the head/hat ('por la cabeza'). Accession number: AC203; origin: Bolivia, Prov. Loaiza, Azambo near Luribay. Harvested 1993. The farmer, Sr. Luis Masí has bought the seeds from his uncle Sr. Luis Palo in Anquinoma. Collected by: Bo Ørting, Wolfgang Grüneberg and Jonas Ørting. Date: 19th April 1994. Seed colour: dull black. Approx. altitude: 2500 m asl. Photo, B. Ørting.

b. Accession number: AC205; origin: Bolivia, Prov. Ayopaya, Sanchu Panpa near Machaca. Farmer: Sr. Luis Orellano. Collected by: Bo Ørting, Wolfgang Grüneberg and Jonas Ørting. Date: 30th April & 1st May 1994. Pods harvested April 1994 from seeds sown September 1993. Seed colour: mauve. Approx. altitude: 2250 m asl. Photo, B. Ørting.

c. Harvested tubers from plants, accession AC102, with (right) and without (left) reproductive pruning; cultivated at the DRATOM experimental station near Mirandela, Tras-os-Montes, Portugal. Photo, J. Vieira da Silva.

Ahipa has been tested in field trials in Tonga, Mexico and Portugal. These are the first trials reporting yield size under different climatic conditions (Table 5). In Tonga the species has been tested during three growth seasons and the yield averaged between 3 and 22 t/ha depending on whether the flowers were removed or not and with plant populations ranging from 38 095 to 111 111 plants/ha. The first trials involving this species conducted in Mexico were flood-irrigated, with removal of fertile shoots and a plant population of 38 095. The yield was between 16 and 20 t/ha. The plant density was increased to 110 000 plants/ha in subsequent trials, resulting in a marked yield increase (see Section 13.7). The experiments in Tonga have shown *P. ahipa* as having one of the highest dry matter contents recorded among the cultivated *Pachyrhizus* species as much as 20% or higher (see also Section 4.3). This amount compares favourably with the traditional African tuber crops like cassava and yams *(Dioscorea* spp.). Hence, the possibility exists for breeding new high-yielding 'yam bean' cultivars which are more like the better-known tuber crops with a higher dry matter content.

Additional information concerning the layout and results from the field trials is reported in Grum *et al.* (1994), Heredia G. (1994) and Morera (1994).

The field trials conducted in Mexico, Tonga and Portugal have yielded quite different results (see Table 5). The tuber quality varies according to climatic conditions, i.e. faster growth and lower dry matter in warm climates and short growth seasons. The very high dry matter contents recorded in the trials in Portugal demonstrate the possibility of utilizing *P. ahipa* tubers in processed and non-food products (see Section 4.4)

There are very few studies available on the quality aspects of forage hay of *P. ahipa.* The recent field experiment conducted in Mexico by Castellanos *et al.* (1997) reports the following yields and nitrogen contents of *P. ahipa* aboveground parts:

- accession number AC102: 1.7 t/ha dry matter with 55.1 kg N/ha in reproductively pruned plants, and 5.8 t/ha with 147.7 kg N/ha in unpruned plants
- accession number AC521: 1.8 t/ha dry matter with 62.8 kg N/ha in reproductively pruned plants, and 5.9 t/ha dry matter with 129.8 kg N/ha in unpruned plants.

These results demonstrate that the nitrogen concentration as a percentage in the aboveground parts increases as a result of reproductive pruning although forage yield decreases, i.e. from 3.24-3.49% in pruned plants to 2.20-2.54% in unpruned plants. Also, the total amount of nitrogen fixed (kg/ha, tuber + aboveground parts) did not differ significantly between the pruned and unpruned plants, in *P. ahipa* – 68.7-74.3 kg N/ha for pruned plants and 58.4-79.7 kg N/ha for unpruned plants (see also Section 4.1).

Table 5. Results from P. ahipa field trials in Tonga, Mexico and Portugal†

Site	Access. no.	Plant density (plants/ha)	Fresh weight tuber, pruned (t/ha)	Dry matter tuber, pruned (t/ha [%])	Crude protein, pruned (kg/ha [%ofdry matter])	Fresh weight tuber, unpruned (t/ha)	Dry matter tuber, unpruned (t/ha/%)	Crude protein, unpruned (kg/ha/ % of dry matter)	Pods (t/ha)	Accum. N, tuber, pruned (kg/ha)	Accum. N, tuber, unpruned (kg/ha)
Tonga-1990	AC102	38 095	11.8	1.7							
Tonga-1989/90	AC524	38 095	5.3-6.1	1.1	71.0 [5.1%]						
Mexico	AC102	110 000	38.2	8.2	3.6	0.5				93.8	6.6
Mexico	AC521	110 000	41.0	7.8	2.5	0 .3				80.5	3.2
Portugal-1992	AC102	166 667	46.1	11.4 [24.7%]	991.8 [8.7%]	16.0	4.1 [25.9%]	496.1 [12.1%]			
Portugal-1992	AC521	166 667	39.2	13.8 [25.4%]	1324.8 [9.6%]	16.6	3.6 [21.5%]	442.8 [12.3%]			
Portugal-1992	AC524	166 667	54.3	14.6 [26.8%]	1620.6 [11.1%]	15.8	4.5 [28.3%]	598.5 [13.3%]			
Portugal-1993	AC102	166 667	8.2		7.5						
Portugal-1993	AC521	166 667	15.1		8.7						
Portugal-1993	AC524	166 667	10.1		8.9						
Portugal-1994	AC102	166 667	28.1			15.5			10.2		
Portugal-1994	AC521	166 667	17.5		14.2		12.6				
Portugal-1994	AC524	166 667	24.6		11.2		13.7				

† The growth period in Tonga was 137 days for the 1989 season and 173 days for the 1990 season; in Mexico, 1994 season, the reproductively pruned plants were harvested 180-210 days after sowing (DAS) and the unpruned plants after 220-246 DAS; in Portugal the 1992 season was 263 days, the 1993 season 245 days, and the 1994 season was also 245 days.
Sources: data from Mexico – Castellanos et al. 1997; data from Tonga – Grum et al. 1994; data from Portugal – Vieira da Silva 1995.

13.4 Diseases and pests

Although diseases and pests are listed below according to observations made in the three cultivated species, there is little doubt that the majority of both the diseases, regardless of the disease-inflicting organism, and the insect pests will in fact be common to all three species. Thus the differences recorded are due to geographic, climatic, ecological, and edaphic conditions rather than specificity. This has been confirmed in field trials in Tonga, Costa Rica, Ecuador and Thailand when cultivating all five species in one location, e.g. Bean Common Mosaic Virus (BCMV) will infect all three cultivated species and will also – although with some delay due to the prominent hairiness of all vegetative parts which has some repelling effect on the aphid vectors – successfully infect the wild species *P. panamensis.* Only the other wild species *P. ferrugineus* appears to possess some resistance or tolerance to this virus.

When introduced to other areas for evaluation, most insect pests normally associated with the other species will attack *P. ahipa.* However, in Bolivia the local producers did not identify any leaf-damaging insect pests as being of importance when cultivating the crop (Ørting *et al.* 1996).

Even though the mature seeds have the highest amount of endogenous rotenone of any part of the plant it is the seed which suffers the most serious attack by an insect

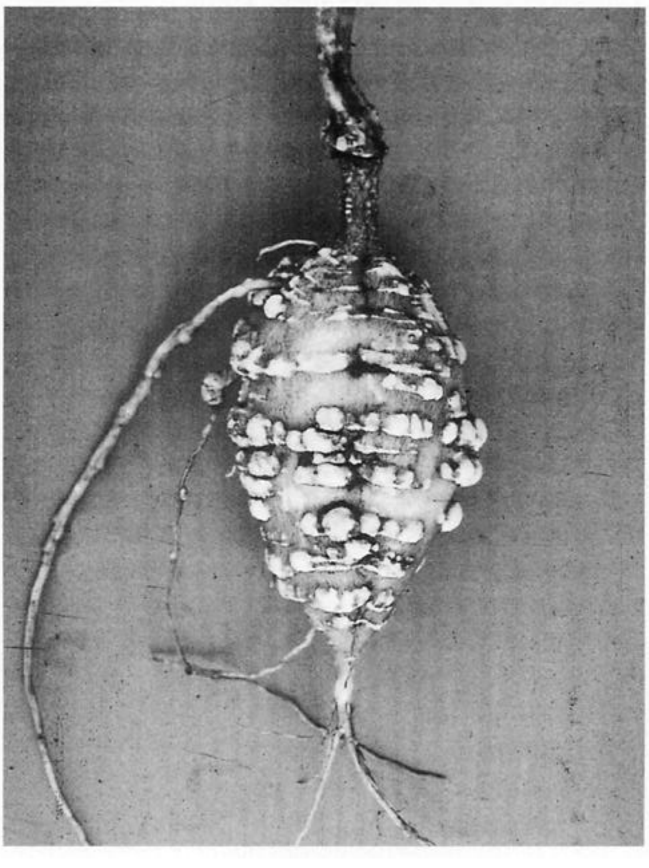

Fig. 10. *P. ahipa,* accession AC102. Tuberous root damaged by nematodes *(Meloidogyne* sp.). Grown at the CEBAJ experimental station near Celaya, State of Guanajuato, Mexico. Photo, E. Heredia G.

pest, i.e. the bean weevil Bruchideae). The bruchid *Caryedes icamae* Guerin-Meneville was identified in five seed samples from different localities in Bolivia (in 1994).

Nematodes may be a problem (Fig. 10); during evaluation of a Bolivian accession in Esmeraldas, Ecuador, the nematode *Meloidogyne* sp. completely destroyed all tubers in the test plants (Bertelsen and Stagegaard, unpubl. data).

In Bolivia the most severe tuber damages observed were rot due to lack of irrigation management, and/or nematodes causing a warty appearance. No other serious damages caused by pests or diseases during the vegetative period were recorded. This may be due to the presence of rotenone in the leaves and stems.

13.5 Harvesting

Harvest takes place once the tuberous roots have attained marketable size, i.e. depending on consumer preference whether small, medium sized or large tubers are preferred. The *P. ahipa* tubers are generally harvested after 7-9 months in Bolivia (as confirmed in field trials in Portugal), but the species has been found to be the earliest of all genotypes belonging to *Pachyrhizus* tested in the field trials in Mexico, i.e. marketable tubers were produced after 4 months! The preferred marketable tuber size is from 0.4 kg and up.

Bolivian growers of *P. ahipa* are reported to harvest the tubers by hand, using a hoe. The vegetative top is left to be incorporated in the soil in some cases, but many will clear the *P. ahipa* hay from the field.

13.6 Post-harvest handling

The chilling sensitivity of the tuberous roots of *P. erosus* has been demonstrated and low-temperature storage has been found to reduce storage life considerably (Bruton 1983; Barile and Esguerra 1984; Paull and Jung Chen 1988; Cantwell *et al.* 1992). The optimal storage temperatures are between 12.5 and 17.5°C. Similar storage characteristics may well apply to *P. ahipa.*

Prolonged storage will serve to change the composition of the starch/sugar ratio. Paull and Jung Chen (1988) found that after 3 months storage at 12.5°C the sucrose content tripled and only one-sixth of the starch remained. As many consumers prefer a sweeter tuber this may also explain the post-harvest treatment observed for *P. ahipa* in Bolivia, where some producers leave the tubers in a sunny place for up to 2 weeks prior to marketing (Ørting *et al.* 1996).

13.7 Yield

In Bolivia, according to Ørting *et al.* (1996), the yield varies from 8 to 30 t/ha regardless of tuber size. Field trials conducted both at the DRATOM experimental Station, Tras-os-Montes, Portugal and at the INIFAP/CIFAP-CEBAJ experimental station, Celaya, Guanajuato, Mexico, have during the past 4 years tested the three accessions initially available. With a growth season of 7 months (in Portugal) and 4 months (Mexico), yields of fresh tuberous roots ranging between 29 and 50 t/ha have been recorded with dry matter percentages of 19-25% (Vieira da Silva 1995; Castellanos *et al.* 1997).

14 Limitations of the crop

The obvious principal constraint in transforming the yam beans from being considered a minor root/tuber crop into one of the major ones can be ascribed to a number of adverse coincidences. If the crop was multiplied in sufficient quantities, i.e. a broad range of genotype-lines, the scientific and developmental interest in the yam beans, which until recently has been negligible, would most certainly increase. With their numerous apparent advantages, there is little doubt that once the crop receives more attention by scientists engaged in both basic and applied research the knowledge and subsequently the production would increase dramatically.

On a trait basis the major constraint is the 'fruity' tuberous root quality found in the majority of the yam beans if they are to constitute an attractive alternative to the starchy traditional root crops. This is especially of relevance when introducing the crop to areas unfamiliar with tuber/root crops of this type. The solution to the problem has fortunately become within reach with the identification of the Chuin cultivar group in Peru *(P. tuberosus* complex). This will allow the introduction of a high-yielding tuberous legume with a tuber dry matter content similar to that of the traditional root crops. Once the Chuin has been successfully introduced it will be easier to widen the range of yam bean cultivars in addition to those having the fruity or vegetable-like tuber quality. Therefore if new lines with the fruity quality of the *P. ahipa* tuber are to be bred, as is taking place at the INIFAP Campo Experimental Bajío, this is accomplished by using *P. erosus* x *ahipa* hybrids. At present the limited germplasm available has been included in a number of field trials evaluating yield performance and tuber quality. In general the tuber quality of the *P. ahipa* is not in accordance with the preferences of the Mexican consumer, i.e. the quality suffers from too high a dry matter content and too much sweetness. This is the tuber quality preferred by the Bolivian and Northern Argentinean consumer. However, the new lines of hybrid origin have the tuber quality of *P. erosus* in combination with the short cropping period of *P. ahipa* !

Because of the obvious competitive source/sink relationship between tuber growth and seed production, unpruned plants show a much less attractive tuber formation than those reproductively pruned (see Fig. 9c). Reproductive pruning is considered a major constraint owing to the laboriousness of the process, especially in *P. ahipa* because of the location and morphology of the inflorescences, i.e. simple, short racemes often placed close to ground level in both determinate and indeterminate genotypes. This is a major reason for the reluctance by Bolivian farmers to continue growing this crop (Ørting 1996b; Ørting *et al.* 1996) and must also be regarded as a major constraint in advanced production areas. No clear solution to this constraint has been identified so far (Matos and Vieira da Silva 1997). This problem may be overcome by the introduction of genotypes with reduced flower/pod set, or with a growth habit approaching the habit of *P. erosus* where the erect inflorescences are produced above the vegetative part of the plant, thus facilitating easy removal. Further field and laboratory studies with different cultivars/landraces targeted on the correlation between tuber yield and other traits

in pruned and unpruned plants are needed to obtain more information on the physiological source/sink relationships (Grum *et al.* 1997). At this point it is of interest that random plants have been observed to initiate tuber growth prior to flowering. However, in yam bean it is necessary to ensure tuber formation in combination with sufficient seed production. In the future, it will be important to breed for new cultivars which will produce high tuber yields without reproductive pruning.

One of the main constraints to the cultivation of yam beans is the rapid decrease in germination when the seeds are stored under humid conditions, which has been observed repeatedly by the Yam Bean Project partners in Ecuador, Costa Rica and Tonga. There is an apparent correlation between seed weight, robustness/thickness of the testa and tolerance to high levels of humidity, i.e. the small and durable seeds of the wild species *P. panamensis* have been found to retain a high germination percentage for a considerably longer period under adverse storage conditions.

The most serious pest problem is also related to the seeds, i.e. the various species of bean weevils/bruchids, but as the susceptibility to attack by this pest group varies between the species as well as between accessions belonging to the same species it may be feasible to breed for increased resistance (see Section 15).

Among the leaf-damaging insects the genus *Diabrotica* is doubtless the most serious pest recorded in the humid parts of the Latin American tropics. Again, considerable resistance to attacks has been recorded between the different accessions with an obvious reduced susceptibility recorded in all genotypes possessing various degrees of pubescence due to the presence of strigose hairs.

The bean common mosaic virus (BCMV) is the most serious viral disease in yam beans. Although not fatal, the affected plants will produce yields reduced by 20-30%. As this disease maybe seed-transmitted at a low rate, individual infected plants should be removed if seen in plots for seed production.

The splitting or cracking of the tubers prior to harvest may be a serious problem under certain climatic/edaphic conditions (Ramaswamy *et al.* 1980). If the crop is irrigated, care should be taken not to irrigate for some weeks before harvest (Ing. Agr. A. Heredia Z., pers. comm.).

Tubers that are physically damaged during harvest are susceptible to attack by common fungi and increased dehydration during storage (Cantwell *et al.* 1992). Wounded yam bean tubers suffer greatly from textural changes, decay and internal browning caused by the fungi *Rhizopus stolonifer* (Ehrenb. ex Link) Lind., *Cladosporium* sp. and *Penicillin* sp. when stored at low temperatures and high relative humidity (>80%) (Bruton 1983).

Experiments examining possible processing procedures of *P. ahipa* tubers have yet to be conducted.

No negative effects from consuming *P. ahipa* tubers have been reported.

15 Prospects

The advantageous features shared by all three cultivated species are first and foremost due to the unique combination of the general characteristics present in most cultivated legumes:

- the producer - good adaptability to a wide climatic and edaphic range with the yield reliability of the root/tuber crops
- the consumer-a well-balanced and nutritious composition of the protein/starch contents with an agreeable taste
- the processor - good post-harvest/ storage characteristics
- the environment - the biological nitrogen fixation (sustainability) and little demand for fuel wood in the preparation of food (all *P. ahipa* cultivars produce tubers which are consumed/used fresh).

The quality aspects of each of the parts utilized - tuberous root, forage hay and mature seed for the extraction of rotenone and rotenoids - differ among species.

The only results available on seed yield in *P. ahipa* are based on greenhouse experiments involving 20 different accessions. The number of mature seeds harvested per plant is given in Table 6.

Table 6. Seed yield in *P. ahipa,* based on an experiment conducted under greenhouse conditions (Ørting 1996)

Accession	No. of seeds/plant	No. of plants in test (n)
AC102	7.7 ± 7.4	7
AC201	83.6 ± 33.3	9
AC202	98.8 ± 24.2	6
AC203	80.0 ± 25.9	7
AC204	86.0 ± 33.7	8
AC205	91.3 ± 38.5	6
AC206	86.9 ± 26.2	7
AC207L	130.3 ± 51.8	6
AC207S	106.3 ± 26.9	4
AC208	101.7 ± 31.7	3
AC209	23.3 ± 19.8	6
AC213	39.4 ± 22.5	8
AC214	29.1 ± 18.8	7
AC215	18.8 ± 21.1	4
AC216	49.0 ± 9.0	3
AC217	78.0 ± 0.0	1
AC521	6.2 ± 9.1	5
AC524	15.6 ± 10.1	5
AC525	74.0 ± 46.2	6
AC526	4.8 ± 3.2	4

The yield results, but especially the seed yield results, indicate that also within this species sufficient variation may be available to implement a pre-breeding programme aimed at the development of new high-yielding cultivars with acceptable seed production.

A possible future use of the Andean yam bean as an industrial crop (non-food crop) has become a possibility following recent analysis of *P. ahipa* tubers (see Sections 4.2 and 4.4). The dry matter composition of *P. ahipa* tubers contains 45-55% starch (practically pure amylopectin), 10-15% sugar (glucose, fructose, saccharose) and 10-18% protein. The protein does not precipitate over a wide range of pH values. The latter characteristic may be attractive to the food industry. However, the main interest in the Andean yam bean tuber as a renewable resource for the industry is due to its high content of virtually pure amylopectin. The pure starch yield of *P. ahipa,* calculated from landraces, reaches that of high-yielding potato cultivars. Nevertheless, until now no investigations on pre-industrial processing of *P. ahipa* starch, sugar and protein have been carried out; this is currently being undertaken. If industrial processing were to be verified on a laboratory scale, *P. ahipa* could be considered when breeding new industrial crops.

Thus, mainly two breeding aims must be considered:

- the extension of the production area to include higher latitudes (production further north than Spain and South France would be possible, if the growth period required was to be genetically reduced)
- the avoidance of the laborious reproductive pruning, by selection for those genotypes that have good tuber formation without pruning.

That the necessary genetic variation within the Andean yam bean germplasm exists to allow such breeding efforts has been indicated in the recent *P. ahipa* greenhouse evaluations (Ørting 1996a).

16 Research needs

From the results of the experiments concluded so far, a number of specific points of interest can be identified.

- Taxonomic and phylogenetic studies using both molecular and numerical systematic methods of analysis in order to clarify the origin of and relationship between the cultivated species
- Field collecting of *P. ahipa* germplasm (both wild material and rare landraces) in Peru
- Conservation and field evaluation of *P. ahipa* germplasm (both wild material and rare landraces) originating in northern Argentina, Bolivia and Peru
- Initiation of a breeding programme to improve the existing landraces of *P. ahipa* in order to ensure continued cultivation of these endangered crops in Argentina and Bolivia
- Breeding of new interspecific hybrids involving: (a) the recently identified *P. tuberosus* landraces with high dry matter and starch content (the Chuin), (b) high-yielding *P. erosus* accessions, and (c) early, bushy *P. ahipa* accessions
- Physiological analysis of the source/sink relationship in *P ahipa,* with specific reference to the competition between tuberous root growth and legume formation
- Physiological analysis of the biological nitrogen fixation
- Biochemical analysis of the nutritional composition of the most promising interspecific hybrids, i.e. lines which are approaching release as new cultivars
- Biochemical analysis and evaluation of *P. ahipa* landraces as a potential non-food crop
- Biochemical analysis and evaluation of *P. ahipa* as sources of rotenone/rotenoids with technical and/or agronomic potential
- Evaluation of pests and diseases and the resistance/tolerance present in *P. ahipa.*

Further research of the phylogeny on the whole genus as well as on the Andean Yam Bean must be considered as extremely interesting from both the scientific and the applied side. Recent molecular studies of the phylogeny of the different species have indicated that *P. ahipa* must be considered as a monophyletic group with *P. tuberosus* as the closest entity.

Nevertheless, interspecific hybridization experiments involving the three cultivated species have demonstrated that the genetic distances between the species allow for the development of fertile hybrids. To substantiate the present perception of the phylogeny of this species, additional field collecting is necessary, targeted on wild as well as cultivated *P. ahipa* material. The diversity in the appearance of genotypes belonging to *P. tuberosus, P. ahipa* and *P. erosus* is remarkable. This has been observed for a considerable number of important agronomic traits. In *P. tuberosus* both multituberous and monotuberous 'landraces' exist as well as types with both low and high dry matter content (Sorensen et al. 1997). However, the approximately 2000 to 3000-year-old mummified tubers found in the South American funeral bundles are superficially similar to *P. ahipa* tubers (and Jíquima

tubers) (Ugent *et al.* 1986). This yam bean material, the oldest found to date, supports the conclusion that also within *P. ahipa* a high infraspecific genetic variation had developed and has, perhaps, not yet entirely disappeared. In addition, today virtually nothing is known about the present status of *P. ahipa* in Peru, even though, with reference to the archaeological remains, this may be where the centre of origin of the (South American) yam bean was located.

Regarding the physiology of the tuber formation, few relationships have yet been examined. Those that have were done in a descriptive manner, based on correlation. More clarity with regard to the yield physiology of the yam bean is of extreme importance to make this crop more attractive. Like other tuber-forming legumes *(Psophocarpus, Sphenostylis,* etc.), yam beans exhibit an extremely competitive source/sink relationship between tuber growth and seed production. As was mentioned earlier, this relationship has been known in the yam beans since pre-Columbian times and led to the traditional, practised technique of reproductive pruning. However, the functioning of the physiological mechanisms of tuber formation in yam beans, as well as the other tuberous legume genera listed above, is as yet poorly understood. For example, it is obvious that, within both *Psophocarpus* and *Sphenostylis,* distinction must be made between those genotypes that are cultivated mainly for seed production and those for tuber production. Future research will have to concentrate on the primary effects of tuber initiation in yam beans and tuberous legumes in general by identification of the causal relationship of characters, i.e. characters which are correlated to tuber formation and tuber yield. Once more is known concerning the functioning of the assimilate distribution into competitive sinks within tuberous legumes, clear breeding targets may be set up for indirect selection (see also Lamaze *et al.* 1985; Robin *et al.* 1990; Vaillant *et al.* 1990, 1991; Zinsou *et al.* 1987a, 1987b, 1987c, 1988; Zinsou and Vansuyt 1991; Zinsou 1994). Furthermore, it may become possible to resolve the heritability and identify the genetic factors responsible for tuber formation.

Depending on the availability of rapid, quality screening procedures in future estimations of genetic parameters for quality, in combination with other characteristics of agronomic importance, these most-needed analyses could be conducted (e.g. phenotypic and genotypic correlation). Such information is paramount to facilitate improved dimensions of any breeding programme. To estimate these genetic parameters with sufficient precision, additional information is needed concerning the test/plot size for different yam bean characters: which traits may be evaluated under greenhouse conditions and which characters will need field experiments or even a series of field experiments. Initially such experiments have to be linked with an estimation of genotype x environment variance components of important yam bean characters. Furthermore, the attractiveness of the Andean yam bean for sustainable multiple cropping systems has to be quantified. Considerable positive effects by including *P. ahipa* in such systems are to be expected: being a legume (N-fixation) and in addition a tuber/root crop (stability under environmental stress) with determinate or semideterminate growth habit (short season/early).

Therefore, multiple cropping system test/trial and evaluation problems involving yam beans should receive more attention, especially when series of test genotypes are involved.

At this point the authors would like to draw attention to the current research concerning genetic resources which at present is concentrated on the efficiency enhancement of the management and evaluation of genebank material (for an overview, see Brown 1989). From the applied side of breeding, involving underutilized crops - and among tubers/legumes in particular, the yam bean must be regarded as extremely underutilized in view of its agronomic potential - it is essential to increase the breeding time efficiency in order to improve a few of the essential agronomic traits within a population. The importance of such a population improvement by recurrent selection was stressed repeatedly by Gallais (1979,1984, 1990). In recurrent selection schemes with underutilized crops it is vital that a few more or less correlated characters are improved without changing the mean and variability of several attractive characters within a population. In the case of the yam bean such character is obviously the improvement of the dry matter content of the tubers in combination with the assimilate partitioning to the seed/tuber, if the crop is to be used as a staple/basic food rather than a ‘fruit’, but simultaneously without causing negative secondary effects with regard to the nutritional composition and the wide range of adaptability. More research and applied solutions aimed at recurrent multitrait improvement are needed for the initiation of rapid population improvement programmes involving underutilized crops. Such efforts could be defined as pre-breeding research in underutilized crops. Also, in spite of the advantages of genetic molecular markers for distance estimation and characterization within and between accessions, further studies of the implementation of molecular markers in breeding strategies for rapid population improvement must be conducted. In relation to pre-breeding in yam bean, and perhaps most underutilized crops, special attention should be given to comparative examinations of RAPDs and AFLPs, i.e. methods that are easier to manage and less expensive than RFLPs and microsatellites.

17 Future needs

It is of major importance to conserve, both *in situ* and *ex situ,* as wide a range of variation as possible in endangered landraces within all three cultivated species. Also, surveys of wild populations - whether belonging to the cultivated or the exclusively wild species - should be completed. All genotypes yet to be studied cytologically (including molecular analyses) and evaluated for agronomic/breeding potential should be included in research projects as quickly as possible, to ensure the optimum foundation for the publication of a complete manual encompassing the variation available and the identification of wild populations and 'rare' landraces most urgently in need of conservation measures.

As indicated above, a number of the present constraints limiting a worldwide breakthrough for the yam beans as an attractive alternative to traditional root/tuber crops may be overcome either by using interspecific hybridization combined with intensive breeding methods or by comprehensive screening and selection within existing landraces.

In conclusion, the yam beans have long been considered minor or even lost crops (National Academy of Sciences 1979; National Research Council 1989; Sorensen *et al.* 1993) in spite of their obvious potential. The research carried out in the Yam Bean Project has so far served to demonstrate the existence of considerable genetic variation within the genus and genotypes with high yield capacity, adaptability and sustainability. However, in order to establish the yam beans as attractive multiple-purpose crops pantropically (including in many subtropical regions), further research combined with an intensified promotion is needed.

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Arracacha

(Arracacia xanthorrhiza Bancroft)

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Contents

1 Introduction

Arracacha *(Arracacia xanthorrhiza* Bancroft) is the only umbellifer domesticated in South America and still largely confined to that continent in its distribution. There are numerous domesticated umbellifers from Eurasia, many of which form edible roots or other subterraneous storage organs, such as parsnip, parsley, carrot and celeriac. All these cultigens and the vast majority of other umbelliferous crops from the Old World are biennials and seed-propagated. Most remarkably, cultivated arracacha is a vegetatively propagated perennial. The recent discovery of wild *Arracacia xanthorrhiza* populations with tuberous storage roots could shed light on an old discussion of the origin of agriculture or, more specifically, on the reasons for the preponderance of vegetative propagation in South American crops as opposed to seed-based agriculture in the Old World (Hawkes 1969). Evidence for both biennial (in Peru) and perennial wild arracacha (in Ecuador) will be presented in this paper for the first time. If the hypothesis that both forms occur over larger areas in the Andes can be confirmed, an interesting question arises: Why did early people in the Andes domesticate the perennial form and not the biennial, seed-propagating one?

There are several reasons to consider arracacha the most promising crop among the nine minor Andean root and tuber species. Not only does arracacha have the widest range of culinary uses but it also appears to be free from undesirable substances that seem to limit the acceptability of oca (oxalates), ulluco (mucilage), mashua (isothiocyanates) and mauka (astringent principles). Arracacha adds an interesting texture and flavour to a variety of dishes and it seems to be much less of an acquired taste than other Andean roots and tubers. Little arracacha is currently being processed, but various processed arracacha products have received praise for their quality. Undoubtedly, versatility in processing will be instrumental in promoting arracacha for urban consumption.

As opposed to high-altitude species (oca, ulluco, mashua, maca) with their narrow ecological range and short-day requirements for tuber formation, arracacha adapts to a wide range of mesothermic and tropical highland environments as well as daylength regimes, although the environmental plasticity of the crop does not match that of achira *(Canna edulis).* Another comparative advantage of arracacha is the fact that the propagule is derived from aboveground plant parts. The economic product - the storage roots - can therefore be marketed entirely and no part of it needs to be reserved as seed for the next crop. Diseases and pests, though, can become a problem, certainly more so than in other ARTC. Many diseases and pests that afflict arracacha, however, can be controlled by long rotations and integrated management practices.

Arracacha is essentially a starchy food and its utilization is intimately related to its elevated starch content. Arracacha can, however, be recommended for human nutrition also on the grounds of other nutrients, namely P-carotene, ascorbic acid and calcium, the daily requirements of which are contained in comparatively small portions. In cuisine, this fine vegetable has versatile uses and adds diversity to poor and rich people's diet alike, but it is not a staple food as is occasionally stated. The

average per capita consumption of this root rarely exceeds 10 kg per year. From information presented in the next section, which will analyze the status of arracacha use across growing regions, we can conclude that arracacha is a secondary food item for some 80 to 100 million people. With this figure in mind, and in view of the eminent commercial role of arracacha in major producing countries, it becomes clear that it is far more important economically than other Andean roots and tubers. Their combined value is probably exceeded by arracacha alone.

Although it is little known that arracacha was introduced to Brazil, in the southern states of this country it now probably covers a larger area than in any Andean country. Not only is the crop expanding into areas in Brazil where it was previously unknown or thought to be poorly adapted, there is also considerable and rising interest in arracacha on the part of industrial processors, extensionists, researchers and, notably, small farmers who value the crop's low-input requirements. The clearest indication of the high interest in arracacha in Brazil is the comparatively large body of literature on the crop in Portuguese. An exhaustive bibliography, the result of many years of searching of arracacha literature, including theses, reports and other unpublished material, yielded 274 titles, of which 186 were in Portuguese, 53 in Spanish, 33 in English and two in French (Santos and Spina 1994). The literature in Portuguese deals extensively with crop husbandry and related themes, and it is virtually our only source on reproductive biology, seed physiology and breeding efforts. Although much of this literature has been published in obscure journals of limited distribution, this paper will draw on it heavily.

2 Geographical distribution, economic importance and varietal diversity

"El señor o cacique de los Chibchas había mandado alzar el bastimento, de manera que tuvieron algunos hambre, por lo cual les fue forzado aprovecharse de lo que por naturaleza la tierra produce, y ansi debajo della sacaban unas raíces amargas, que yo creo tienen por nombre 'arracachas', porque si no me engaño no pocas dellas he comido; su sabor declina un poco a zanahorias; destas y de otras yerbas comían los que con Centeno andaban."[1]

(Cieza de León, a Spanish chronicler describing the use of arracacha in 1545, in what is today Colombia, by Spanish rebels fleeing from Pizarro's troops; cited in Patiño 1964)

Several lines of evidence point to Andean South America as the place of domestication of arracacha. Although the genus *Arracacia* is particularly diverse in Mexico, the wild species most closely resembling arracacha are known from Peru and especially Ecuador (Fig. 1; see Section 6.2.1). The linguistics of the vernacular names of arracacha also provides clues to its Andean origin. *Racacha, virraca, lacache, arrecate* and other related words of autochthonous languages used for the crop attest to its great antiquity in the Andes. Outside the Andes, names for arracacha are derived mostly from European languages. Finally, the chroniclers of the Spanish conquest of South America refer to arracacha frequently (reviewed in Patiño 1964) and its cultivation is documented for what is today Peru (upper Huallaga, 1533), Colombia (Popayán, 1545) and Ecuador (Rio Chinchipe, 1549; Cañar, Chimborazo, 1582). Using historical accounts of the conquest, Hodge (1954) convincingly argues that the "dispersal of arracacha as a cultigen throughout most of its present range in the Andes clearly came in pre-Columbian times" and, one might add, probably a long time before the Inca conquest subjugated much of South America.

Today, arracacha is produced mainly in four countries - Brazil, Colombia, Ecuador and Venezuela - whose total production area is probably somewhat over 30 000 ha. In these countries, arracacha is a regular item in urban markets, and is consumed and known by a majority of the population (in Brazil, only in the southeast region). Implicit to this observation is that arracacha is traded over long distances to supply regions where the crop cannot be grown for climatic reasons (tropical lowlands, high Andes). In the Andes, arracacha is also widely grown in Peru and Bolivia, but most production is for subsistence; some surplus goes to local markets.

[1] "The chief or cacique of the Chibchas had ordered a limit on provisions, so that some of the people were hungry, and they were forced to exploit what the land produces naturally. As a result, from under the ground they pulled out some bitter roots, which I believe are given the name 'arracachas', because, if I don't deceive myself, I have eaten several of them: their taste slightly resembles that of carrots. Of these and other herbs the people who went around with Centeno were eating." (Translation by Bill Hardy).

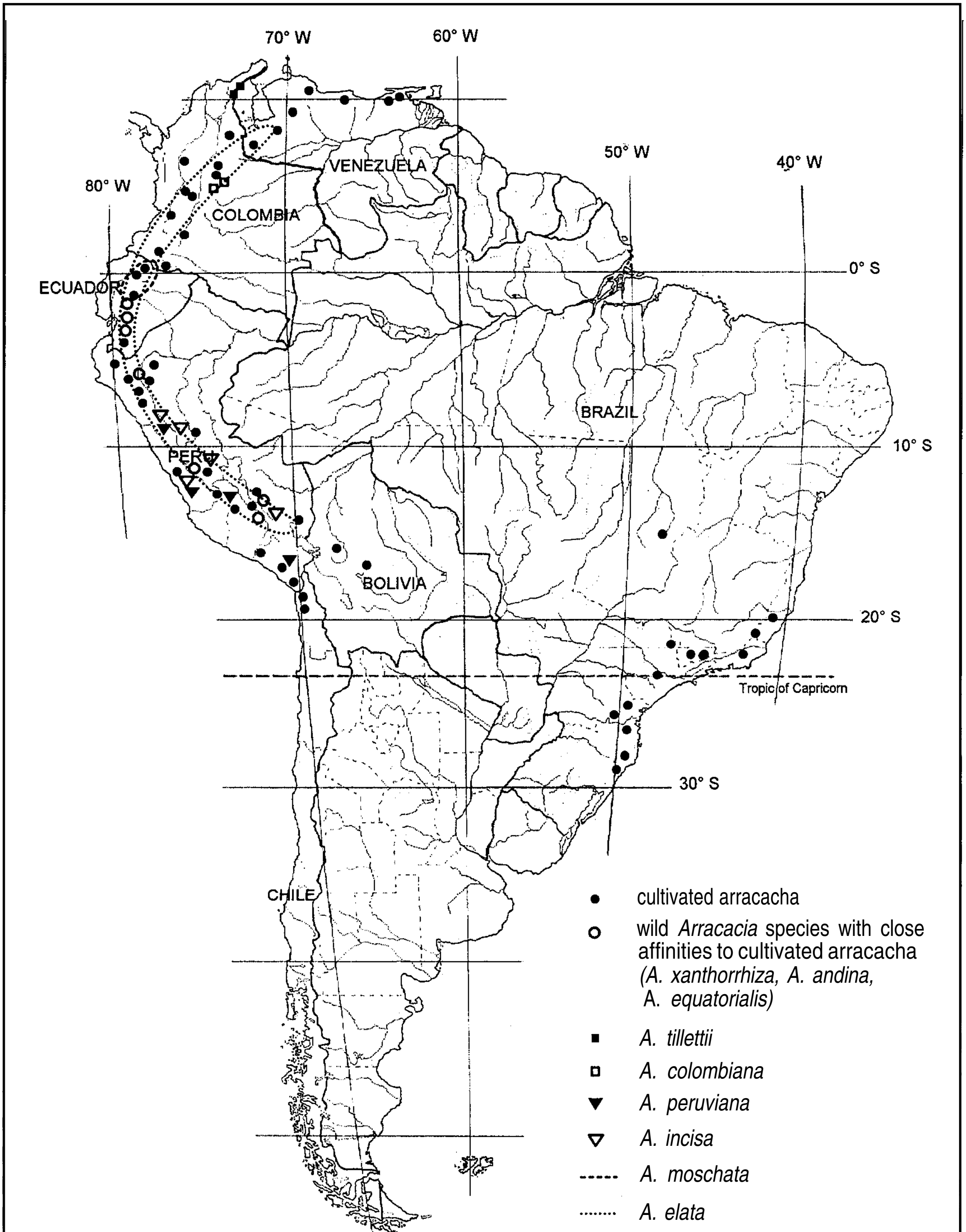

Fig. 1. Distribution of arracacha cultivation and wild *Arracacia* species in South America (Goode's series of base maps, University of Chicago, 1937; sinusoidal equal-area projection).

The crop has also spread to Central America and the Caribbean, but significant production seems to be limited to Costa Rica and Puerto Rico. Some reports mention attempted introductions to the Old World, but to my knowledge, nowhere outside the New World has arracacha ever been established as a crop.

2.1 Andes

Importance, distribution and other characteristics of arracacha production relevant to the crop's genetic resources will be presented for the Andean range, from north to south, which roughly coincides with the declining economic importance of the crop. Arracacha production areas in the Andes range over 32 degrees of latitude from 10°N (Mérida, Venezuela) to 22°S (southern Bolivia), with marketed production coming mostly from north of the equator.

2.1.1 Venezuela

Of all the Andean countries, it is perhaps in Venezuela where arracacha is held in the highest esteem. This is reflected by frequent consumption (Camino and Díaz 1972) and high prices for arracacha compared with those of other commonly used tubers such as cassava, potato, ocumo *(Xanthosoma* sp.) and ñame *(Dioscorea* sp.) (Revetti 1967). *Apio,* as the crop is called in Venezuela because of its resemblance to celery (celery, *Apium graveolens,* is referred to as *apio España),* is considered ideal to wean children (Revetti 1967). Moreover, elegant restaurants have it on the menu (Dr Maria L. Garcia, 1996, pers. comm.) in dishes such as *sancocho,* purées and *buñuelos de apio* (see Section 5.3).

According to official statistics, in 1970, 845l ha of arracacha were grown in the Andean Cordillera and the coastal mountain range in the north of the country. Average yield was 5.4 t/ha (Camino and Díaz 1972). A recent document gives a total of 3619 ha for 1988-89 (Anonymous 1990). Major production regions are Monagas, Trujillo, Sucre, Táchira, Yaracuy and Mérida. There appears to be only one commercial cultivar with yellow flesh (Reyes 1970; Dr María L. Garcia, 1996, pers. comm.) and comparatively small roots of 5-15 cm length and a mean weight of 100 g as determined by Czyhrinciw (1952) in the market of Caracas. Yields are between 5 and 10 t/ha after a typical crop duration of 14 months (Reyes 1970). The high perishability of arracacha has prompted research by Venezuelan scientists into storage behaviour and storage diseases (Czyhrinciw and Jaffé 1951; Czyhrinciw 1952, 1969; Revetti 1967; Camino and Díaz 1972; Díaz and Camino 1976).

2.1.2 Colombia

At the time of Bukasov's explorations in Colombia (1925-26), 20 000 ha, or the equivalent of 75% of the total arracacha area in the country, were grown in Cundinamarca (Bukasov 1930). Bukasov speaks of arracacha as the favourite tuber in this department, taking up 20% of total arable land (versus potato with 10%!). He reports significant areas also from Boyacá Santander, Norte de Santander and Tolima, but limited cultivation in the rest of the country. In 1954, when Hodge

published his account of arracacha use in Colombia (Hodge 1954), the most significant arracacha area was in Antioquia.

In 1991, Colombia had a total of 12 000 ha, of which 6000-8000 ha were grown in the department of Tolima, with 4000-5000 ha in the municipality of Cajamarca. The better part of the Tolima production goes to the three major Colombian cities: Bogota, Medellín and Cali. Other arracacha-producing departments are Nariño, Cundinamarca and Boyacá, and, to a minor extent, Antioquia. National yield averages about 12 t/ha; thus, national production of arracacha in 1991 would have been around 144 000 t (Mr J.J. Rivera, 1996, pers. comm.). Thompson (1980) reported marketed production at 123 000 t in 1977; hence arracacha consumption appears stable, if not slowly growing, over the last two decades.

Surveys of consumers stratified by income and conducted by Ríos (1985) in Manizales, Caldas Department showed that annual per capita consumption of arracacha ranged between 8 and 22 kg. The very poor and the wealthy share low consumption levels, the former probably because of lack of purchasing power for a relatively expensive root vegetable, the latter because of high dietary diversification and increased consumption of animal products.

Disease problems in Tolima and falling prices for coffee in recent years have stimulated interest in arracacha. Typically, arracacha is intercropped with maize, which is harvested after 150 days. According to altitude, arracacha can be harvested 10-14 months after planting. There is a wide range of producers, with smallholders at one extreme and large absentee landowners at the other (Mr J.J. Rivera, 1996, pers. comm.).

Although yellow-rooted clones are preferred in Colombia, especially in Bogota (Higuita 1969; Hermann 1994; Mr J.J. Rivera, 1996, pers. comm.), local preference for white roots in Medellín has been reported (Higuita 1969). This city is supplied with the variety Salamineña Blanca, which reportedly accounts for most of the production of the La Ceja valley in Antioquia (Higuita 1968). Salamineña Blanca matures in 10 months.

Higuita (1969, 1970) recognizes nine morphologically distinct varieties in Colombia, with yellow and white clones being the most common. On the basis of linguistic and morphological data, Bristol (1988) claims the existence of at least 18 distinct clones in the Sibundoy valley near Ecuador, known for its Kamsá-speaking population. Little is known about the arracacha in Sibundoy and since more than 30 years have passed since Bristol's explorations, it is urgent that collecting what remains of presumably unique genotypes be done.

2.1.3 Ecuador

As in Colombia and Venezuela, arracacha in Ecuador is a root vegetable known and consumed by the vast majority of the population and found regularly on supermarket shelves. According to a consumer survey conducted in the three major cities – Guayaquil, Quito and Cuenca – 91, 97 and 68%, respectively, of the households interviewed reported consumption of arracacha (Espinosa *et al.* 1995). It is the fourth

most popular root crop after potatoes *(Solanum* spp.), melloco *(Ullucus tuberosus)* and cassava. The same survey found no evidence for a continuous decline in arracacha consumption as stated by Castillo (1984). Annual per capita consumption was found to be 2.7 kg in Cuenca, 8.1 kg in Quito, and the highest in Guayaquil, with 8.9 kg. The latter finding is noteworthy because Guayaquil is a tropical lowland city where the perishability of arracacha would seem to limit its use. If we assume that in this nation of about 12 million people the mean annual per capita consumption of arracacha is at least 2 kg, and yield averages 10-20 t/ha, then the total arracacha area in Ecuador would be at least somewhere between 1200 and 2400 ha. This is in striking contrast to the 150 ha accounted for in 1993 by official statistics of the Ministry of Agriculture.

Although the arracacha crop is widely distributed across the Sierra, commercial exploitation is concentrated in San Jose (northeast of Quito), Baños (Tungurahua), Imbabura and Loja. San Jose de Minas is located on the western slope of the Andes. Its humid Pacific climate at 2000 m altitude with rainfall throughout the year makes it one of the most productive arracacha areas, with yields well above 30 t/ha. The average altitude for arracacha cultivation in Ecuador is 2500 m, but some germplasm accessions have been collected at as low as 1450 m and up to 3200 m (Hermann 1988).

A range of cultivars has been collected in Ecuador and several root shapes and pigmentations, from white over yellow to orange, have been observed (Mazón 1993); however, 70% of the accessions of the national collection have white-fleshed roots. Only white roots are available in urban markets throughout Ecuador (Espinosa *et* al. 1995). Another peculiarity in Ecuador is that the name arracacha, widely used for the crop in the Andes and beyond, will not be understood. Ecuadoreans eat *zanahoria blanca,* Spanish for 'white carrot'. In Loja, the crop is simply called *zanaharia,* with the real carrot *(Daucus carota)* receiving the name *zanahoria extranjera* (the foreign carrot) (Mrs Joy Horton de Hofmann, 1996, pers. comm.). The use of the term *zanahoria* apparently extends into Nariño, southern Colombia (Jaramillo 1952), and Cajamarca, northern Peru (Arbizu and Robles 1986).

Five wild *Arracacia* species occur in Ecuador *(A. andina, A. elata, A. equatorialis, A. moschata, A. xanthorrhiza;* see Section 6.2.1), along with the closely related Neonelsonia acuminata. Rural people invariably refer to these plants as *sacha zanahoria (sacha = quechua* for 'wild') or 'wild carrots' and know their habitats, which is of great help to plant collectors. There is a widespread belief across the Sierra that these plants have medicinal qualities for a variety of uses, *post partum* applications being the most common.

2.1.4 Peru

A production manager of Nestlé-Brazil, a company known for its processed arracacha products in Brazil and Colombia, had lived for several years in Lima, Peru, where the company has a subsidiary. He had traveled widely in Peru, but returned to his native country thinking of arracacha as a genuinely Brazilian vegetable. He

had not seen it in Peru. Nothing could better illustrate the paradoxical situation of arracacha in Peru, a country so rich in genetic resources of this and other Andean crops. One can live a lifetime in Peru and yet never come across arracacha. It is used only sporadically in Lima (where roughly half of the national population lives); as a matter of fact, most limeños are not aware of it. Restaurants do not offer it and national cookbooks ignore it. Even in highland towns, there appears to be social prejudice against arracacha and other tuberous foods associated with the (economically and socially depressed) Indians (Fano and Benavides 1992).

Some authors suggest that some Nazca pottery designs, formerly attributed to cassava, may in fact represent arracacha (reviewed in Towle 1961, pp. 74-75). Vivid accounts of the Spanish chroniclers refer to arracacha as a food plant widely used in Peru in the 16th century (Patiño 1964). Today, arracacha continues to have some commercial scope in Cajamarca, Cusco and other highland cities and towns, but it has more importance for the subsistence and diet diversification of poor rural people.

According to Seminario (1995), Peru has about 2000-3000 ha of arracacha, of which 60-80% corresponds to the department of Cajamarca. The second most important department is Amazonas, also in the north of the country (Table 1).

Table 1. Altitudinal range of arracacha cultivation in Peru according to department (arranged from north to south)

		Elevation (m asl)	
	No. of sites	Average	Range
Piura	23	1788	1600 - 1900
Amazonas	22	2109	1610 - 3240
Cajamarca	56	2298	870 - 3460
La Libertad, Ancash, Huanuco	7	2877	2610 - 3240
Cusco	20	2286	1938 - 2590
Apurimac	11	2784	2540 - 3275
Arequipa	5	2918	2370 - 3190
Moquegua, Tacna	8	1848	950 - 3050

Source: Hermann, field notes.

Traditionally, arracacha has been cultivated in Peru in three different agro-ecologies with widely varying environmental conditions: the Ceja de Selva, the humid and rainy eastern slope of the Andean Cordillera toward the Amazon between 1500 to 2200 m altitude (Amazonas, Cusco, Huánuco, La Libertad, San Martin); the dry inter-Andean valleys between 2500 and 3200 m (Ancash, upper Apurímac and

Cajamarca); and the coastal desert oases of Moquegua, Piura and Tacna at 1000-2500 m (see Table 1 for details on the altitudinal range of arracacha cultivation in Peru).

On a visit to Tacna in 1993, a town known in the past for its arracacha production, I found only a few arracachas in the market from Moquegua, and none from Tacna. Farmers offered these explanations for their abandoning the crop: lack of planting material, lack of market demand and a common belief among Aymará and Quechua people that the crop became jealous and lazy once the Taceños had sent planting materials to the people of Moquegua. Only after an extensive search could one farmer be found who grows the plant for his own consumption (Don Uldarico Velasquez Rejas, Calana, Tacna).

The city of Cusco receives arracacha from Quillabamba. In the nearby Sacred Valley, arracacha has not had any importance in the recent past (Gade 1975). Peru has numerous cultivars with some variation in pigmentation and root shape, but yellow-fleshed clones are preferred over white material on urban markets (Meza 1995). Farmers often also grow a purplish variety that is not commercial.

2.1.5 Bolivia

Like Peru, Bolivia produces little commercial arracacha. This seems to have been so at the time of Vavilov, who wrote in the 1930s: "... Arracacha ... rare in Peru and Bolivia; a staple crop on the Bogota Plateau" (Vavilov 1992). According to an authority on Bolivian economic botany, the late Martin Cárdenas, arracacha has been grown traditionally in the Yungas of La Paz (Cárdenas 1969), in the provinces of Camacho and Larecaja, where I have seen it in the early 1990s. *Lacache,* as the crop is called in the Aymará language, is offered in the markets of La Paz and Cochabamba, the latter city being supplied from the Chapare, also known for its coca leaf production.

2.1.6 Chile

Latcham (1936) reports the use of arracacha in the extreme north of Chile. This was confirmed during a 1993 collaborative germplasm-collecting mission conducted by Professor Andres Contreras from the University of Valdivia and me. However, the crop is so marginal that many inhabitants of this region are not aware of it at all. It is safe to say that arracacha is on the verge of becoming extinct in this country. The crop was found in three villages: Nama (37 km northeast of Camiña, Iquique Province, 19°ll’ S, 69°24’ W, 2900 m altitude), Socoroma (Parinacota Province, 18°16’ S, 69°36’ W, 3050 m altitude), and Codpa (Arica Province, l8°50’ S, 69°44’ W, 2200 m altitude). All three localities are remote highland oases of the Atacama desert, with aging populations of no more than a few hundred people. Interestingly, the crop is called by its Aymará name *lacache,* evidence of cultural ties of the Atacama region with the Bolivian Altiplano. Codpa, for example, is known for its subtropical and temperate fruit production, which was traditionally bartered for potatoes and dry meat from Bolivia. The arracacha clones seen in Chile are white-fleshed and, in the

case of Nama, were said to be remnants from the 'old times' when this part of Chile still belonged to Peru (until 1879).

Arracacha has not been reported from neighbouring Argentina, nor have I seen the plant during explorations in 1992 in Jujuy and Salta, the two northernmost provinces where most of the other Andean roots and tubers are still cultivated.

2.2. Brazil

Zanin and Casali (1984a) present circumstantial evidence for the introduction of arracacha to Brazil early in this century. The crop must have been spread quickly since it was widely consumed as early as in the 1920s in rural areas of Minas Gerais, São Paulo and Rio de Janeiro (Hermann, unpublished field notes). Today, arracacha is mostly grown in the uplands of southern and southeastern Brazil, particularly in the Serra do Mar (Paraná, São Paulo, ca. 26° S), in the Serra de Mantiqueira (Minas Gerais, 22-23° S, 1000-1800 m altitude), in the Serra de Espinhaço (Minas Gerais, 16° S, under 1000 m), and the Planalto Central (Minas Gerais, Goiás, Tocantins, 15-18° S, 800-1000m). According to an extensive survey by Santos (1993), the four foremost arracacha-producing states in 1993 were Minas Gerais (3500 ha), Paraná (2800 ha), Santa Catarina (850 ha) and Espírito Santo (660 ha). The area is expanding in Espírito Santo and Minas Gerais and total national area in 1996 is estimated to exceed 12 000 ha. Moreover, the area under arracacha shows high growth rates in Goiás and Tocantins, states to which arracacha culture was introduced a few years ago (Dr F.F. Santos, 1996, pers. comm.). In São Paulo, where arracacha was in the 1960s a source of "great wealth" (Normanha and Silva 1963) and grown to a larger extent than in any other federal state, arracacha production has been reduced to some 200 ha in the 1992/93 growing season (Monteiro *et al.* 1993). Booming service industries have forced out arracacha culture around metropolitan São Paulo. For example, the former arracacha-growing municipality of Piedade near São Paulo nowadays acts as a transshipment point for arracacha from all over Brazil. Piedade no longer produces arracacha, but washes, classifies and packs arracacha from other states for sale on the wholesale market CEAGESP in São Paulo (Fig. 2C).

The average farm-gate price in recent years has fluctuated between US$0.40 and $0.60/kg and, assuming an average value of $0.50/kg, the off-farm value of total arracacha production in Brazil should have been around US$55 million in 1996. Arracacha is a regular item in all major cities of southern Brazil (São Paulo, Rio de Janeiro, Belo Horizonte, Curitiba, etc.). Retail prices are typically between US$1.50 and 2.00/kg; arracacha is thus the most expensive root and is as highly valued as fruit vegetables such as *giló* (*Solanum* sp.), *Capsicum* peppers and *quiabo* (*Abelmoschus esculentus*) (Hermann, field notes, 1991, 1994, 1995). In early 1995, arracacha retail prices soared to unprecedented levels, because of frost-related crop losses in the 1994/95 season. In August of 1995, supermarket prices in Brasilia were still between US$4.00 and 6.00/kg. This suggests inelastic demand, which is likely the result of habitual purchases of small quantities of arracacha for child nutrition by many

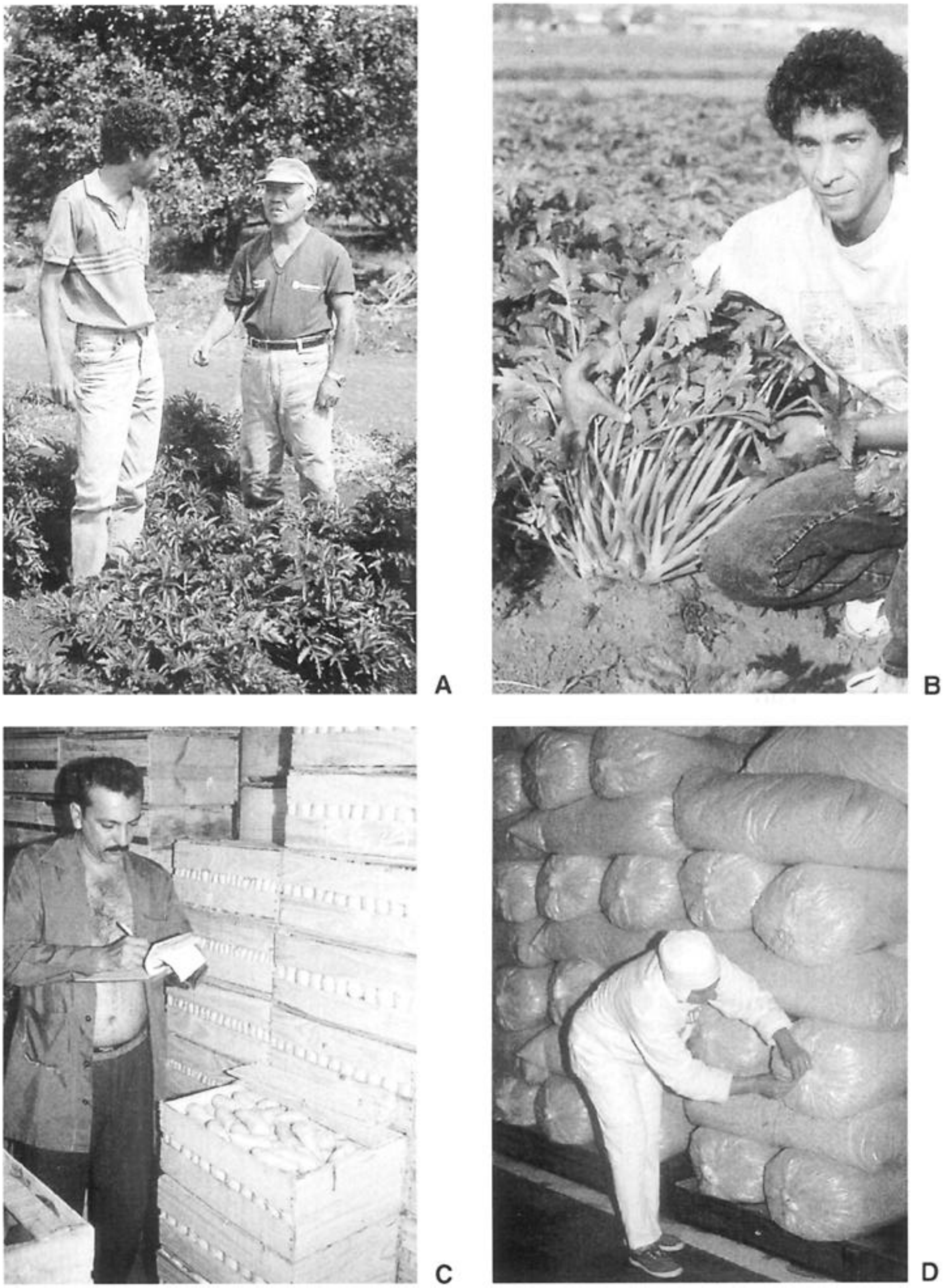

Fig. 2. Arracacha utilization in Brazil. **A:** arracacha specialist Dr Fausto Santos (CNPH-EMBRAPA) interviewing Japanese immigrant farmer in Distrito Federal (loc. Alexandre Gusmão, 50 km S of Brasilia, 1100 m asl, photograph July 1992); **B:** productive arracacha plant in EMBRAPA germplasm collection, Brasilia (photograph 1994); **C:** arracacha on wholesale market CEAGESP in São Paulo (photograph August 1994); **D:** processed arracacha flakes ready for shipment at Nutrimental Company, São José dos Pinhais, Curitiba, Paraná (photograph August 1994).

Brazilian families. During a visit to the Federal District in August 1996, I noted that arracacha prices had decreased but were still high (farm-gate value varied between US$1.40 and 1.80/kg washed roots).

Brazilian researchers agree that only one yellow-rooted clone is being grown in Brazil. This is based on the evaluation of germplasm accessions from different parts of the country, which have not revealed morphological or agronomic variation attributable to genetic causes. The Brazilian clone which is often referred to in publications as Amarela de Carandai has an intensive yellow root pigmentation, purplish petiole bases and, compared with the more common Andean germplasm, a strong flavour. Intensive yellow colour and strong flavour are required by the fresh market and the processing industry. Casali *et al.* (1984) report germplasm trials conducted at the Instituto Agronômico Campinas (IAC) which did not result in the identification of clones superior in this regard to the Brazilian material. Likewise, introduced materials from Ecuador were not considered promising in evaluations in Brasilia. Although this predominantly white-fleshed germplasm yielded more than the Brazilian clone, root colour and flavour were considered unsatisfactory (Dr F.F. Santos, 1994, pers. comm.).

Arracacha is typically grown by small farmers with less than 1 ha of arracacha per holding. Yields average 6-14 t/ha in Paraná and Minas Gerais (Hamerschmidt 1984; Santos 1984), 15-30 t/ha in São Paulo (with irrigation; Monteiro *et al.* 1993) and a nation-wide mean of 8 t/ha has been reported (Santos 1993). Plantings are year-round, with marketed volumes reaching a maximum between July and September when prices are lowest (Santos 1993). Several Brazilian companies process arracacha for instant food (see Section 5.4.1, Fig. 2).

Since 1984, five biannual *mandioquinha-salsa* meetings have brought together the major players of the arracacha industry in Brazil, namely farmers, market people, industrial users, extensionists and researchers, and their informal cooperation has greatly stimulated research and arracacha utilization.

2.3 Central America and Caribbean

Arracacha as a botanical genus (*Arracacia* Bancroft) and species was described from cultivated material introduced to Jamaica in the early 19th century (Mathias and Constance 1944). The plant seems to have been spread widely in the Caribbean, although it is only sporadically grown. We have only limited knowledge on its cultivation in Puerto Rico and Cuba.

Williams (1981) quotes reports of arracacha in Central America, specifically in Guatemala and Costa Rica, but says he has not seen it there. According to Dr Jorge Leon (1996, pers. comm.), the crop was cultivated in Panama around 1920. Hodge (1954) relates some evidence pointing to limited arracacha culture in the past in this country, specifically in the highlands around the Chiriquí volcano near the border with Costa Rica (approximate latitude: 8°45’ N). Significant commercial arracacha production in Central America appears to be limited to Costa Rica’s central highlands (Cordillera Central).

2.3.1 Costa Rica

According to Andean crop and Central America specialist Dr Jorge Leon (1996, pers. comm.), there are no references of arracacha cultivation in Costa Rica until the 1940s. He specifically refers to publications of Pittier (1908; 'Plantas usuales de Costa Rica') and Wercklé (1914; 'San Jose market survey') who do not mention arracacha (full bibliographic data not available). Since the 1940s, however, arracacha is reported to have been grown in the central highlands, especially in Cartago (Pacayas, Capellados), Heredia (San Isidro, Santa Barbara, Irazú region) and Alajuela (Zarcero, San Ramón, Carrizal) at altitudes of 1500-2200 m. There are probably not more than 10 ha of arracacha in all of Costa Rica, typically grown in small plots. The only variety referred to in the country under the name of arracacha has white roots and green foliage (Dr J. Leon, 1996, pers. comm.). Finely chopped arracacha ready for cooking is sold in farmers' markets at a price of US$2.00-2.50/kg. It is used as a filling for *picadillos,* a traditional Costa Rican dish served on patron saint's day (see Section 5.3) (Mr J.A. Morera, 1996, pers. comm.).

2.3.2 Puerto Rico

This small island's cosmopolitan past has made it a 'melting pot' for food plants from Europe, Africa, South America and Asia. Cultural influences and exotic ingredients in Puerto Rico have blended into a unique cuisine which, according to Sokolov (1993), is the richest expression of Caribbean cooking. It is thus no surprise that Puerto Ricans annually consume about 0.7 kg of arracacha per capita (calculated from data provided in Valle *et al.* 1989 and assuming a total population of 3.3 million for Puerto Rico in the same year).

According to Cook and Collins (1903), *apio* has been grown in Puerto Rico at least since 1903 when it was found planted extensively "in the mountains behind Ponce." Today it continues to be grown commercially in the central mountains near Barranquitas and Orocovis, in deep clay soils at altitudes less than 900 m and comparatively high mean temperatures (over 23°C). Although not ranked as a major root crop, *apio* is "very popular and in great demand when available" (Valle *et al.* 1989). Total insular production in 1985-86 was 2295 t, with a total farm value of US$1.05 million; hence, the farm-gate value was $0.46/kg. Valle *et al.* (1989) report the results of sensory evaluations of four clones introduced to Puerto Rico from Colombia. Interestingly, yellow-fleshed clones received higher ratings than a white clone which was moderately acceptable in appearance, flavour and texture.

2.3.3 Cuba

Arracacha, or *afió,* is believed to have been introduced to Cuba by French immigrants from Santo Domingo, Dominican Republic, and Haiti (Esquivel and Hammer 1992) and is used in Guantánamo for certain desserts. However, arracacha is rarely offered on markets and Cubans are usually unaware of this crop (Dr Lianne Fernández, 1996, pers. comm.). According to several authors reviewed by Esquivel *et al.* (1992), the

name *afió* has an African origin. The same authors report the use of arracacha leaves and stems in fritters, a popular food across the Caribbean.

2.4 Old World

Several documents from the late 19th century testify to attempts by the British colonial government to introduce arracacha from Jamaica via the Kew Botanical Garden to India and what is today Sri Lanka. Some of the shipments survived the long sea journey to Sri Lanka and were apparently bulked up for distribution of planting material "to the headmen of villages at 2000 feet or more elevation, in the hope of its culture being taken up by the villagers" (Anonymous 1887, quoting colonial administrative correspondence). We do not know whether these efforts ever succeeded and what the status of arracacha in Sri Lanka is today.

Similarly, L'Heureux and Bastin (1936) state that arracacha was introduced to Central Africa (Burundi, Rwanda), but the authors do not say to what extent the crop spread, if at all.

3 Vernacular names

> *"No nos hemos atrevido, por no salir con alguna arracachada" ... "Fíjese, Eloy, en el compañero que le va a tocar, para que no le haga case quando le salga con alguna arracachada"*[2]
>
> Idiomatic expressions using the derivative 'arracachada' as a synonym of 'nonsense', 'blunder' or 'silliness', used in the Cauca valley, Colombia (Jaramillo 1952)

'Arracacha' is derived from the Quechua word *racacha* (Alvarez 1990) and is widely understood in the Andes, except in Ecuador and Venezuela. Even Aymará-speaking people in Bolivia often use it instead of their own word *lacachu* (Hermann, 1989, field notes in Larejaca). Arracacha has also been accepted as the standard term in the English literature. Terms such as 'Peruvian carrot' or 'Peruvian parsnip' are confusing and their use in the literature should be discontinued.

Peru undoubtedly has the greatest variety of vernacular names for arracacha (Table 2). The term *racacha* is widespread in Arequipa, Puno and Tacna, but in Cusco and Apurímac, *virraca* seems to be preferred, whilst *ricacha* is popular in the north of the country (Amazonas, Cajamarca).

The Quechua language spread in the late 15th century from a limited area in the Cusco valley to become the lingua franca of the Inca empire that came to comprise the Andes from Ecuador to northern Chile. In the course of this cultural expansion, many indigenous languages perished and *racacha* supplanted previously used names. As Table 2 shows, indigenous words denoting arracacha are reported from Colombia and Venezuela, specifically from areas that were hardly ever controlled by the Incas, and only then for a few decades before the Spanish arrived. The record of words like *aricachi* (Ayomán language, Venezuela) or *arocueche* (in the extinct Muzo language, middle Magdalena, Colombia) raises the interesting question as to whether these terms are derived from *racacha* and, if so, whether the derivation occurred during and after the Inca conquest, or in archaic times, when arracacha spread across the Andes. Patiña (1964) presents some linguististic evidence for *arocueche* being an autochthonous Muzo word and considers it unlikely to have been merely a late deformation of *racacha.* Arracacha, he argues, might well be of northern Andean origin, and it might in remote times have been taken to the central Andes where the original term evolved into *racacha* only to return to replace its linguistic precursors. We can conclude with Patina that "these are issues to be proposed but not to be resolved".

[2] "We have dared not, in order to not say something foolish" ... "Pay attention, Eloy, to the mate you are going to have, so that you don't pay any attention to him when he does something foolish" (Translation by Bill Hardy).

Table 2. Vernacular names of arracacha

Vernacular name	Language	Country/Region	Source
Afió	"from an African language"	Cuba	Esquivel and Hammer 1992
Apio	Spanish	Puerto Rico	Cook and Collins 1903
Apio	Spanish	Venezuela	Mathias and Constance 1971
Apio criollo	Spanish	Venezuela	Reyes 1970
Aricachi	Ayomán	Venezuela	Jahn 1927
Arocueche	Muzo	Colombia/ Middle Magdalena	Patiño 1964
Arracacha	Quechua/ Spanish	Bolivia/ Colombia/ Peru	Patiño 1964; Soukup 1970
Arrecate, arecate	?	Venezuela	Pittier 1926
Batata-aipo	Portuguese	Brazil	Zanin and Casali 1984a
Batata-baroa	Portuguese	Brazil/ Rio de J.	Zanin and Casali 1984a
Batata-cenoura	Portuguese	Brazil	Zanin and Casali 1984a
Batata-fiusa	Portuguese	Brazil	Zanin and Casali 1984a
Batata-jujuba	Portuguese/?	Brazil	Zanin and Casali 1984a
Batata-salsa	Portuguese	Brazil	Zanin and Casali 1984a
Batata-suiça	Portuguese	Brazil	Zanin and Casali 1984a
Batata-tupinambá	Portuguese/ Tupí	Brazil	Zanin and Casali 1984a
Cenoura amarela	Portuguese	Brazil	Zanin and Casali 1984a
Guaud, Huahué	Páez-Coconuco	Colombia ?	Rivet 1941
Huisampilla	Quechua	Peru	Meza *et al.* 1996
Kiu-titsí	Timote	Venezuela	Jahn 1927
Lacache	Aymará	Chile/ Iquique	Hermann, field notes, 1993
Lacachu	Aymará	Bolivia/ Camacho	Hermann, field notes, 1991
Mandioquinha-salsa	Portuguese	Brazil/ São Paulo	Zanin and Casali 1984a
Pacucarrá	"Chocó indians"	Colombia/ Chocó	Jaramillo 1952
Pastinaca	Portuguese	Brazil/ Rio Grande do Sul	F.F. Santos, 1996, pers. comm.
Racacha	Quechua	Peru/ Arequipa, Cusco, Puno, Tacna	Arbizu and Robles 1986
Racacham	Quechua?	Bolivia/ La Paz	Rea 1995
Ricacha	Quechua	Peru/ Cajamarca, Amazonas	Arbizu and Robles 1986
Sacarracacha	?	Colombia/ Pasto, Quindío	Pérez-Arbeláez 1978

Vernacular name	Language	Country/Region	Source
Virraca	Quechua	Peru/ Apurímac, Cusco	Arbizu and Robles 1986
Yengó	Kamsá	Colombia/ Sibundoy	Bristol 1988
Zanahoria	Spanish	Colombia/ Nariño	Jaramillo 1952
Zanahoria	Spanish	Ecuador/ Loja	Hermann, field notes, 1994
Zanahoria blanca	Spanish	Ecuador	Castillo 1984
Zanahoria blanca	Spanish	Peru/ Cajamarca	Arbizu and Robles 1986
Zanahoria del país	Spanish	Peru/ Amazonas	Arbizu and Robles 1986
Zanahoria morada	Spanish	Peru/ Cajamarca	Arbizu and Robles 1986

In Spanish, the term arracachal (plural: arracachales) denotes an arracacha field. In the Cauca Department, Colombia, another derivative, *arracachada,* is synonymous in vernacular language with 'nonsense', blunder' or 'silliness' (see epigraph).

As shown in Table 2, outside South America, names for arracacha are derived predominantly from Spanish and Portuguese. Simple or compound terms involving *apio* (= celery), *zanahoria* and *cenoura* (= carrot), *pastinaca* (= parsnip) and *salsa* (= parsley) were coined by European immigrants and their folk taxonomy correctly identifies arracacha as closely related to these plants (they all belong to the umbelliferous subfamily Apioideae).

Brazil has a great variety of common names for arracacha. In Rio de Janeiro, for example, *batata-baroa* or the 'Baron's potato' is used. This name alludes to the alleged introduction of arracacha to Brazil by Baron de Friburgo, a nobleman from the state of Rio de Janeiro (Zanin and Casali 1984a). A São Paulo vegetable vendor, however, will not understand the term and may, eager to please the foreign customer as it happened to me, search for especially immaculate potatoes. To resolve the confusion arising from the wide range of terms for arracacha in Brazil, *mandioquinha-salsa* from the state of São Paulo was adopted as the official Brazilian word and it is now widely used in science and commerce. *Mandioquinha* is the Portuguese diminutive for cassava and *salsa* means parsley, so the official word nicely describes the similarity of arracacha with root and leaf shapes of these plants.

Cultivar names in Spanish refer to root colour, as in *arracacha amarilla* (yellow arracacha) or *arracacha blanca* (white arracacha), or denote a supposed origin, as in Salamineña (from Salamina), but there is not a great wealth of such names. In Peruvian Quechua, cultivar names are also mostly descriptive of colour and do not suggest great genetic variability as the rich folk taxonomy of the potato does. For example, in Cusco, an arracacha variety with pinkish pigmentation in the vascular ring, vaguely resembling make-up on an eyelid, is referred to as *pasña racacha* (= girl's arracacha). Then, there is *qu'ello racacha* (= yellow), *yurac racacha* (= white) and *qu'ulli racacha* (= deep purple). However, the same name is often applied to different cultivars (Hermann, field notes, 1990). Meza (1995) reports the following Quechua

varietal names for arracacha: *ñut'u racacha* (= small arracacha), *toctoccha* and *walla* (= cordillera arracacha). Herrera (1942) says that four types of arracacha are distinguished in southern Peru: *r'umur'accacha* (= cassava arracacha), *arros-r'accacha, huaisampilla* and *morada.* A good source for Peruvian varietal names of arracacha is Arbizu and Robles (1986). Among the many names listed in this germplasm catalogue, *chaucha amarilla* (= early yellow) and *chaucha blanca* (= early white) are perhaps the most remarkable since they indicate the existence of arracacha varieties with shorter crop duration. Bristol (1988) lists several varietal names in the Kamsá language of the Sibundoy (southern Colombia).

4 Biology and agronomy

4.1 Life form

Arracacha is a perennial plant. In the absence of vigorously competing weeds, arracacha will survive in a state of minimal growth for many years even without human intervention. This is of significance to the germplasm collector since the plant, in contrast to the tuber crops potato, oca and ulluco, may still be found where people have abandoned its cultivation but provide a niche for its survival such as in backyard gardens or fruit groves. Cultivation practices seek to maintain planting stocks vegetative; however, arracacha flowers occasionally. Certain conditions, especially dehydration, may induce very strong flowering responses that exhaust the plant and lead to its death (Section 4.3.1). This phenomenon presumably has led some authors to believe that arracacha is a biennial plant (for example, León 1964); Generally, however, the development of generative structures does not intervene with its continued vegetative growth.

4.2 Plant architecture, morphology and development

4.2.1 The vegetative plant

Figure 3 shows a mature vegetative arracacha plant from highland Ecuador, 20 months after the vegetative propagule was planted in sandy soil. Although this plant shows an undesirably large aboveground plant mass (which also results from the abnormally long crop duration of 20 months), the picture serves to illustrate arracacha's unique architecture, and its implications for plant development and propagation. The plant has four distinctive fractions: the storage roots, the central rootstock, the aerial stems and the leaves (for terms in Spanish and other languages, see Table 3).

The conical to cylindrical storage root (Fig. 3A) constitutes the principal economic product. A storage root can reach a weight of around 1 kg, but, more typically, individual roots weigh between 100 and 300 g. The root is proximally constricted and connected to the rootstock through 'necks' which break easily at harvest. Like the cassava or yac6n *(Polymnia sonchifolia)* storage root, it does not regenerate shoots. The storage root can therefore not be used as a propagule.

The central rootstock (Fig. 3B) is a highly swollen and compressed stem structure. In the cultivar shown, the rootstock is comparatively large. In other cultivars, the rootstock may be less prominent. Although genetically determined to some extent, shape and size of the rootstock depend greatly on the propagule used and cultivation practices (especially hilling).

The aerial stems or offshoots (Fig. 3C are very peculiar structures unique to arracacha and several authors have struggled to find an appropriate term for them (e.g. Hodge 1954). For the sake of convenience, we will call them 'cormels', although these are normally more compressed structures as, for example, in *Gladiolus* species. However, the arracacha cormels are also derived from stem tissue and are composed of internodes, nodes and scars left by shed leaves. The cormels therefore have a segmented structure.

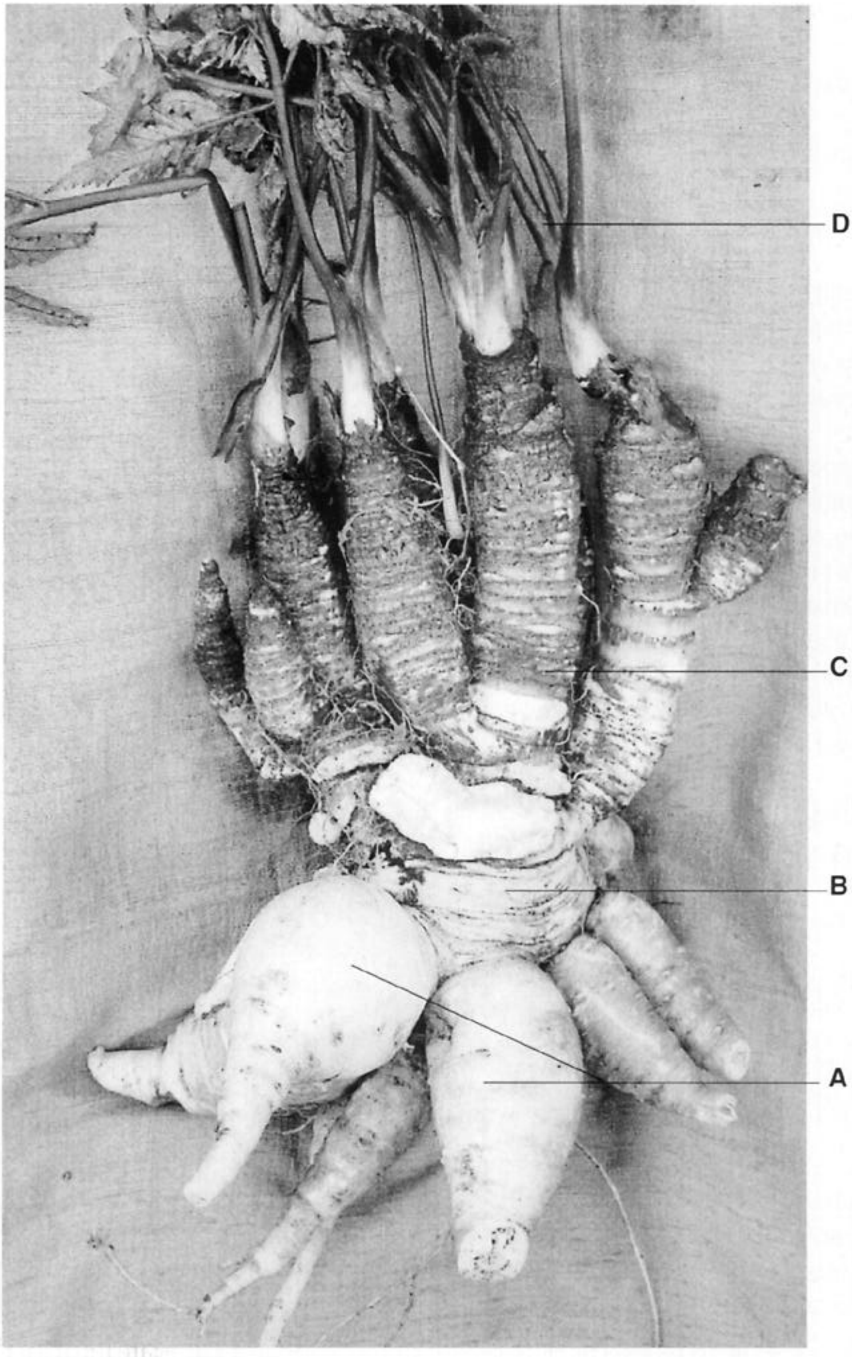

Fig. 3. Mature 20-month-old arracacha plant grown in the equatorial Andes (Ecuador) at 2400 m altitude (accession ECU1161, planted in July 1994, harvested in March 1996, density 15 000 plants/ha, propagated from entire cormels). **A:** storage roots; **B:** rootstock; **C:** stems or cormels; **D:** leaves. In this specimen, roots, rootstock, cormels and leaves accounted for 38, 17, 41 and 4% of a total dry matter of 702 g (fresh weight 3674 g).

Table 3. Terms applied to arracacha plant parts

Plant part	English	Quechua	Kamsá[†]	Spanish	Portuguese
Storage roots	arracacha, arracacha root	racacha, virraca	lengó, ingó	raíz	raíz
The entity of aerial parts and rootstock (which remain after removing the storage roots)	crown	n.a.	n.a.	partes aéreas	touceira
The central enlarged stem developing from propagule tissue; carries shoots and has storage roots inserted beneath soil surface	rootstock	n.a.	lengó, ingó	cepa, tronco	coroa, cepa
Entity of cormel and attached leaves	shoots	n.a.	n.a.	hijuelo	filhote, rebento
Apical part of cormel serving as propagule	stem cutting, sucker	k'ullucha,[‡] malqui[§]	jenashq, jenaviá, ingoshá[¶]	colino	muda
Buds inserted on cormels	eye, bud	ñahui		yema	gema

[†] The Kamsá language is spoken in the Sibundoy valley, southern Colombia; all terms are taken from Bristol (1988).
[‡] Used in Cusco, source: Hermann, unpublished field notes.
[§] Quoted in Bristol (1988) as Quechua.
[¶] Also used for the arracacha plant as a whole.
n.a. = not available.

Apical sections of the cormels with the basal part of the petioles serve as propagules; these develop over the crop's duration by growth and enlargement into the rootstock.

Each cormel carries on its apical nodes 3-5 petioled leaves which are of comparatively short duration (Fig. 3D). The leaf consists of a long petiole with a weakly developed basal sheath and the characteristically bipinnate blade. The leaves are 30-60 cm long; leaf size and dissection vary considerably within a plant and with the conditions of cultivation (Fig. 4).

The storage root formation of arracacha has been painstakingly studied by Roth (1977) in her microscopic investigation of a yellow-rooted cultivar in Venezuela (Fig. 5).

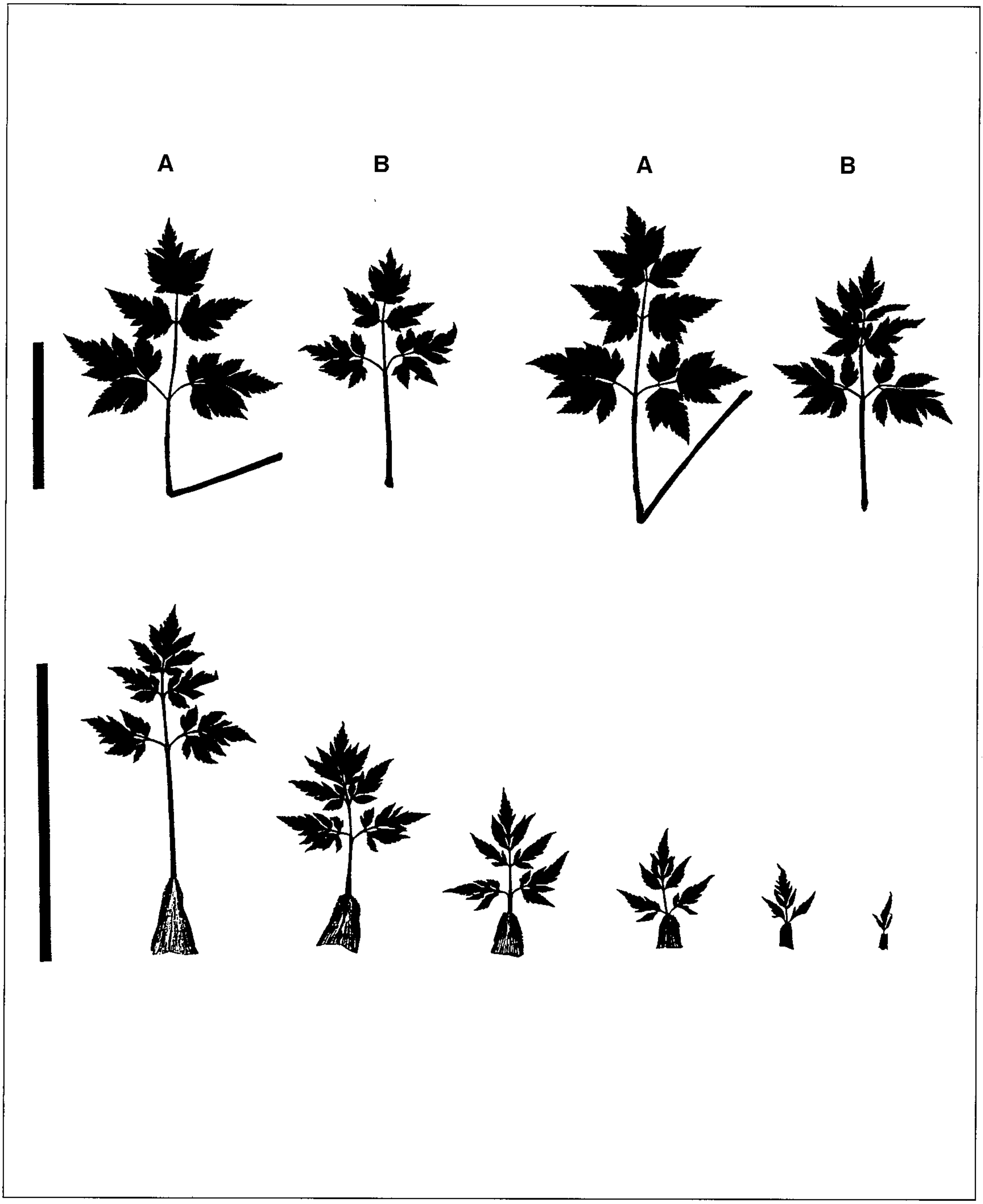

Fig. 4. Plasticity of leaf shape and size of cultivated arracacha. Leaves in the upper row show the influence of nutrient supply on two accessions (left pair: MH800; right pair MH548): **A:** field-grown plants with abundant nutrient supply; **B:** starving greenhouse plants. In the lower row, a succession of leaves along a generative shoot is shown (accession ECU1224). Scales: 20 cm.

Storage roots can be differentiated from filamentous roots by the naked eye about 2-3 months after planting. Initially, the filamentous root enlarges mainly owing to the growth of phloem parenchyma (Fig. 5A). When the root diameter has reached 2-3 cm, the xylem (the inner part of the root enclosed by the vascular ring) begins to develop starchy parenchymatic tissue which makes up most of the root at maturity Starchy parenchyma in the (outer) cortex contain numerous longitudinal oil ducts, which are lined with secretory cells (Fig. 5B, C). In open-cut roots, the ducts exsude a yellow, resinous oil with a typical umbelliferous odour. In wild *Arracacia* species, these oil ducts are more numerous and cause the astringent taste. Owing to root enlargement the rhizodermis experiences enormous dilation and a special mechanism of cork formation ('Etagenkork'), which is typical rather of monocotyledons, has evolved to allow for the continuous renewal of the root skin. Rhizodermic cork is formed in tangential layers separated by several layers of periclinally deviding cells. As new layers are formed from the underlying phloem tissue, the outer (= older) layers scale off (Fig. 5D, E, F).

4.2.2 The generative plant

The generative structures of arracacha and the factors inducing their emergence are poorly studied. Arracacha inflorescences and fruits are also conspicuously absent from most herbarium specimens. In most arracacha-growing regions, the plant rarely flowers. As will be seen later (Section 4.3.1), this is the result of cultivation practices and prevailing climatic conditions. Given appropriate flowering stimuli, however, all arracacha genotypes studied so far can reproduce sexually (Hermann, unpublished results).

Each well-developed cormel has the capacity to develop one generative shoot bearing several inflorescences. Therefore, flowering responses in a given arracacha plant range gradually from one generative shoot to as many generative shoots as there are cormels (see Fig. 6). Spontaneously flowering plants in the Andes seldom have more than 2-3 generative shoots. Figure 7 presents schematically a vigorous generative shoot (actually a ramified shoot system) of about 1.20 m height (the only generative shoot spontaneously developed on a greenhouse plant). It carried 38 umbels, none of which was found to be fruiting. Fruiting specimens have a more restricted shoot growth and a lower number of umbels. The umbels appear to be terminal. Sheathed nodes below each umbel continue shoot growth and the formation of new umbels until a certain size (and carrying capacity ?) is reached. Because of this growth pattern, the proximal umbels flower first and the peripheral ones last. The flowering period of any given shoot is between 1 and 2 months.

Leaf size and thus the photosynthetic capacity are largely restricted along the generative shoots (Fig. 4). Farmers remove these sinks as soon as they become visible, knowing that their undisturbed development can reduce root yields. Usually the 'generative' cormel develops a basal vegetative shoot which ensures the survival of vigorously flowering plants (those with generative shoots developing from all cormels).

The arracacha inflorescence is a compound umbel as shown in the schematic drawing (Fig. 8). This figure also gives the terms used to describe the inflorescence

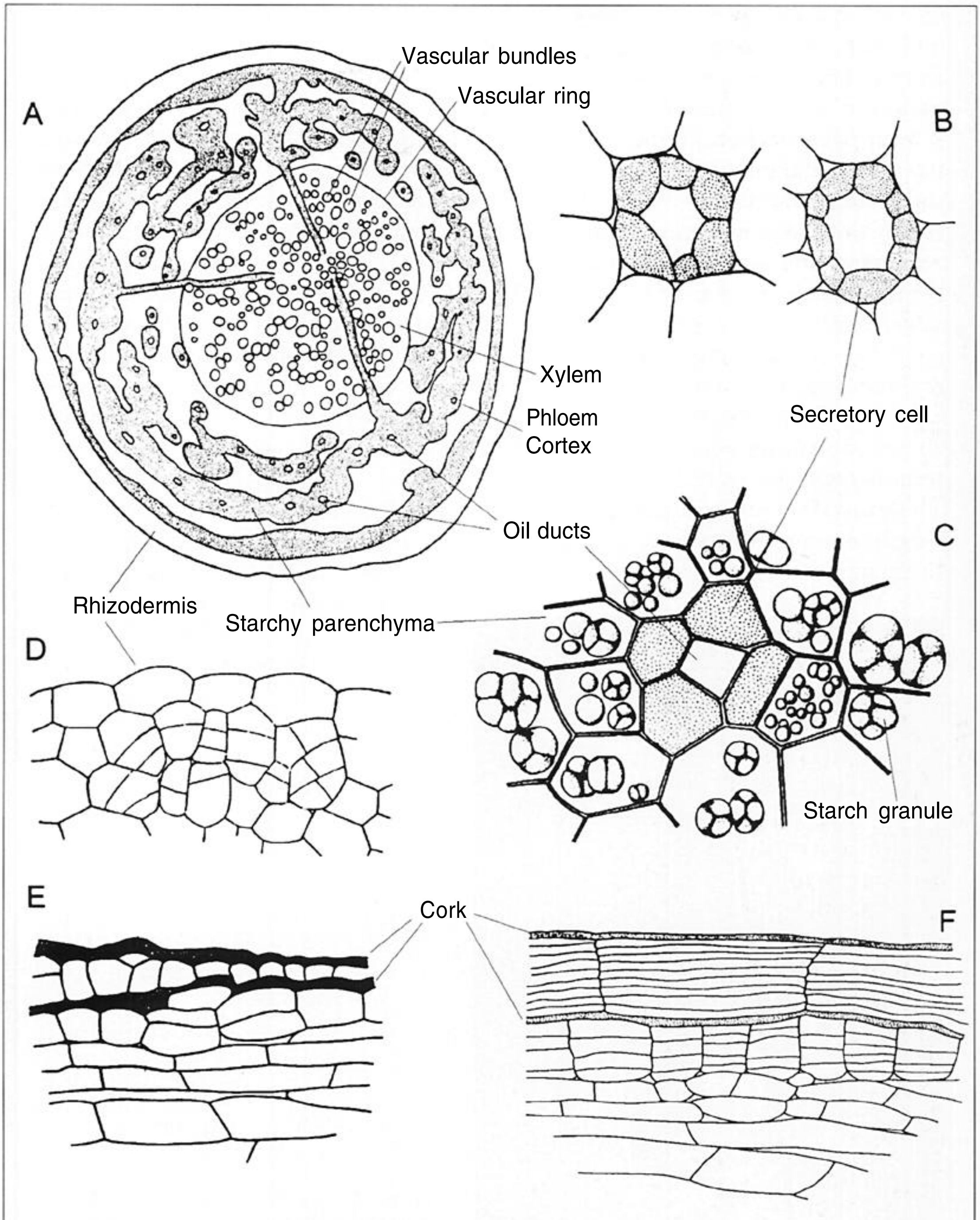

Fig. 5. Storage root development in arracacha. **A:** cross-section of a root with 4 mm diameter; **B:** mature oil ducts surrounded by secretory cells; **C:** developing oil duct within starchy parenchyma; **D, E, F:** progressive stages of 'Etagenkork' formation in rhizodermis (Source: Roth 1977).

of *Arracacia* species. The umbel has 8-14 rays, which carry the 10-25-flowered umbellets. The outer rays are stronger and carry more flowers than the inner ones. Hermaphrodite or perfect flowers, that is flowers with stamens and functional gynoecia, are found mostly on the outer umbellets; there are typically 3-5 perfect flowers per umbellet. The number of perfect flowers per umbellet decreases toward the centre of the umbel and the inner umbellets consist almost always of male or staminate flowers only. However, there are arracacha accessions, such as CA5026 (Peru, Yauyos), which deviate from this common pattern in that almost all flowers are perfect irrespective of the umbellet position. In such cases, the number of flowers per umbellet is lower and ranges from 5 to 20. Clearly, such genotypes have potential as seed parents as the possible seed yield per umbel and plant is greatly increased.

Across a wide range of genotypes, perfect flowers account typically for 15-25% of all flowers, except in a few accessions such as the aforementioned CA5026 with 85-90% perfect flowers. A distinctive feature of the arracacha umbel within genus *Arracacia* is the absence or reduction of the involucre to one lanceolate bractlet (for terminology see Fig. 8).

Arracacha flowers are actinomorphic (= radially symmetric) and with 2-5 mm length comparatively small (see Fig. 9). The epigynous, perfect flower has five petals, five stamens and two carpels, each with only one ovule; hence only one seed develops

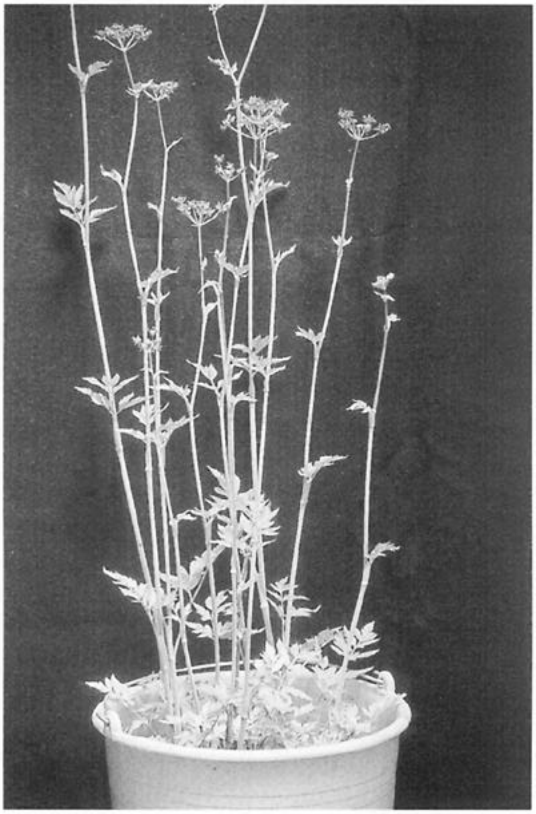

Fig. 6. Flowering arracacha plant (clone JJV-006 from San José de Minas). In this plant, flowering was induced by dehydrating the rootstock until 35% weight loss. Note that owing to this treatment, several generative shoots developed.

per carpel, and two seeds per flower and fruit. The styles emerge from an epigynous disk which functions as a nectary. The styles are basally enlarged to form the more or less conical stylopodium (Fig. 9). The stylopodium varies little between genotypes of cultivated arracacha, but its variable shape between wild *Arracacia* species is of diagnostic value (see Section 6.2.1). The formation of aberrant perfect flowers with 3 or 4 styles is characteristic of certain arracacha genotypes.

The male or staminate flower is similar to the perfect flower as far as petals, stamens and the basal disk is concerned, but it lacks functional female organs. In most genotypes, sepals are normally absent from both perfect and male flowers (asepalous flowers; see Fig. 9A-D, F). There are, however, genotypes with sepalous flowers, although these seem to be rare (Fig. 9E, G, H). The petals of immature flowers are green but they always turn maroon at anthesis. Other flower parts, such as petals, anthers, filaments, carpels and styles, are either free of the purple-maroon pigment or have it at varying intensities and combinations. Pollen from green anthers is white and pink in the more common maroon anthers. In the Ecuadorean accession JJV06, anthers with either pink or white pollen can occasionally be found within the same flower. It is obvious that the pigmentation of the various parts of the arracacha flower would lend itself for use in germplasm characterization.

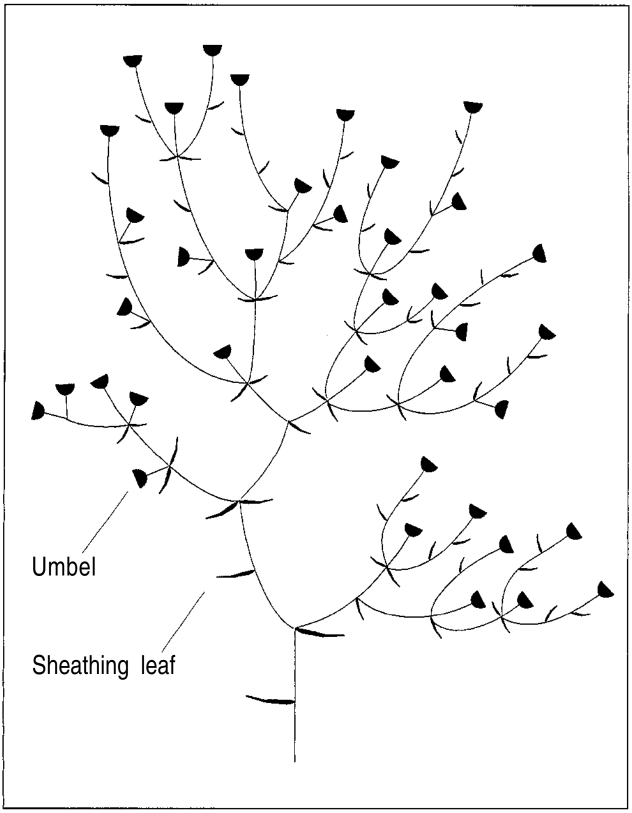

Fig. 7. Ramification of a (non-fruiting) generative shoot of *Arracacia xanthorrhiza* (schematic drawing of clone ECU-1223).

The first flowers of an umbel to commence anthesis are the perfect flowers of the outer umbellets. The development of such a flower is illustrated in Figure 9A-D. In the embryonic flower (Fig. 9A) the styles barely protrude from the perianth and their stigmatic surfaces lean against each other. Carpels and styles expand greatly until anthesis. Recent pollination experiments (Hermann, unpublished results) have shown that the stigma becomes receptive when the styles separate and display the stigmata as seen in Fig. 9B, C. At this stage, the stamens are still curled underneath the petals. Three to four days later, the stamens straighten, expand and project through the perianth, dehisce and release pollen (Fig. 9D). Anther dehiscence concurs with the peak of nectar production from nectaries on the epigynous disk. Anthers and petals now become caducous. During the entire flower development the petals remain curled.

Flowering progresses gradually from the periphery of the umbellet to the central staminate flowers and from outer to inner umbellets. Total flowering time of an umbel is about 15 days.

Generative characters of the arracacha plant show a certain variation that offers potential for the morphological differentiation of genotypes, a circumstance which is overlooked in arracacha germplasm characterization.

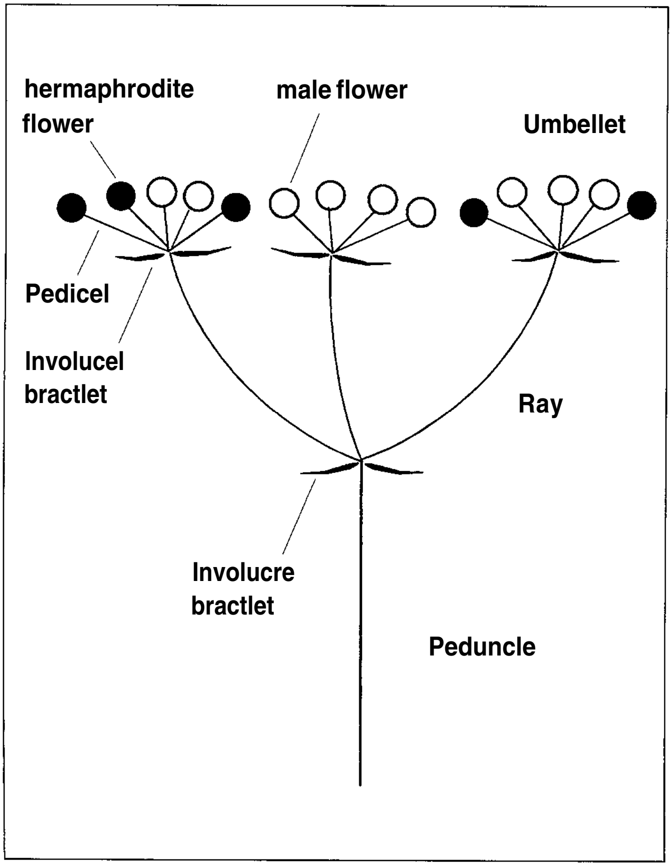

Fig. 8. Schematic drawing of the inflorescence (compound umbel) in genus *Arracacia* and terms to describe it.

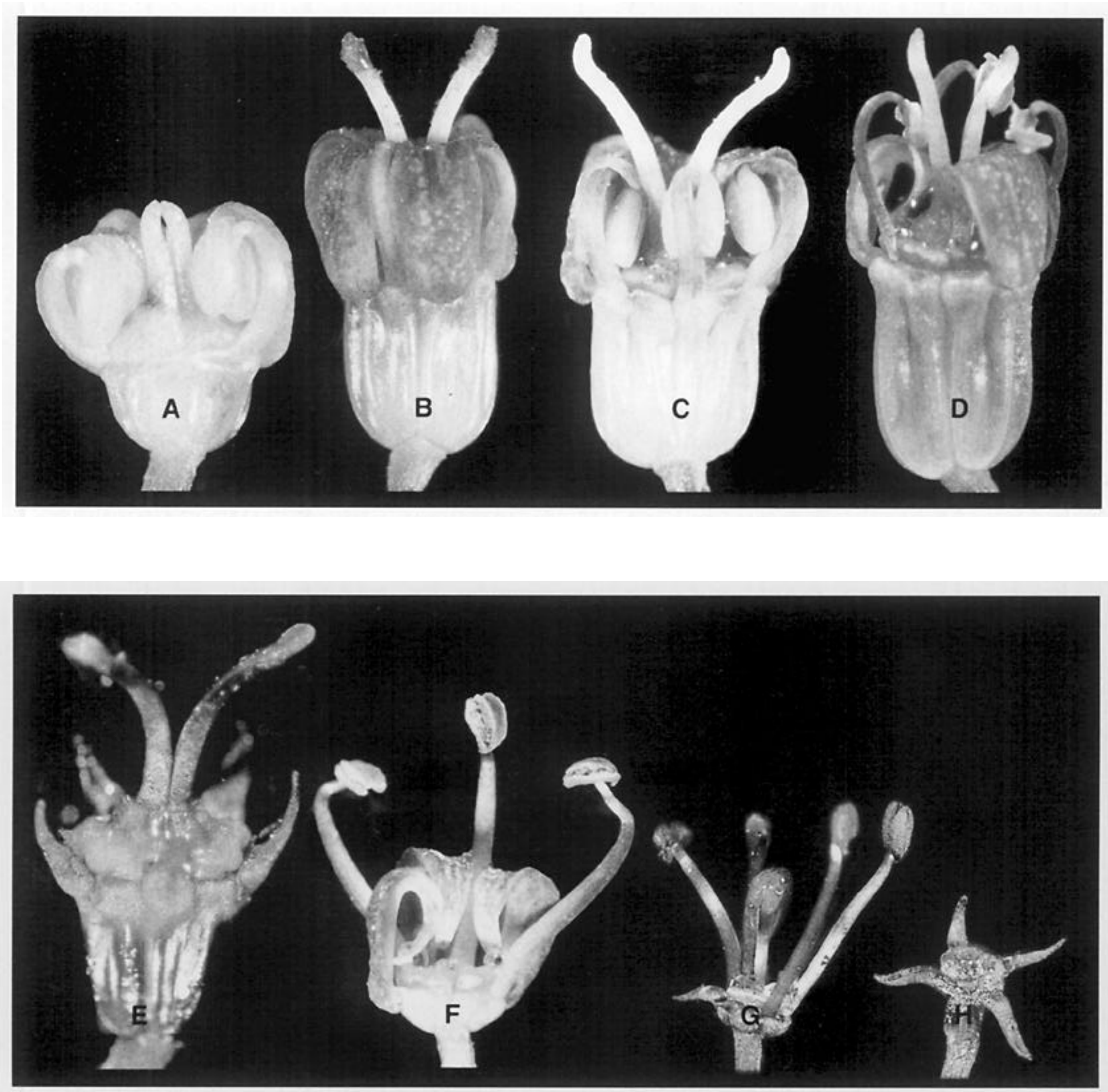

Fig. 9. Flower morphology and phenology of cultivated Arracacia xanthorrhiza. **A:** hermaphrodite flower a week before displaying stigmata (front petals and stamens removed); **B:** receptive hermaphrodite flower; **C:** receptive hermaphrodite flower with 2 front petals removed; **D:** hermaphrodite flower toward end of anthesis; note nectar production, dehiscent anthers and caducous petals; **E:** sepalous hermaphrodite flower, petals and stamens removed (length 4 mm); **F:** male asepalous flowers (2 petals removed); **G, H:** male sepalous flowers with dehiscent anthers, stamens and sepals partially removed. Length of hermaphrodite flowers from carpel base to stamen tips in B, C, D, E and A is 4-4.5 mm and 2 mm, respectively. Male flowers are 2-4 mm wide. Accessions JJV06 (A, B, C, D, F) and ECU1154 (E, G, H).

4.3 Reproductive biology

4.3.1 Flower induction

Whereas flowering arracacha can be observed only occasionally in the Andes (Bukasov 1930; Hodge 1954; Higuita 1970; Bristol 1988), flowering is frequent in Brazil, especially in the southern states of Minas Gerais, São Paulo and Paraná over 900 m altitude (Zanin and Casali 1984b). It is important to remember that arracacha production in this region is south of the 20th parallel, that is, south of the latitudinal range of Andean arracacha production. Seasonal variations in temperature and daylength in southern Brazil are therefore much more pronounced, and have been related to the seasonal pattern of arracacha flowering. Zanin and Casali (1984b) proposed that the low temperatures and/or short days at midyear induce flowering in commercial plantings from July to October. (Higuita (1970) also briefly mentions "low temperatures" as the cause for occasional flowering in Colombia.)

To test this hypothesis, Bajaña (1994) conducted a two-factorial greenhouse trial varying night temperatures (5-8°C vs. 12-15°C) and photoperiod (10 hours vs. 15 hours). Of the 10 genotypes used, only three flowered. Flowering responses were in general weak (only 15 out of a total of 160 plants). The treatments with short days and low night temperatures did not have statistically significant effects on flowering. In a collateral experiment, the same author removed the storage roots from mature plants and left the crowns to dry until they lost about half of their weight. Eighty percent of the replanted crowns flowered. Recent experiments with the same clone (from San José de Minas, Ecuador) showed that dehydration of mature plant crowns (20-30% weight loss) and subsequent culturing of the crowns induces, in over 90% of plants tested, the formation of nearly as many inflorescences as there are cormels in a plant (Hermann, 1996, unpublished results; see Fig. 6). These results confirm observations of Dr F.F. Santos in Brazil (1994, pers. comm.), who has repeatedly seen vigorous flowering responses in arracacha plantations that were subjected to drought, such as in abandoned fields in Goiás. Farmers in Ecuador also report increased flowering after spells of dry weather. Since drought (in Brazil) is often associated with short photoperiods and low temperatures, the effects of these factors cannot be separated. On the basis of present evidence, however, it is dehydration rather than vernalization that induces flowering in arracacha. In this context, it is perhaps noteworthy that the recently found putative ancestor of arracacha flowers after extended periods of drought (in the Ecuadorean Andes; see Section 6.2.1.5). By contrast, flowering in Old World apioid cultigens such as celery, carrots and parsley is induced by vernalization.

Flowering also seems to depend on genotype, as shown by Bajaña (1994) and observed by Plasencia and Huertas (1986) and in field collections in Brasilia by Dr F.F. Santos (1994, pers. comm.). The preliminary conclusion from these observations is that flowering is more easily induced in Ecuadorean accessions than in Peruvian and Brazilian cultivars.

4.3.2 Breeding system

As described in Section 4.2.2, the styles of the perfect flowers in a given umbel become receptive several days before the first stamens shed pollen. This phenomenon, known as protogyny, hinders self-fertilization and thus promotes outcrossing. Seed progenies of arracacha have been found to segregate considerably (Dr V. Casali, 1991, pers. comm.), which suggests a high degree of heterozygosity of arracacha cultivars and is consistent with the putative outbreeding nature of the species. The fact that spontaneous seed set can also be observed where only one clone is grown, as in Brazil, or in commercial plantations elsewhere, indicates that arracacha is sexually self-compatible, or at least is so for certain cultivars. In light of this preliminary evidence, arracacha appears most likely to be a facultative outbreeder.

4.3.3 Seed formation, storage and germination

The 'seed' of arracacha is shown in Figure 10. It is an achene or mericarp, a dry one-seeded fruit resulting from a schizocarp. At maturity, which is reached 8-10 weeks after pollination, the fruits are not shed but remain connected to a carpophore. Seed set is impaired or absent in sites that have comparatively high temperatures (Tacna, Peru; Brasilia) (Hermann, unpublished field observations). This is possibly due to the heat-induced internal breakdown of anther tissue which prevents the thecae from dehiscing and releasing pollen. During periods of daily peak temperatures above

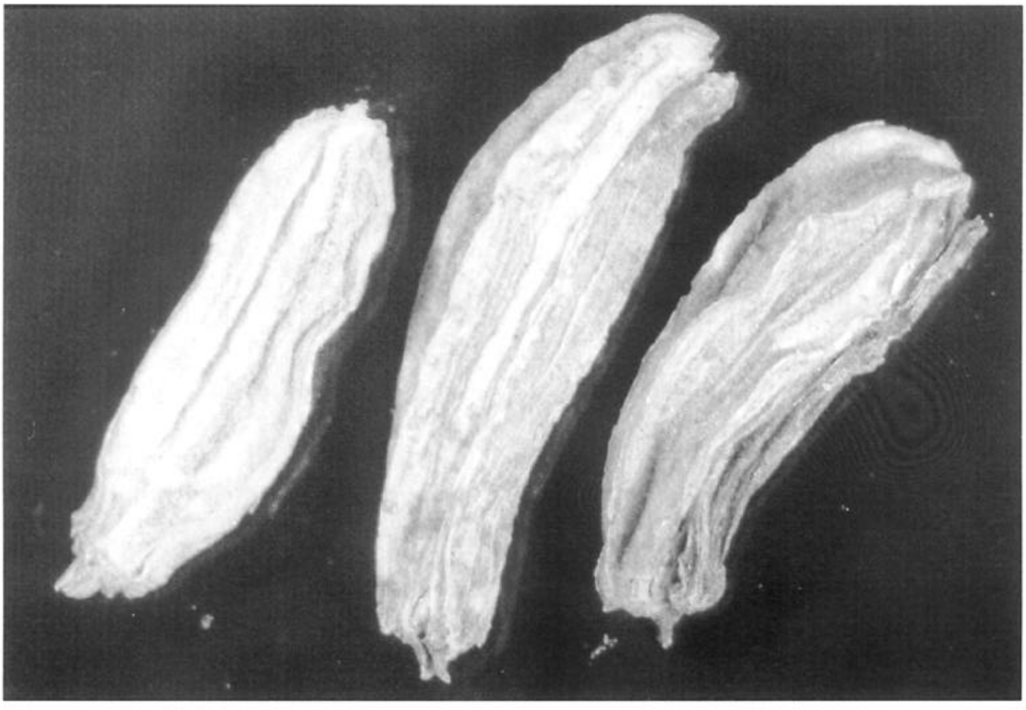

Fig. 10. Mature arracacha fruits (accession AMM5161). Length: 8-10 mm.

35°C and less than 30% relative humidity (as observed in Quito greenhouses), the anthers shrivel before they can shed pollen.

The seed of arracacha and other *Arracacia* species is orthodox, meaning that it can be dried to a low moisture content, which allows storage at temperatures below freezing point. Germination of recently harvested seed is rarely higher than 30%. The effects of plant origin, vernalization and seed treatment with chemicals and fungicides on germination have been studied to some extent, but no conclusive treatment to enhance germination has been identified (Sediyama 1988; Sediyama *et al.* 1990a, 1990b, 1991a). Larger seed, though, has significantly higher germination (Sediyama *et al.* 1991b).

4.4 Plant propagation

Plant propagation is the single most important issue in growing arracacha profitably. First, this is because the propagules can be produced on-farm, year after year, without degeneration of stocks. This, combined with robustness and nutrient efficiency, makes arracacha quite attractive to small farmers, who do not need to obtain credit to buy seed. Second, as will be seen below, root productivity depends greatly on the preparation of the propagule.

As outlined in Section 4.2.1, the cormel is used traditionally, and exclusively, as the propagule. Depending on age and development, the cormel has a few to several dozen buds, each of which has the capacity to sprout and form a new shoot, which

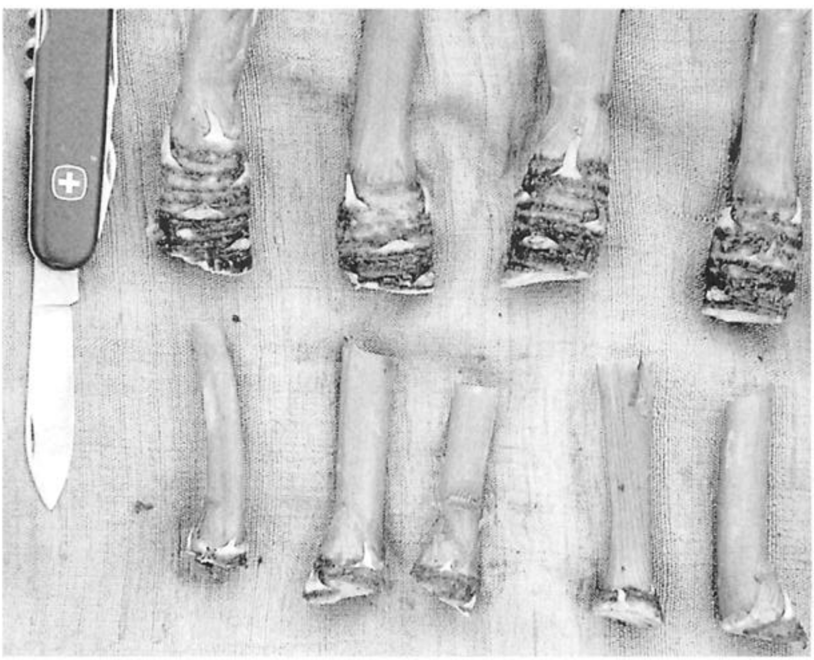

Fig. 11. Arracacha propagules. Propagules in lower row develop into more productive plants (with higher harvest index).

will swell at its base into a new cormel. A large or entire cormel, if used as the propagule, will therefore grow into a plant with many shoots (as in Fig. 3), whereas a propagule consisting of only the apical part of a cormel will result in a plant with fewer shoots, less foliage, smaller aerial parts and a higher proportion of total dry matter being allocated to the economic product, the storage roots (Casali *et al.* 1984). This relationship, which is rarely appreciated in the literature, is of the utmost importance for growing arracacha successfully.

Arracacha propagules can be taken at any stage of plant development. Senescent crowns from a mature crop are not really dormant (unlike those of *Arracacia andina;* see Section 6.2.1) and cormels taken from them will immediately root and sprout given appropriate conditions of temperature and moisture. To prepare the propagule, the cormel-offshoot is detached from the rootstock, and its leaves are trimmed back to leave only a few centimetres length of the petiole. Then the proximal two-thirds or three-quarters of the cormel are cut off in a slant cut, as seen in the upper row of Fig. 11. In the Andes, it is customary to cut a cross into the surface of the cut. This is believed to result in better spacing and a more equal lateral distribution of the storage roots. Before the propagules are planted, they are left for a few days to permit the cut surface to dry.

The more observant farmers are acutely aware of the importance of a good propagule with a minimum of eyes, yet one that has sufficient reserves to support post-planting dehydration and stress. As can be seen in Fig. 12, plants resulting from

Fig. 12. Mature 14-month-old arracacha plant from a commercial plantation in San José de Minas, Ecuador (1960 m altitude, 0°08’58”N, 78°24’15”W, annual precipitation 1000-1400 mm).

the right propagule can be tremendously productive. Such plants have as few as 10 shoots but no more than about 20, whereas more than 40 shoots (and cormels) are normally found on unproductive plants with 'hypertrophic' rootstocks. Table 4 provides data on dry matter partitioning of arracacha in three locations in highland Ecuador. Ironically, it is the small farmers of San José de Minas without access to 'technology' and 'advice' from research institutes who raise the most productive plants, with a harvest index of 82%. This is most remarkable for a root crop, especially for one that has never been 'improved' by plant breeding.

Table 4 also shows the extreme variation in dry matter partitioning of arracacha that can occur in different sites under different practices. This aspect must be observed in germplasm evaluation trials to ensure that genetic differences in plant architecture are measured and not phenomena that result from poor propagation techniques.

The multiplication rate of arracacha, that is, the number of propagules obtained from a mature plant through the conventional field method, depends on the number of cormels. In the Brazilian clone, the number of cormels per plant varies between 15 and 40 (Zanin 1985). Briceño (1977), evaluating 10 Bolivian, 12 Colombian and 4 Ecuadorean accessions, found the multiplication rates of this diverse material to range between 9 and 48 after one year of crop duration (mean and standard deviation: 27±11; calculated from data in Briceño 1977). This rate, however, can be greatly increased by common horticultural methods such as bud cuttings, removal and rooting of sprouts from the planted cormel and other methods.

Table 4. Yield and relative dry matter partitioning (DMP) of mature arracacha plants in three locations in the Equatorial Andes

Variable	San José de Minas	Tumbaco	Cumbayá
Fresh root yield (t/ha)	35-52	n.d.	18-24
Total DM yield (t/ha)	6.9 - 10.2	n.d.	12-13
Single plant DM yield (g/plant)	345-1181	284 - 901	280-294
DMP rootstock (%)	0.03 ± 0.01	0.15 ± 0.08	n.d.
DMP cormels (%)	0.07 ± 0.01	0.49 ± 0.09	n.d.
DMP leaves (blades and petioles) (%)	0.07 ± 0.08	0.10 ± 0.08	n.d.
DMP rootstock + cormels + leaves (%)	0.18 ± 0.04	0.73 ± 0.23	0.55 - 0.68
DMP storage roots (%) (=harvest index)	0.82 ± 0.02	0.27 ± 0.12	0.32 - 0.45

Conditions of cultivation: *San José de Minas:* from commercial production by small farmers at 1960 m asl, crop 14 months old (source: Hermann, unpublished data); *Tumbaco:* germplasm field collection (accessions ECU1161, ECU1179, ECU1181), 2400 m asl, crop 20 months old (source: Hermann, unpublished data); *Cumbayá* Nestlé experimental station, 2500 m asl, crop 10 months old, derived from data in Raffauf and Izquierdo 1994; all localities near equator. (Example: "DMP rootstock (%)" is the fraction of total plant dry matter accounted for by the rootstock.)
n.d.= no data.

Tissue culture of arracacha from meristems or protoplasts has been pioneered by Brazilian authors (Reis *et al.* 1989; Pessôa and Esquibel 1991; Pessôa *et al.* 1991a, 1991b, 1994) but it is of no commercial relevance to date. Recent research (Landázuri 1996) identified promising culture media for shoot-tip culture and micropropagation. A protocol is now available to propagate the plant *in vitro* at a rate of six to one per 8-week cycle by using an MS medium supplemented with 3% sucrose, 56 ppm BAP (6-benzylamino purine) and 0.05 ppm ANA (a-naphthaleneacetic acid).

4.5 Crop husbandry

4.5.1 Planting

Generally, the unrooted propagule is planted at the onset of the rainy season. A very promising development in Brazil, promoted by extensionists and increasingly adopted by farmers, is the rooting of propagules and subsequent transplanting to the field. This improves early plant development and, as a classical horticultural technique, brings about a number of benefits, the most significant being more homogeneous plant canopies, reduced crop duration and higher yields (Câmara 1992, 1993). According to farmers in Goiás I have interviewed recently, pre-rooting of propagules takes about 45-50 days. It is conveniently achieved on small plots with improved soil substrate. At planting, transplants can be selected and subsequent crop establishment is rapid. As a consequence, the crop can be harvested 6-7 months after planting compared with a crop duration of 8-10 months for unrooted planting material. Planting densities vary between 15 000 and 30 000 plants/ha (Higuita 1970; Santos *et al.* 1993). Santos *et al.* recommend a spacing of 0.8 m between rows and 0.4 m within rows. This seems to be a common practice for growers in Brazil.

Popular belief in Northern Peru has it that during the planting season one should avoid sleeping with crossed legs as this will cause the storage roots to become twisted and result in deformed arracachas at harvest.

The reason for the slow initial plant development of arracacha is unknown, but possibly the early allocation of dry matter to storage structures (cormels and rootstock) causes reduced leaf area replication. Because initial plant growth is slow, arracacha is, in the traditional cropping systems of the Andes, often intercropped with maize, which matures after 5-6 months. Weeding, either mechanical or chemical (in Brazil), is needed during early crop development. Once the arracacha canopy closes, however, arracacha can form high leaf area indices and thus suppress weed growth.

Hilling is traditionally done in the Andes and in parts of Brazil. Farmers believe that this stimulates storage root formation. A recent experiment, however, has shown that hilled plants have reduced harvest indices and lower yields (Raffauf and Izquierdo 1994). Hilling (as well as deep planting) can lead to elongated and hypertrophic rootstocks. Farmers in Brazil are discouraged from continuing this practice because of doubtful benefits and the labour costs involved (Dr F.F. Santos, 1996, pers. comm.). Some caution is perhaps indicated to not prematurely dismiss hilling as inappropriate.

4.5.2 Fertilization

In the Andes, fertilizers are often not or only sparingly applied to arracacha. Higuita (1970) probably has Andean soils of poor fertility in mind when he recommends for Colombia 500-600 kg of compound fertilizer (N-P-K = 10-30-10 or 12-24-10). It is not clear whether this recommendation is based on experiments, but the suggested quantities do not emphasize nitrogen. In Brazil, arracacha is typically grown from residual nutrients left over from a preceding potato crop (Santos 1993). Santos *et al.* (1991) recommend, for the cerrado latosols (poor in P and K), 600 kg/ha of compound fertilizers (N-P-K = 4-14-8) and an additional 20 kg/ha of borax every second year. However, Mesquita-Filho *et al.* (1996), who investigated the effects of borax fertilization on loamy latosols, found that borax dressings of 60 kg/ha (in a range of 0-90 kg/ha) gave the highest arracacha yields. With nitrogen supplies higher than those indicated above, arracacha produces exuberant foliage, harvest indices drop and crop duration is prolonged.

4.5.3 Harvest

Root bulking is notoriously late in arracacha. Therefore, the crop is harvested, in general, not earlier than 10 months after planting, especially if unrooted propagules were used. Farmers, however, are compensated for the inconvenience of long crop duration by the possibility of leaving the crop in the ground for later harvest, either to profit from rising prices or to take advantage of seasonally changing availability of family labour. Typically, harvest takes place after 12 months but can be delayed up to 16 months after planting. Harvesting begins with completely pulling up the plants with the roots. The roots are easily broken away from the plant and the remaining crown is divided into rootstock (mostly for feed) and cormels. Often the entire crowns are left in a heap for a few days or weeks until needed for the preparation of propagules. To maintain a given area of arracacha, only one cormel per harvested plant is needed and the remaining aerial plant mass is used for feed or left to rot.

A continuous range of yields from 3 to 63 t/ha has been reported in a collection of Ecuadorean germplasm (Nieto 1993), but it is not clear how much of this variation is genetic. Yield figures usually include the storage roots as the only marketable product, but because of the highly variable dry matter partitioning of the plant, the total of roots and rootstocks would be a more appropriate measure for the capacity of the plant to build up starchy dry matter. For example, in varietal trials in the Sabana de Bogota comprising nine varieties, average yields of 20.1±4.2 t/ha were reported, of which only 3.22±1.78 t/ha were storage roots and the remainder were rootstocks (calculated from data in Higuita 1969). As will be seen in Section 5, the chemical composition of the rootstock is very similar to that of the storage root and could therefore have potential for processing.

In general, root yields are below 20 t/ha and reflect growth under residual nutrient availability. According to a nation-wide survey conducted by Santos (1993), average yields in Brazil are 8 t/ha. Where adequate care is provided to the crop through irrigation, fertilization and the use of appropriate propagules, arracacha

yields are well above the national average (>20 t/ha), even in the arid cerrado uplands of Goiás (1000 m altitude, 16° S), hitherto considered unsuitable for arracacha culture (Santos 1993).

4.5.4 Pests and diseases

Arracacha is generally regarded as a robust crop with few disease or pest problems if it is appropriately rotated. But insects, bacteria and fungi can cause significant damage.

According to my field observations, acari *(Tetranychus urticue)* harm the crop frequently and are the most widespread and serious arracacha pest (Normanha and Silva 1963; Higuita 1969; Fornazier 1996). A beetle pest locally called 'chisa' is increasingly limiting arracacha culture in Tolima, Colombia (Mr J. Rivera Varón, 1996, pers. comm.; Sánchez and Vásquez 1996). 'Chisa' larvae mine the root and up to 40% of yield losses are reported. They belong to several genera of the subfamily Melolonthinae of the Scarabaeidae (*Cyclocephala, Ancognata, Phyllophaga, Serica, Macroductylus, Plectris, Issonychus, Anomala*). Sánchez and Vásquez (1996) claim that excessive use of pesticides occurs in Colombia to combat the pest. Other minor pests in Brazil include the moth *Agrotis ipsilon* and the mining larvae of the beetle *Conotrachelus cristatus* (Fornazier 1996). In Brazil, nematodes of genus *Meloidogyne* have become a problem, but they can be controlled readily by long rotations (Santos *et al.* 1991; Ventura and Costa 1996).

Among bacteria, *Erwinia* species are widely considered to be the most harmful to storage roots both in the field and in the store (Ventura and Costa 1996). *Erwinia* occurs especially at high temperatures. It infects the plant systemically and the disease is thus distributed via the propagules (Reyes 1970; Camino and Díaz 1972; Zapata and Pardo 1974).

A number of fungi attack different plant organs of arracacha. The most important disease in Brazil, especially in conditions of high soil moisture, is *Sclerotinia sclerotiorum.* It causes the plant and roots to rot and may lead to total crop losses. Rotation is recommended to combat the disease. Other fungi damaging the roots in the field and during storage include *Sclerotium rolfsii, Fusarium* sp., *Phoma* sp. and *Rhizopus* sp. (Normanha and Silva 1963; Ventura and Costa 1996). Leaf spot diseases in arracacha are caused by *Septoria* sp., *Cercospora* sp. and *Xanthomonas campestris* pv. *arracaciae* (Ventura and Costa 1996).

Several arracacha viruses and their features have been described (Jones and Kenten 1978, 1981; Kenten and Jones 1979), but it is not clear how they affect plant performance and yield. No degeneration of arracacha seed stocks has been observed as it occurs in the case of virus-infested potatoes. To date, five viruses infecting arracacha are known: AVA (arracacha virus A, nepovirus), AVB (arracacha virus B, nepovirus), the potyvirus AP-1, the carlavirus AV-3 and PBRV/A, a recently found variant of the potato black ring spot virus. PBRV/A was found to infect a range of potato cultivars (Lizárraga *et al.* 1994). Recently, simple and multiple virus infections were found in a sample of 40 plants belonging to 10 Ecuadorean arracacha accessions.

Only 23% of the plants were free of the five arracacha viruses tested. AP-1 and AV-3 were found in 53 and 38% of the plants, respectively (Mr L.M. Duque, 1996, pers. comm.). These two viruses also accounted for most of the infections found in a sample of Peruvian arracacha accessions (Lizárraga 1997).

4.5.5 Post-harvest

For a root, arracacha must be considered highly perishable and this constrains the commercial exploitation of the crop. Within a few days after harvest, and before the roots actually start to deteriorate, they develop brown spots, lose their brilliance and become unattractive in market displays. Also, large roots frequently crack at harvest even when carefully handled. The marketable life of arracacha at 25°C extends barely a week, the main cause for deterioration being rapid weight loss and subsequent rotting (Czyhrinciw and Jaffé 1951; Thompson 1980). Thompson observed that roots, at 18.5°C and 69% relative humidity, had lost 10.6% weight in 7 days. Under these conditions infections with *Rhizopus, Penicillium, Aspergillum, Nigrospora, Mucor* and *Syncephulastrum* occurred after 4 days. Arracacha is much more susceptible than carrot to mechanical damage which causes soft lesions and subsequent infections with opportunistic parasites (Henz 1995).

Deterioration, however, can be delayed over several weeks, either by reducing storage temperatures (3°C or 12°C; Czyhrinciw and Jaffé 1951), or, more economically, by measures that prevent root desiccation. A promising approach involves the application of plastic wrappings to individual roots. Using PVC cling or shrink films, Thompson reports a reduction of daily weight loss rate to less than 1 g/kg compared with about 17 g/kg for unwrapped roots. Likewise, Casali *et al.* (1988) found minimal weight loss (<1%) of roots "stored in polyethylene film" during 90 days at 5°C.

Leaving arracacha roots unwashed has also proved to enhance shelf-life (Thompson 1980; Câmara 1984b), but markets usually require washed roots. In this context, it is interesting to note that the Sibundoy Indians in Colombia used to bury harvested arracachas to keep them fresh for up to three weeks (Bristol 1988). Washing itself does not cause deterioration but rather the small wounds inflicted on the root surface during handling. These provide entry points for bacteria (Henz 1995). In Brazil, the most common post-harvest diseases are caused by the bacterium *Erwinia* and by the fungus *Rhizopus* (Henz 1995). Revetti (1967) reports doubled shelf-life after gamma-irradiation of arracacha.

Arracacha plant crowns discarded at harvest and often left near fields may survive for several months and this demonstrates that the storability of these parts is much better than that of the storage roots, despite the fact that they closely resemble the roots in chemical composition.

4.6 Crop ecology

No experimental data on the ecological requirements of crop growth of arracacha are available, but a number of conclusions can be drawn from the analysis of

temperature and rainfall patterns at arracacha-growing sites, which display enormously varying ecological conditions (Fig. 13). Altitudes range from 900 m (coastal Peru) to 3300 m (Peru, Bolivia) and annual rainfall varies from 0-30 mm (coastal Peru) to 5000 mm (Sibundoy, southern Colombia). Near the equator, arracacha is grown in the diurnal climate of tropical highlands, usually above 2000 m altitude. Farther away from the equator, such as in the subtropical climates of southern Brazil (not south of 26° S) the seasonal variation of temperature (and daylength) is much more pronounced and the crop is confined to lower altitudes where mean daily minimum temperatures during the cold season are above 5°C. Because frost kills the plant, plantations at high altitudes in southern Brazil (>1000 m) are at risk in the three coldest months of the year. If cultivars with reduced crop duration became available, arracacha could possibly be cultivated in the 7-8 frost-free months of many climates at higher latitudes and altitudes. It is not clear why the plant is not cultivated in the tropical lowlands, but there is some evidence from Florida that arracacha does not produce storage roots in hot and wet environments (Hodge 1954). On the other hand, I have recently seen well-developed arracacha plantings with precocious storage root bulking in the hot, albeit semi-arid, conditions of the upper São Francisco valley (northern Minas Gerais, Brazil; locality: Mocambinho, 14°55' S, 43°57' W, 450 m altitude; mean daily minimum (maximum) temperatures: 15-20 (30-33)°C). It remains to be seen whether arracacha can be cropped sustainably in the hot tropics where pests and diseases, particularly bacteria afflicting storage roots, are often more of a problem than in cooler environments. Mean monthly temperatures in arracacha-growing sites vary mostly between 15 and 20°C; they rarely exceed 20°C (see Fig. 13).

Although the formidable storage tissues of arracacha may confer some resistance against temporary drought, the plant thrives best when soil moisture is available throughout the cropping cycle. This may partly explain the widespread cultivation of arracacha in the humid Venezuelan and Colombian Andes with their bimodal rainfall patterns (see climate diagrams for Mérida, Bogotá and Pasto in Fig. 13). Also the rather wet conditions of Paraná, southern Brazil (exemplified by the diagram of Curitiba, Fig. 13), and of the Amazonian slopes of the Andes (no diagrams shown) allow its rain-fed cultivation with annual precipitations well over 1000 mm. However, root yields can double in southern Brazil when supplementary irrigation is provided (Dr F.F. Santos, 1995, pers. comm.). At sites with pronounced dry seasons (usually with less than 1000 mm precipitation) or in arid environments, however, arracacha needs to be irrigated; examples include the inter-Andean valleys, which lie in the rain shade of the Eastern Cordillera (see diagrams for Ambato and Cochabamba in Fig. 13) and the oases of the Peruvian and Chilean coastal desert (for example Tacna; see Fig. 13).

In conclusion, arracacha is largely restricted to relatively cool, but frost-free, montane tropical environments; it thus resembles arabica coffee in ecological requirements although the latter crop might be somewhat less cold tolerant. It should be possible to crop arracacha where arabica coffee has been successfully grown.

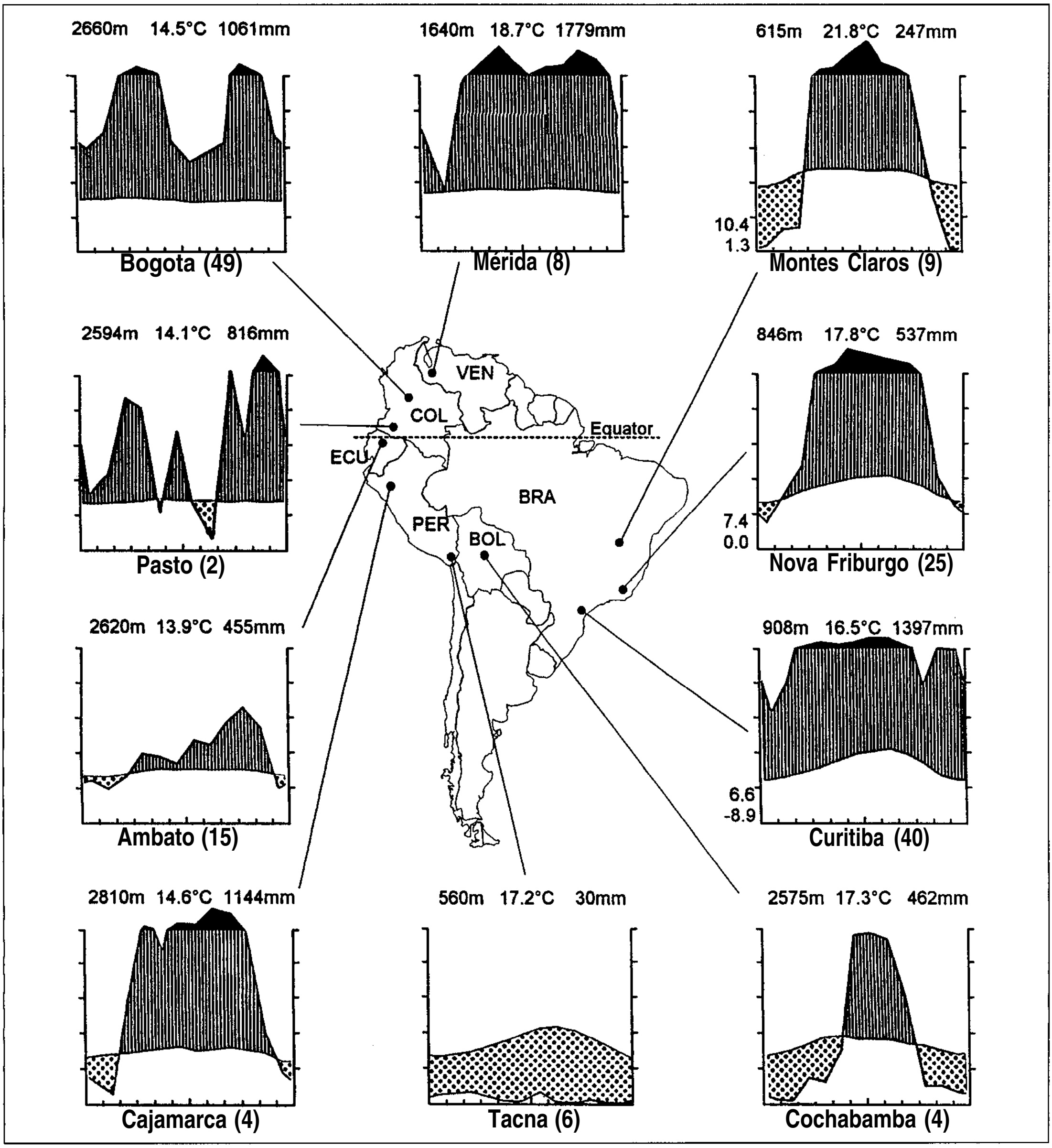

Fig. 13. Climates of arracacha growing sites. The lines in each diagram provide mean monthly temperature and precipitation data; units on left and right vertical axes are 10°C and 20 mm precipitation, respectively. Arid periods are represented by dotted areas (when the precipitation goes below the temperature curve). Humid periods are indicated by hatched areas. Periods with monthly precipitation above 100 mm are in solid black and reduced in scale by 1 :10. Altitude (m), yearly mean temperature (°C) and yearly mean precipitation (mm) are given on top of each diagram; numbers to lower left indicate (where available) the mean daily minimum temperature of the coldest month (Curitiba: 6.6°C) and the lowest temperature ever measured (Curitiba: -8.9°C). Numbers following the location name are years of meteorological observations. Source of diagrams: Walter and Lieth (1960).

Indeed, arracacha culture often provides an alternative for small producers abandoning coffee cultivation for lack of profit or because of phytosanitary problems (Colombia, Brazil).

Little else can be said about the crop ecology of arracacha, except perhaps that the susceptibility of its storage root formation to environmental conditions deserves further study. For example, storage root initiation and bulking of arracacha are retarded by conditions that induce lush foliage growth as observed in fields of high nitrogen availability or excessive irrigation (Dr F.F. Santos, 1995, pers. comm.). Arracacha forms only minute storage roots in container culture as various trials under a variety of nutrient and temperature conditions in Quito greenhouses have shown. Clearly, this sets arracacha apart from other crop plants including sweetpotato, potato and the other species discussed in this volume, which readily form tubers or storage roots in pots.

Daylength effects on root formation of arracacha have not been reported yet. Daylength appears to have no influence on flower induction (Bajaña 1994; see also Section 4.3.1).

5 Utilization

"The root yields a food, which is prepared in the same manner as potatoes, is grateful to the palate, and so easy of digestion, that it frequently constitutes the chief aliment of the sick. Starch and pastry are made from its fecula; and the root, reduced to pulp, enters into the composition of certain liquors, supposed to be efficacious as tonics. In the city of Santa Fé, and, indeed, wherever it can be produced, the arracacha is as universally used as the potato is in England."

M. Vargas describing in 1805 the use of arracacha
in his native Colombia, especially in Bogotá
(as quoted in Hooker 1831).

Arracacha is grown for its storage roots and, overwhelmingly, these constitute the principal economic product. However, all harvestable plant parts can be used for human and animal nutrition. The texture and chemical composition of the rootstock and cormel are similar to those of the storage root, but the rootstock is somewhat more fibrous (Higuita 1969). The rootstock is even superior in nutritional quality, as it has elevated protein (1.3 times) and mineral contents (e.g. calcium 2.1 times) compared with the roots (calculated from data in Camara 1984a; data from Brazilian commercial clone only). Table 5 compares dry matter content and its variation of the root, rootstock and other harvestable plant parts for different clones and growing sites. According to this table, dry matter of the rootstock varies more than that of other plant parts. Cormels always have lower dry matter content than either roots or rootstocks.

Table 5. Variation in dry matter content (%) of arracacha by plant part

Plant part	Commercial Brazilian clone (1)	Ecuadorean clones (2)	Commercial crop, Ecuador (3)
Storage roots	24.5 ± 0.8	19.4 ± 1.4	19.6 ± 0.3
Rootstock	23.5 ± 1.0	20.4 ± 4.5	15.4 ± 1.6
Cormels	n.d.	15.7 ± 1.6	13.9 ± 1.0
Leaves (including petioles)	n.d.	11.2 ± 0.8	9.6 ± 0.6
Leaf blades	18.0 ± 1.8	n.d.	n.d.
Petioles	8.2 ± 0.6	n.d.	n.d.

Source and growth conditions: (1) Calculated from data presented in Câmara 1984a, experiments in Viçosa, Minas Gerais (Brazil), only values for plants harvested between 8 and 11 months are taken into account; (2) Hermann, unpublished data, clones ECU1161, ECU1179, ECU1181, germplasm field collection, 2400 m asl, plants 20 months old; (3) Hermann, unpublished data, from commercial production by small farmers in San José de Minas, Pichincha, 1960 m altitude, crop 14 months old.
n.d. = no data.

In the Kamsá language of the Sibundoy Indians of southern Colombia, the same words denote both arracacha roots and rootstock (Bristol 1988; see Table 3). Indiscriminate use and preparation of both parts for food and lumping them in one pile during harvest, as observed by Bristol in 1962-63, corroborates that the Sibundoy indeed have no concept for roots as opposed to rootstock in arracacha. In his noteworthy review on the ethnobotany of arracacha in Colombia, Hodge (1954) pictures a Bogota vegetable vendor selling arracacha rootstocks, presumably for human consumption. Fifteen years later, presenting yield responses in nine Colombian genotypes, Higuita (1969) pooled root and rootstock weights to give "total yields". This probably indicates widespread commercial use of the rootstock in Colombia at the time of publication of the article. According to Mr J.J. Rivera (1996, pers. comm.), the use of arracacha rootstocks is still common in the Colombian department of Boyacá.

Usually, however, the rootstock and aerial plant parts (cormels, petioles and leaf blades), which can account for a considerable part of total biomass, are fed to domestic animals, especially pigs. The tender petioles and leaves have been reported to be eaten in Cuba (see Section 2.3.3), but I have never encountered this practice during extensive travel in South America nor references to it. Non-food uses of cultivated arracacha or its processed products have, to my awareness, not been recorded. (See, however, the medicinal uses of wild *Arracacia* species described in Section 6.2.1.5).

5.1 Chemical composition and its variation

Root dry matter of arracacha can range from 17 to 34% of the fresh weight according to data in the literature (reviewed in Pereira 1995; see Table 6). Values beyond 30%, however, occur only in genotypes which were recently selected by Brazilian researchers (Santos and Pereira 1994). Relatively high dry matter values have been reported from commercial ware in Venezuela (27%; Czyhrinciw and Jaffé 1951) and Colombia (24-28%; Higuita 1968, 1969) and from trials in Brazil (22-25%; Câmara 1984a). In Ecuador, a lesser range of 16-20% has consistently been found (Mazón *et al.* 1996; Hermann, unpublished data). The overwhelming part of arracacha root dry matter is carbohydrates, of which about 95% is starch and 5% is sugars (mainly sucrose) (Câmara 1984a).

Data in Table 6 show that arracacha is also a good source for ascorbic acid, vitamin A and minerals, especially calcium. The daily requirements for these nutrients can be met by consumption of comparatively small amounts of arracacha. The root, however, is a poor source for protein, with an average of about 1% protein in the fresh matter or 4% protein in the dry matter. There are conflicting reports as to the most limiting amino acid in arracacha protein: analyses reported in Câmara (1984a) identify lysine, whereas Pereira (1995) concludes from independent results that isoleucine is in the minimum compared with the FAO standard protein.

As can be seen in Table 6, vitamin A or carotenoids are by far the most variable nutrients, with the maximum value being 27 times the minimum observed. Carotene

is a pigment and its varying concentrations cause the wide range of root colours from white over cream to yellow and orange in arracacha germplasm collections. Studies by Almeida and Penteado (1987) showed that b-carotene is the principal carotenoid present in the commercial Brazilian clone (86 mg/100 mg edible portion) and that 30% of it is lost by cooking roots for 10 minutes.

Table 6. Variation in chemical composition of arracacha roots (per 100 g edible portion)†

Component	Unit	Mean	Range	Max./Min.‡
Total solids	g	26.0	16.8 - 34.1	2.0
Carbohydrates	g	24.9	19.3 - 29.9	1.5
Starch	g	23.5	16.9 - 25.5	1.5
Total sugars	g	1.66	0.65 - 1.98	3.1
Proteins	g	0.96	0.60 - 1.85	3.1
Lipids	g	0.26	0.19 - 0.35	1.8
Fibre	g	0.85	0.60 - 1.24	2.1
Ashes	g	1.30	1.05 - 1.38	1.3
Ascorbic acid	mg	23.0	18.3 - 28.4	1.5
Vitamin A (carotenoids)	I.U.§	1760	255 - 6879	27.0
Thiamine	mg	0.08	0.02 - 0.12	6.0
Riboflavin	mg	0.04	0.01 - 0.09	9.0
Niacin	mg	3.45	1.00 - 4.50	4.5
Pyridoxine	mg	0.03	0.01 - 0.07	7.0
Calcium	mg	65	45 - 128	2.8
Magnesium	mg	64	55 - 98	1.8
Phosphorus	mg	55	33 - 159	4.8
Iron	mg	9.5	3.6 - 15.4	4.3
Potassium	mg	2.40	1.86 - 3.04	1.6

† Adapted from Pereira 1995 (based on a literature review and the author's results).
‡ Author's calculations.
§ International units.

5.2 Food uses

The use of arracacha in food, whether for direct consumption or for processed products, can be explained in terms of three characteristics: starch content and quality, colour and flavour. Particular, and not yet understood, functional properties of arracacha starch are of crucial importance for most dishes and processed products. There is also a widespread belief that arracacha (or its starch) is easily digested and

therefore an ideal food for children and the ailing. Hodge (1954) claims that arracacha starch is less flatulent than the starch of potato *(Solanum tuberostum).* In Loja, southern Ecuador, a strict 40-day diet commonly followed by women after giving birth includes arracacha to the exclusion of potatoes (Mrs Joy Horton de Hofmann, 1997, pers. comm.). Arracacha adds unique colours to dishes and processed products, especially the yellow-rooted clones, which assume a vivid orange colour after heat treatment. Opinion as to the umbelliferous aroma of arracacha, however, is divided. Some people are fond of it, and others loathe it. It is a unique aroma, but it is clearly reminiscent of parsley, celery and other umbelliferous vegetables.

Unlike many other roots, arracacha is not unpleasant to eat raw, but cooking is required to soften its tissue and gelatinize its starch, thus rendering it more digestible. This is why arracacha roots are never eaten raw. Even thinly sliced, arracacha does not hold much promise for applications in salads or other raw food, as it lacks the acid or sweet compounds present in oca *(Oxalis turbeuosa)* and ahipa *(Pachyrhizus ahipa)* which, combined with special textures, provide interesting new tastes.

5.3 Direct consumption

Traditionally, arracacha is used in soups, purées and especially stews locally called *chupe* (Peru), *locro* (Peru, Ecuador), *sancocho* (Colombia) and *cocido* (Venezuela). The classical sancocho and the closely related cocido include meat, pork, potato (*S. tuberosum*), cassava, plantains, arracacha, optional pork sausages, onions and the indispensable leaf coriander (*Coriandrum sativum*). Variations of this dish include *viudo de pescado* from the Magdalena valley (Tolima, Colombia), in which fish replaces meat and pork, and the *mondongo* from Antioquia, a stew with arracacha, potatoes, sausages and beef tripe as the characteristic ingredients.

Soups and purées having arracacha as their main starchy ingredient are deliciously creamy and light food. Frying arracacha also gives interesting results; however, it reduces the typical arracacha aroma and deep-fried arracacha strips are, especially when made from the white-rooted, less aromatic clones, virtually indistinguishable from (potato) french fries. Frying also compromises reducing sugars in the Maillard reaction, and produces dark and undesirable colours in some arracacha genotypes that are presumably high in reducing sugars.

Modern Brazilian cuisine has added quite a few creative arracacha recipes. *Soufflé de mandioquinha-salsa* requires cooked and hot arracachas to be mashed and mixed with butter and egg yolks. After stiffly beaten egg-whites are folded into this mixture, it is baked to expand greatly in volume (Sangirardi 1988). Rio de Janeiro has invented *batata baroa em calda* (arracacha compote), which involves blanched arracacha pieces being cooked in dissolved sugar (Weiss 1995) as is also done with a variety of fruits. Another popular arracacha dessert comes from the northern Andes. Called *pasteles* in Ecuador or *buñuelos de apio* in Venezuela, this recipe calls for the cooked and mashed arracacha roots to be mixed with butter, eggs and sugar. This mass is shaped and fried in oil. A salty version of this dish is equally popular in Venezuela (Dr Maria L. García, 1996, pers. comm.).

In Minas Gerais, Brazil, descendants of Italian immigrants use arracacha instead of potato in the well-known gnocchi dish. This gives a special and light consistency and arracacha is thus preferred over the original ingredient. Sokolov (1993) mentions the use of arracacha in the *alcapurrius* of Puerto Rico. This is a fritter whose dough is a mixture of purees from arracacha, glutinous plantain and starchy yautía (*Xanthosoma sagittifolium*). This dough is stuffed with a meat filling, shaped into fritters and deep-fried.

In Costa Rica, arracacha is used finely chopped and fried with minced meat and onions as a filler in *tortillas de maiz.* This traditional dish is called *picadillos;* it is served during church celebrations on patron saint's day(Drs J. León and N. Mateo, 1996, pers. comm.). In conclusion, arracacha offers a great variety of culinary uses, which is unsurpassed by other starchy roots and tubers.

5.4 Processing

Arracacha is overwhelmingly used for direct consumption, but several processed products would almost certainly be produced in higher volumes were it not for the elevated raw material prices that result from the popular esteem of the root for direct consumption. The almost complete absence of processed arracacha in the Andes, however, can only be explained in terms of a lack of entrepreneurial initiative since the crop can be produced with great ease and is relatively inexpensive. On the other hand, Brazil has a wide range of processed products, but its companies struggle with high raw material costs that limit the proportion of arracacha in processed products (Hermann 1995).

5.4.1 Instant food

In its processing plant in San José de Rio Pardo, São Paulo state, Nestle-Brazil uses arracacha as an ingredient in both wet and dry formulae of instant soups and baby food. In fact, all non-sweet Nestlé products in Brazil contain some arracacha, but only up to about 15% of total product dry weight. The particular flavour and food consistency achieved by using arracacha are considered decisive for its use. The company processed about 300 t of arracacha annually between 1985 and 1993.

Nutrimental, a company in Curitiba, Paraná, Brazil, specializes in the production of dehydrated vegetables, which are sold to other food-processing companies such as Knorr for use in dry formulations of purees and soups (Fig. 2D). Nutrimental produces flour and flakes from arracacha. The bright orange colour of dehydrated arracacha flakes is particularly attractive and not found in other vegetables (dehydrated carrots are deep red). Processing involves abrasive peeling, slicing, blanching and drying flakes batch-wise in forced-ventilated ovens. Nutrimental processed 400 t of arracacha in 1991. Nutrimental managers are considering the development of an instant purée for infants based on arracacha because of the good reputation this dish enjoys with the population (Hermann 1995).

5.4.2 Chips

Arracacha chips have been available for several years in Quito supermarkets from production by the Quiteña company in Calderón, near Quito. This company processed 50 t of fresh roots in 1994. Although the quality of these chips leaves room for improvement, they sell well, and with a better supply of raw material, the company could sell more. Arracacha processed in Quiteña comes from San José de Minas in Pichincha province. It is comparatively low in dry matter (up to 20%) and darkens after frying, as do a few other Ecuadorean clones tested so far (Hermann 1996).

Promising results with arracacha chips have been achieved in pilot trials at the Krebauer company, Brasilia, using the traditional Brazilian clone. Experiments yielded arracacha chips of excellent quality and acceptance. Crispness was similar to that of potato chips, but a trained panel consistently rated the appearance of arracacha chips superior to that of potato chips. Panelists emphasized the light sweetness of arracacha chips as an attractive and distinctive feature. Additional advantages included lower fat absorption, the possibility of direct packing and reduced frying temperatures (Santos and Hermann 1994).

5.4.3 Starch

Arracacha starch was widely used for pastry in Colombia during the first half of the 19th century. In 1831, Hooker wrote: "The root [of arracacha] rasped and macerated in water, deposits a fecula, which is in very general use at Bogotá, as a light nourishment for the sick, in the same manner as the fecula of the *Maranta arundinacea* is in Jamaica" (Hooker 1831; see also epigraph in Section 5). Today, arracacha starch is sporadically extracted in Colombia, but this is no longer of commercial significance. In 1994, I observed rural women in Huila use the starch for small spongy cakes called *bizcochuelos* (for example Doña Lucila Jiménez, El Grifo, Municipio Altamira). In Manta, Cundinamarca, arracacha starch has been used in the past for *bocadillos* (cookies); however, the industry is about to disappear and only one starch processor has remained (Mr Gómez; Dr Isabel Hernández, 1994, pers. comm.). The extraction of starch from arracacha (and other roots and tubers, such as *Canna edulis,* cassava and *Maranta arundinacea)* is basically the same in rural households throughout Colombia. The roots are washed, peeled and grated over a metal sheet, which is perforated with a nail to provide an abrasive surface. The resulting pulp is suspended in water and subjected to several cycles of washing and settling until a white and clean starch sediment is obtained. Households produce hardly more than a few pounds for home consumption or *para el gasto* as people in the northern Andes say.

The only evidence for commercial arracacha starch use comes from the Bogotá-based Ramo company, whose production philosophy is to systematically retrieve traditional cookie recipes and turn them into modern products. The company has offered for decades a successful product line, called *colaciones,* which is a traditional Colombian assortment of cookies. To achieve particular textures in this product, Ramo employs a number of starches, mainly from cassava and achira *(Canna edulis),* but also small amounts of arracacha starch, which was found to enhance crunchiness

in the baked product. The company does not reveal product compositions, but annual use of arracacha starch in 1994 was said to be 5 t, all derived from a company-owned extraction plant. Research at Ramo's laboratories resulted in the development of several pastry products with elevated arracacha starch contents (up to 30%), such as *bocadillos* and *bizcochitos,* but because of problems with arracacha starch supply these products can not be launched yet (Hermann 1994).

Arracacha starch is of a brilliant white colour and has comparatively small granules. In a given sample, the granules between 5 and 35 µm diameter, generally account for 80-95% of total starch volume (as determined with a laser diffraction counter). The granule size distributions for storage roots, rootstocks and cormels (of an Ecuadorean clone) are quite different (Fig. 14). With an average diameter of 17.2 µm, starch granules in roots are bigger than those found in cormels (11.1 µm) or rootstocks (13.3 µm). The size range of cormel and rootstock starch granules, both absolutely and in relation to average size, is narrower than the size range of root starch.

However, viscoamylography shows that during gelatinization there are no significant differences between the starches from different plant fractions. Peak viscosity of arracacha starch measured with a rapid viscoanalyzer (RVA) was lower than that of potato, oca (*Oxalis tuberosa*), achira (*Canna edulis*) and ulluco (*Ullucus tuberosus*) starches (concentration: 2 g/25 ml). Initial, peak and final gelatinization temperatures recently measured by differential scanning calorimetry (DSC) were found to be 50, 58 and 67°C, respectively. The gelatinization enthalpy as revealed by DSC is 2.9 J/g dry starch (Hermann, unpublished results). Amylose content was determined by Dufour *et al.* (1996) in Colombian material (18.5%) and by Villacrés and Espín (1996) in six Ecuadorean clones (average: 20%). Raffauf and Izquierdo (1994) give a range of 10-12% of amylose obtained in different plant parts and under different growth conditions of one Ecuadorean clone. Amylose-free arracacha cultivars have recently been found in Colombia (Dr D. Dufour, 1997, pers. comm.).

The opportunity for arracacha starch on the market lies perhaps with its exceptionally low syneresis[3] (Raffauf and Izquierdo 1994), even at low acidity (pH = 2.4; Dufour et al. 1996). Usually, syneresis in food products is minimized by the use of modified starches. These, however, are increasingly perceived as 'unnatural' ingredients and replaced with native starches to give 'ecological' appeal to processed food. Moreover, native starches are considered food ingredients rather than additives and their proportion in processed food is not subject to regulations. This prompted Raffauf and Izquierdo (1994) of Nestlé's Latin American Research & Development Center near Quito to explore yield potential, extractability and production economics of arracacha starch. It is not clear whether Nestlé contemplates product development involving arracacha starch.

Starch use could add considerable value to the conventional production of arracacha for the fresh market, as starch is also contained at high levels in rootstocks

3 Exudation of a liquid from a starch gel, for example in food products subject to freeze-thaw cycles.

and cormels. These account usually for much of the total biomass (see Table 4) and are often left to rot in the field. The costs of starch manufacture from harvest residues and non-commercial roots would essentially be those for transport and processing.

Starch from arracacha roots, by contrast, would be much costlier to produce as the raw material is highly valued on the fresh market. It remains to be seen whether root starch can be produced at competitive prices and/or whether niche markets can be identified, for example in the food industry, where specific starch qualities are required (see above). Cost estimates based on different scenarios range from US$1.33/kg of arracacha starch in Colombia (Hurtado *et al.* 1997) to US$2.57/kg in Ecuador (Raffauf and Izquierdo 1994). These estimates do not take into account the possibility to reduce costs by selecting clones high in starch content. Likewise the potential for improving extraction efficiencies was not considered by Hurtado *et al.* (1997) who report starch yields of only 6-11% per root fresh matter and extraction efficiencies as low as 24-50% of starch per root dry matter, which may have resulted from the use of inadequate equipment. Although data provided by Raffauf and Izquierdo (1994) were from 10-month-old (and prematurely harvested?) plants, their experiment shows that arracacha can be an interesting starch source when roots and

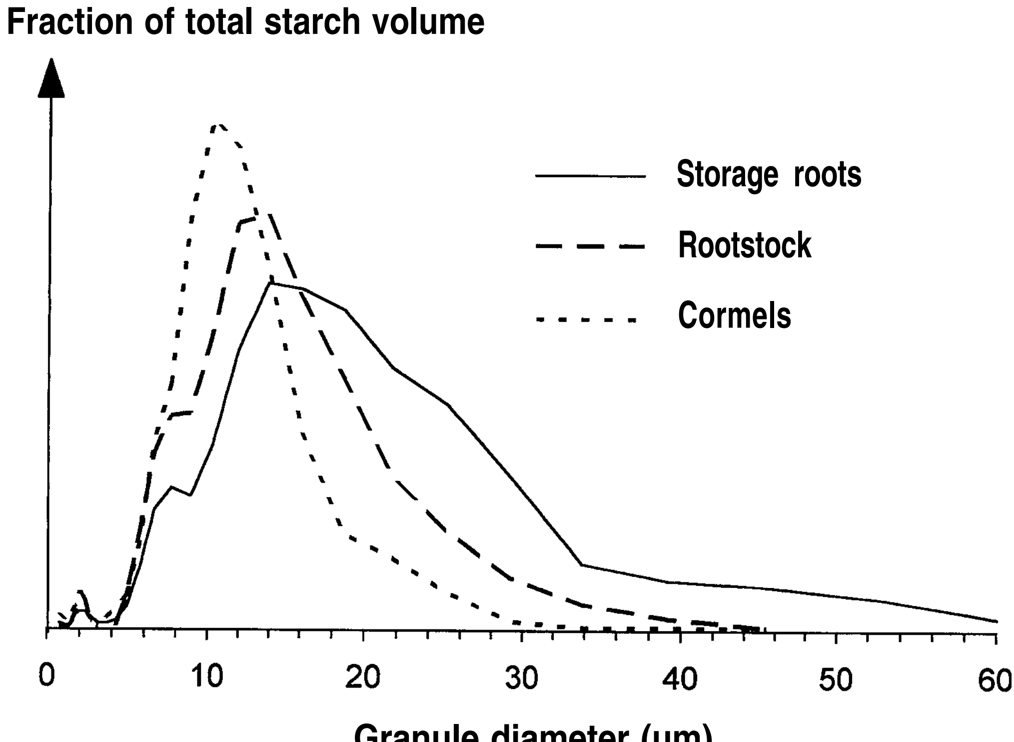

Fig. 14. Granule size distribution of arracacha starch from different plant parts (determined with a Malvern Laser diffraction counter). Accession ECU1181; culture conditions: plants grown in Tumbaco, 2400 m asl; planted July 20, 1994, density 1.00 x 0.80 m, harvested March 20, 1996.

crowns are processed: starch yields were between 4.7 and 8.0 t/ha and 14-18% of fresh matter and the extraction efficiency varied between 64 and 68%.

5.4.4 Fermentation

During field work in Quetame, Cundinamarca, I recorded a use of arracacha that still seems to be common in that part of Colombia. *Guarapo de arracacha* or *chicha de arracacha* is a mildly alcoholic beverage.[4] Its preparation is similar to that of the Amazonian *masato,* which is made from cassava. To prepare *guarapo,* boiled arracacha roots are ground and allowed to cool for a night. Then the ground mass is passed through a cloth or screen, water and raw sugar are added and the mixture is left to ferment for 3 days (information from José Vicente Rojas Torres, Finca Mermejal, Estaquecá, 1994) (Hermann 1994). Bristol (1988) mentions the former use of arracacha for chicha-making among the Sibundoy Indians (southern Colombia) and there is a reference to it for the Colombian Orinoco and Amazonas (Duque 1994). It has also been reported from Peru (Hermann, 1988, field notes).

[4] The term 'guarapo' in general is reserved for fresh and fermented sugar cane juice: 'chicha' denotes maize beer.

6 Taxonomy and biosystematics

6.1 Umbelliferae

There are an estimated 300 genera and between 2500 and 3000 species in this family, which is also called Apiaceae. The Umbelliferae are cosmopolitan but rare in lower latitudes. A little less than one-third of the umbelliferous species occur in the New World, a figure approximating the proportional land mass (Mathias 1971). Umbelliferae are frequent in temperate highland areas and particularly diverse in moderate climates and in the Mediterranean (Heywood 1978). In the tropics, many species occur at high altitudes (Friedberg 1978), some well above the tree limit (Maas and Westra 1993).

Chemically, the Umbelliferae are characterized by high contents of essential oils, coumarins, polyacetylenic constituents and flavonoid compounds. The seeds contain aleurone grains (reserve store of proteins) but are free of starch. Sucrose is the main sugar in subterraneous storage organs (Hegnauer 1978).

The Umbelliferae is a family of eminent economic importance. Its uses involve storage roots *(Bunium bulbocastanum, Daucus cauota, Lomatium* sp., *Pastinaca sativa),* vegetables *(Apium graveolens, Foeniculum vulgare),* kitchen herbs *(Anethum graveolens, Anthriscus cerefolium, Petroselinum crispum, Levisticum officinale),* aromatic seed *(Carum carvi, Coriandrum sativum, Cuminum cyminum),* numerous medicinal and poisonous plants *(Conium maculatum, Ferula* spp., *Oenanthe* spp.) and ornamentals *(Eryngium giganteum, Ferula* spp., *Heracleum* spp.) (Heywood 1978; Kunkel 984).

6.2 Genus *Arracacia* Bancroft

Arracacia BANCROFT, Trans. Agr. Hort. Soc. Jamaica 1825: 5 (1825).

Perennial or biennial, stout to slender, glabrous or pubescent, erect, caulescent, branched or simple herbs from taproots or tubers. Leaves petiolate, alternate or some opposite, pinnately or ternately divided with large leaflets, to decompound with linear to filiform ultimate divisions. Petioles sheathing at base. Inflorescence of lax to compact, usually pedunculate compound umbels. Involucre usually 0. Rays numerous to few, spreading-ascending to divaricate and reflexed. Involucel bractlets few, narrow, longer or shorter than the flowers and fruit, or 0. Calyx teeth 0; petals oblanceolate to obovate with a narrower inflexed apex, yellow, purple (maroon), or white; styles slender to short, erect, spreading or reflexed. Stylopodium conic and conspicuous or depressed and indistinct. Carpophore bifid to deeply 2-parted, flat or terete. Fruit lanceolate or oblong to ovoid, compressed laterally, usually narrowed toward apex, rounded at base; mericarps subterete, glabrous or pubescent; ribs prominent, acute or obtuse, or filiform and indistinct; vittae 1 to several in the intervals, 2 to several on the commissure; seed face usually sulcate or concave.

Arracacia Bancroft is a genus of about 30 species, extending from Mexico and Central America to Peru and Bolivia (Mathias and Constance 1976). The Mexican species are described in Mathias and Constance (1944, 1968, 1973) and Constance and Affolter (1995a, 1995b). *Arracacia xanthorrhiza* is the only cultivated species.

According to Constance and Affolter (1995b), the genus occupies a position central to a number of New World apioid genera, such as *Tauschia, Coaxana, Coulterophytum, Myrrhidendron* and *Neonelsonia,* all of which have been confused with it. The authors conclude that "unsuccessful attempts to define *Arracacia* to the complete exclusion of all these other genera" are more than a century old and that the generic delimitation of *Arracacia* has not been solved yet.

Efforts to properly define species within *Arracacia* have been hampered by the lack of appropriate herbarium material and cytological and field studies. The inadequacy of this situation has changed little since Constance wrote in 1949: "Many of the collections are immature or lack significant structures; others are not readily referable to any described entity but are scarcely adequate for the typification of a new one" (Constance 1949). Mature fruits, which are important in the systematics of the Umbelliferae, are often lacking in herbarium material. Germplasm collectors should therefore seek to include such material in their collections. From the viewpoint of the present paper, it is particularly regrettable that, with few exceptions, botanists have not included root material in their voucher specimens, a problem that greatly impairs the analysis of biosystematic relationships to the cultivated arracacha. On the other hand, germplasm collectors have seldom made herbarium vouchers, so that only fragmentary cultivated material is available in herbaria (Castillo and Hermann 1995).

6.2.1 South American species of genus *Arracacia* Bancroft

We consider now nine *Arracacia* species for South America. The geographical distribution of these species is given in Figure 1. The following account of their taxonomy attempts to synthesize the work of Dr Lincoln Constance and the late Dr Mildred E. Mathias, expert taxonomists for the Umbelliferae who published together from the University of California for almost 40 years (Constance 1949; Mathias and Constance 1941, 1955, 1962, 1976). Their work is being continued at Berkeley by Constance and Affolter (1995a, 199510). Although a revision of *Arracacia* is overdue (especially in those entities that show close affinities with the cultivated arracacha), the species descriptions and localities of voucher specimens provided in the literature are compiled here and discussed. Access to these data is difficult in South America and this compilation should provide a useful tool for explorers of the genepool of *Arracacia.* Exsiccatae resulting from recent collections also have been included.

The following species descriptions define all South American *Arracacia* species as caulescent herbs. According to the definition used here, 'caulescent' is a condition where the flowers and fruits arise from a leafy stem with distinct internodes, as opposed to the 'acaulescent' condition, where the flowers and fruits emerge directly from a basal leaf rosette (Dr L. Constance, 1996, pers. comm.). In that sense, all South American taxa of *Arracacia* are indeed caulescent. However, this definition obscures significant differences in growth habit and phenology in this genus and current taxonomies do not take into account the diagnostic value of these differences which will be briefly explained.

The shoots of South American *Arracacia* species grow from perennial roots that are either woody, wide-ranging and rarely surpassing 1-2 cm in diameter, or tuberous, tapering and often more than 4 cm thick at their base. The shoot systems of species with woody roots, such as those of *A. elata* and *A. moschata,* are of indeterminate growth. Consequently, their shoots are often over 3 m long and can be seen sprawling over (disturbed) roadside vegetation. The habitats of these species are mostly in temporarily moist or perhumid montane forests (>3000 m altitude; Fig. 15). The inflorescences are borne laterally on distal shoot sections. The plants resprout from basal nodes and they will display synchronously vegetative, flowering and fruiting shoots throughout the year (except for extremely dry periods).

The plant habits and phenologies of tuberous species (*A. xanthorrhiza, A. andina, A. equatorialis)* are quite distinct. They result from adaptation to warmer and seasonally arid habitats at lower altitudes (below 3000 m). A rootstock consisting of the greatly enlarged and starchy root and compressed stem structures attached to it at soil surface serves as a storage organ allowing the plant to survive rainless periods of up to 8 months during which all aerial plant parts perish. During the rainy season 'rosettes' of large and petioled leaves emerge from the rootstock. In

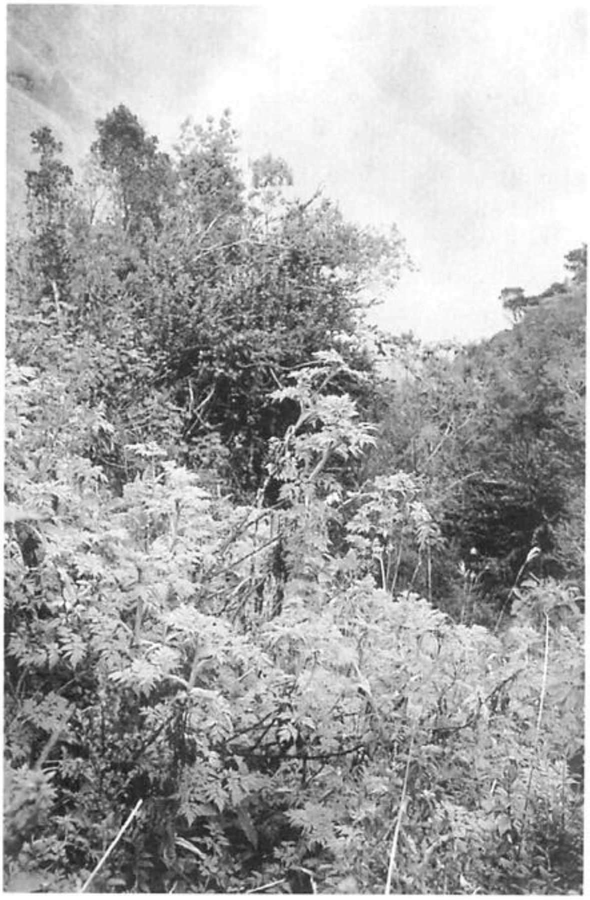

Fig. 15. *Arracacia elata* in páramo vegetation in Ecuador (western slopes of Mount Atacazo, Pichincha; 3550 m altitude, 0°19'57"S, 78o37'31"W, *Hermann, Vásconez & Montalvo 1451;* photograph: 30 October 1996).

plants beyond a certain size, also one to several generative shoots of determinate growth can develop. Each of them bears several inflorescences (umbels). Leaves on the generative shoot are much smaller and have reduced petioles. The development of vegetative leaf rosettes and generative shoots is synchronous in *A. andina* and *A. xanthorrhiza.* In greenhouse material of *A. equatorialis,* the formation of the generative shoot often precedes vegetative growth. This species and *A. andina* display pronounced dormancy of the rootstock, a trait which is absent in cultivated arracacha.

6.2.1.1 *Arracacia colombiana* Constance & Affolter, Brittonia 47: 322-323 (1995)
Rather slender, caulescent, branching, herbaceous, the foliage and inflorescence sparsely scaberulous to hispidulous, to 1 m tall, from woody roots; leaves ovate, 10-15 cm diameter, biternate or ternate-pinnate, the leaflets ovate, 2-5 cm long, 1-3 cm broad, acute to obtuse, rounded or cuneate at base, mucronulate-serrate, scaberulous to hispidulous on the veins beneath; petiole 10-15 cm long, the petiole and petiolules without definite callous thickenings but usually papillose at the main junctures; cauline leaves reduced upward with somewhat dilated oblong to oval scarious sheaths, the upper leaves wholly sheathing; umbels pedunculate, the peduncles 5-12 cm long, scaberulous-hispidulous at apex; involucre absent or of 1 or 2 foliaceous bracts; rays 10-25, the 3-5 fertile rays 3.5-7 cm long, the staminate filiform, much shorter, all spreading-ascending; umbellets about 20-flowered, only 2 or 3 flowers perfect, the mature pedicels (3) 8-20 mm long, filiform, spreading; involucel of about 5 linear, entire, unequal bractlets 3-8 mm long, shorter than flowers and fruit; flowers yellow; calyx absent; petals oblong to obovate, l-veined, vein sometimes branched below apex, with a narrow inflexed apex; stylopodium low conical, the styles about 1 mm long, spreading or reflexed; carpophore bipartite, the halves slender, erect; fruit ovoid-cordate, 3-5 mm long, 4-5 mm broad; little narrowed at apex, cordate at base, the mericarps subterete, glabrous, the ribs low, filiform; vittae rather large, 2 or 3 in the intervals, 4-6 on commissure; seed face deeply sulcate.
List of exsiccatae: **COLOMBIA. Cundinamarca:** En areas abiertas y en monte muy denso, suelos ricos, arenosos, Cordillera Oriental, entre Bogotá y La Calera, 2650-3000 m, 27 Nov 1947, *Barkley, García-Barriga & Vanegas 17C752* (Holotype: COL!; Isotypes: UC!, US!). — Sibaté (2-4 mi S), 13-15 Oct 1917, *Pennell 2452* (paratype, F, K, MO, NY, UC, US and US photo # 230). — **Meta:** Río Arroz well above confluence of Quebrada Pedregal, 29 Aug 1943, *Fosberg* 20915 (US).

This recently described species from a limited geographic range in Colombia is similar to *Neonelsonia acuminata* and the Mexican *Arracacia filipis.* Whether this is a 'good' species will be seen when more material and especially fully mature specimens become available.

6.2.1.2 *Arracacia tillettii* Constance & Affolter, Brittonia 47: 324-327 (1995)
Stout, caulescent, branching, parsley-scented, the foliage and inflorescence sparsely tomentulous, to 1 m tall, from a thick taproot; leaves thick membranous, triangular-

ovate, 10-25 cm diameter, 2-3 ternate or ternate-pinnate, the leaflets lanceolate to ovate-lanceolate, 5-8 cm long, l-3.5 cm broad, acute or acuminate, cuneate, rather coarsely serrate and occasionally lobed or incised, paler and prominently reticulate-veined and scaberulous beneath; petiole 20-35 cm long, both petioles and petiolules papillose at the main junctures, sheathing, the lower third of sheath lustrous near-white; cauline leaves reduced upward with somewhat dilated oblong scarious sheaths, the upper wholly sheathing; umbels pedunculate (or umbels sometimes sessile), the peduncles 5-15 (20) cm long, tomentulous at apex; involucre of 3-5 linear to ovate-lanceolate entire to 3-lobed bracts 5-20 mm long; rays 15-20, the 8-10 fertile rays 4-10 cm long, the staminate filiform and much shorter, all spreading-ascending; umbellets 15-25-flowered, the mature pedicels to 10 mm long, spreading; involucel of about 5 linear to lanceolate, entire or few-lobed bractlets 2-5 mm long, shorter than flowers and fruit; flowers light yellowish green, the petals oblong-oval; stylopodium low conical, the styles spreading, about 1 mm long; carpophore bipartite; immature fruit ovoid-elliptical, 4-5 mm long, 3-4 mm broad, obtuse at apex, rounded at base, glabrous, the ribs narrowly winged (?); vittae and seed face not seen.

List of exsiccatae: **COLOMBIA. Guajira:** Sierra de Perijá, Cerro Pintada, 3200 m, 26 Apr 1987, *Cuadros & Gentry 3543* (paratype, JBGP, MO, UC). — **VENEZUELA. Zulia:** Distr. Maracaibo, Campamento 'Monte Viruela' (10°25' ca. 13" N, 72° 52' ca. 42" W), on tepuí-like limestone massif 5 x 2.5 km on international boundary, Serranía de Valledupar, Sierra de Perijá, ca. 3100 m, 21-28 Jul 1974, *Tillett 747-1194* (Holotype: VEN!; Isotypes: COL!, MO!, NY!, UC!).

This species has recently been described on the basis of two collections from an inaccessible area in the Serrania de Perijá near the border between Venezuela and Colombia. According to Constance and Affolter (1995b), it is difficult to assign generically, partly because of a lack of mature fruit. *Arracacia tillettii* has affinities with *Myrrhidendron* and its isodiametric fruit recalls *Neonelsonia.* Carpologically, A. *tillettii* is very similar to *A. colombiana.*

6.2.1.3 *Arracacia moschata* (Kunth) DC., Prodr. 4: 244 (1830)

Conium moschatum Kunth in H.B.K., Nov. Gen & Sp. 5: 12, pl. 430 (1821).

Plants stout, caulescent, branching, 0.5-2 m tall, the foliage glabrous, the inflorescence scaberulous, from tuberous roots. Leaves ovate, 10-30 cm long, 8-15 cm broad, bipinnate or ternate-pinnate, the leaflets ovate-oblong to ovate, acute, 2-5 cm long, 1-3 cm broad, spinulose-serrate and incised to pinnatifid toward base, paler beneath, squamulose-tufted on the rachis above. Petioles 10-20 cm long. Cauline leaves with oblong inflated sheaths. Inflorescence branching, the peduncles axillary. Involucre usually 0. Rays 10-25, rather stout, spreading-ascending or spreading, scaberulous, 5-13 cm long. Involucel of 3-8 linear to lanceolate, entire or few-toothed bractlets 6-15 mm long. Petals maroon (rarely yellow), oval; styles slender, the stylopodium conical. Pedicels 10-30 mm long, scaberulous. Carpophore bifid ca. half its length.

Fruit lance-ovoid, 6-8 mm long, 3-4 mm broad, the ribs prominent, acute; vittae solitary to several in the intervals, usually 4 on the commissure. (Description taken from Mathias and Constance 1976.)

List of exsiccatae: **ECUADOR. — Azuay:** "Crescit in frigidis Provinciae de los Patos, prope Teindala, 1400 hex. ", *Humboldt & Bonpland 2163* (P. holotype). — **Bolívar:** Canton Guaranda, parroguia Salinas, en Las Tres Mercedes, a 4.8 km desde Salinas hacia Guanjo, 3200 m, 10 May 1994, *Tapia & Cazar* 33 (UC). — **Carchi:** 10 km de El Angel hacia Tulcán en la Panamericana antigua, antes de llegar a los frailejones, 3000-3300 m, 3 Feb 1995, *Hermann & Korntheuer* 1373 (UC) — El Frailejón on road Tulcán-El Carmelo, 3300 m, 6 Mar 1974, *Harling & Andersson* 12518 (NY). — Julio Andrade-Playón de San Francisco road, Cochaseca, 6 July 1978, *Boeke & Jaramillo 2363* (NY). — Las Peñas, between la Rinconada and San Gabriel, 3150 m, *Asplund 7182* (S, UC). — "Hauca & Tusa", 2700-3000 m, *Lehmann 4675* (K). - Ca. 8 km S of Tulcán, 2500 m, *Hitchcock 21005* (GH, NY, US). — Páramo del Angel, 3400 m, *Sparre 14241* (S). —Road Tulcán-El Pun, 3500 m, *Mexía 7580* (UC, US). — **Cotopaxi:** Road Quevedo-Latacunga, Zumbagua, 3500 m, *Harling, Storm & Ström 8906* (GB). — **Imbabura:** Mojanda, ca. 10 km SSW of Otavalo, 2900-3150 m, *Sparre 13462* (S). — Mojanda, on road Otavalo-Minas, 3200 m, *Sparre 16823* (S). — Cerro Cotacachi above Lago Cuicocha, ca. 3300 m, *Asplund 20247* (S). — Sine loco, *Sodiro 80, 80/17* (Q). — **Napo:** Near Archidona, *Jameson 724* (BM). — **Pichincha:** Quito, *Jameson 30* (BM, W). — Quitensian Andes, *Jameson s.n.* (K). — Cerro Pichincha, *Jameson s.n.* (US); *Hall 40* (K); *Benoist 2423* (P, UC). — Cráter de Pululahua, N of Quito, ca. 2800 m, *Barclay, Juajibioy & Tinajero 7901* (UC). — Road Quito-Santo Domingo de los Colorados, km 46, 2000 m, *Dodson & Thien 1064* (LA, WIS).— **Tungurahua:** Road Paso-Ambato, near Río Ambato, 2850 m, *Heinrichs 71* (G, M, NY). — San Fernando, Ambato-Guaranda, km 12, 3300 m, *Sparre 18410* (S). — **Prov. unknown:** Sine loco, *Spruce 5794* (BM, NY); *Jameson 30* (K).

This species is, with *Arracacia xanthorrhiza,* one of the two properly referred classical species in the genus. *Arracacia moschata* is a well-defined taxonomical entity and can be easily recognized because of its distinctive (spinulose-serrate) leaf and seed shape (Fig. 16). The seeds, and to a lesser extent the leaves, have a pleasant umbelliferous fragrance, somewhat reminiscent of the resinous odour of certain conifers and *Citrus.*

It is common in the páramos of central and especially northern Ecuador, on both sides of the Cordillera, between 3000 and 3300 m altitude. However, it has not yet been collected in Loja and it seems to be absent from Peru. *Arracacia moschata* might also occur in southern Colombia, in habitats similar to the ones in which the species is common in northern Ecuador.

I have seen large populations of this species in Carchi (*Hermann & Korntheuer 1373*) (Fig. 16), where it occurs in wet habitats regularly exposed to fog and mist. In these situations, *A. moschata* is associated with *Coriaria,* Ericaceae and *Espeletium.*

Fig. 16. Herbarium specimen of *Arracacia moschata* collected in Carchi, Ecuador. (Lot.: 10 km de El Angel hacia Tulcán en la Panamericana antigua, 0°40' N, 77°53' W, 3300 m asl, 3 February 1995, vern. 'sacha zanahoria', *Hermann & Korntheuer 1373,* UC.) Scale: 10 cm.

Its shoots, which emerge from a lignified and compact rootstock, reach several meters in length and sprawl over roadside thickets. The woody roots can surpass 1 m in length but rarely exceed 2 cm in thickness *(Tapia & Cazav 33).*

6.2.1.4 *Arracacia elata* Wolff, Bot. Jahrb. 40: 304 (1908)

Arracacia Pennellii Constance, Bull. Torrey Bot. Club 76: 71 (1949).

Arracacia Wigginsii Constance, ibid. 43.

Plants stout, caulescent, branching, vining or scrambling, 1-8 m long, the foliage glabrous, minutely scaberulous in the inflorescence, from tuberous roots. Leaves triangular-ovate to ovate, 8-30 cm long, 10-25 cm broad, ternate or 1- or 2-pinnate, the leaflets lanceolate to ovate-lanceolate, acute or acuminate, 2-6 cm long, 0.8-4 cm broad, spinulose-serrate and usually incised or lobed towards base, paler beneath, squamulose-tufted on the rachis above. Petioles 15-45 cm long. Cauline leaves with oblong inflated sheaths. Inflorescence branching, the peduncles terminal and axillary. Involucre usually 0. Rays 15-30, slender, spreading-ascending, scaberulous, 3-7.5 cm long. Involucel of 3-10 linear to lanceolate, entire to toothed bractlets 2-15 mm long. Petals greenish-yellow, oval to obovate; styles slender, the stylopodium conical. Pedicels 3-8 mm long, scaberulous. Carpophore bifid, ca. l/4 its length. Fruit ovoid to oblong-ovoid, tapering at apex, 4-8 mm long, 3-5 mm broad, the ribs prominent, obtuse; vittae solitary to several in the intervals, usually 2 or 4 on commissure.

List of exsiccatae: **COLOMBIA. Cundinamarca:** Río San Francisco, above Bogotá, 13 Sep 1917, *Pennell 1932* (NY type of *A. pennellii* Constance, GH, US). - Macizo de Bogotá, Quebrada del Rosal, 3000 m, 29 June 1939, Cuatrecasas 5700 (US). - **Norte de Santander:** Between Mutiscua and Pamplona, 3400 m, 23 Feb 1927, *Killip & Smith 19728* (GH, NY, US). - **Santander:** Cordillera Oriental, páramo de Santurbán, entre Cuesta Boba y el extremo oeste, 3400 m, 27 July 1940 *Cuatrecasas & Barriga 10314* (US). - Páramo de Romeral, 3800-4100 m, 29-30 Jan 1927, *Killip & Smith 18541* (GH, NY, US). - Vicinity of Vetas, thickets along stream, 3100-3200 m, 16 Jan 1927, *Killip & Smith 17347* (GH, MO, NY, US). — Quebrada de País, north of La Baja, dense forest, ca. 3200 m, 31 Jan 1927, *Killip & Smith 18781* (GH, MO, NY, US). **—ECUADOR. Azuay:** Cruz Pampa region above Baños (ca. 15 km SW of Cuenca), 9000-10000 ft. elev., 29-30 June 1945, *Camp E-3934* (NY). - Panamerican Highway, 65-70 km S of Cuenca, shrubby páramo and roadbanks, 3300-3400 m, 3 Jan 1981, *Balslev 1426* (NY). -Canton Cuenca, Zurucucho, forest edge, 3200 m, 11 Aug 1978, *Boeke, Jaramillo & Narvaez 2631* (NY). - Road Cuenca-Angas, roadside, 3050 m, 28 Dec 1976, *Boeke 664* (NY). — Cerro Soldados (W of Sayausid) below Quinoas, 3400 m, *Harling, Storm & Ström 8762* (GB, UC). — Laguna de Surucuchu, 3100-3200 m, *Sparre 18855* (S). — Pan American Highway 40 km S of Cuenca, 3300 m, *Wiggins 10769* (UC, holotype of *A. wigginsii;* US). — Cruz Pamba region above Baños (ca. 15 km SW of Cuenca), 2750-3050 m, *Giler & Prieto (=Camp E-3934)* (BM, G, K, MO, P, UC, US). — 10 km S of Cumbe, 3000 m, *Harling, Storm & Ström 8013* (GB). — **Cañar:** Road Biblián—Cañar *Harling, Storm & Ström 8621* (GB). — Vicinity of Cañar *Rose & Rose 22715* (US). — Headwaters of

Río Mangán, 20-22 km ENE of Azogues, 3300 m, *Fosberg & Prieto 22818* (UC, US). – **Cotopaxi:** Road Toacazo-Sigchos, 3350 m, 9 July 1996, *Vásconez & Vacas 11.* –Road above Pilaló toward Zumbahua, 3525 m, 11 July 1996, *Vásconez & Vacas 14.* —Western slopes of Cordillera along road Zumbahua-Pilaló, 3400 m, 10 Nov 1996, *Hermann, Vásconez & Jarrín 1471.* — **Pichincha:** 4.5 km de San Juan de Chillogallo a lo largo de la carretera hacia la cumbre de1 Atacazo, 3500 m, 16 Dec 1990, *Hermann 647.* - 10.7 km from San Juan de Chillogallo on road toward Martinez hacienda, 3550 m, 30 Oct 1996, *Hermann, Vásconez & Montalvo 1451.* - Pichincha, SE slope on road to N antenna, roadside, very ashy soil, 3500-3700 m, 21 July 1982, *Clemants, Boeke, Holmgren & Crisafulli 2064* (NY). - San Juan, 3500-3700 m, *Fagerlind & Wibom 1557* (UC). — "Crescit in umbrosis humidis montes Pichincha" 3350 m, *Jameson 281* (Sodiro 610) (Q) — Valle de Lloa (Unguí), *Benoist 2709* (P). — **Prov. unknown:** "In coll. apric. interand. Sanlagua", *Sodiro (2574) 609* (G). **PERU. Amazonas:** "A Chachapoyas orientem versus, inter Tambo Ventillas et Piscohuañuma", 3600 m, *Weberbauer 4423* (type photos: F, GH, UC, US). — Province Chachapoyas, Cerros Calla Calla, west side, 45 km above Balsas, midway on the road to Leimebamba, 3100 m, 19 June 1964, *Hutchison & Wright 5748* (UC, USM, F, NY, MO). – Chachapoyas, uppermost slopes and summit of Cerros de Calla Calla, near km 403-407 of Balsas-Leimebamba road, 3400-3550 m, 18 Aug 1962, Wurdack 1718 (NY). — **Ayacucho:** Choimacota Valley, 3000 m, *Weberbauer 7584* (F. GH, US). — **Cajamarca:** 3500-3800 m, *Vargas 10369.* — Province Hualgayoc, Hacienda Taulis, Río La Quinoa above La Playa, vining 2-3 m, streamsides, *2900* m, 4 Sep 1964, *Hutchison & Von Bismarck 6506* (UC, USM, US, F, NY, MO, K, MICH). — **Cusco:** Province Urubamba, woods, 3000 m, *Rauh & Hirsch 1049* (UC). — **Huánuco:** Province Pachitea, Tambo de Vaca, ca. 12,000 feet, *MacBride 4456* (F, US). — **La Libertad:** Provincia Otuzco, Chilte, Hacienda Llaguén, en quebrada pedregosa, López 615. — **Piura:** In summit area on road to Canchaque, 30-38 km above and west of Huancabamba, 3200-3300 m, vining 4 m through trees, 17 Sep 1964, *Hutchison & Wright 6651* (UC, USM, US, F, NY, MO, K, MICH). — **Puno:** Provincia Carabaya, entre Ayapata y Kahualluyoc, 3595-3800 m, *Vargas 10747.* — **VENEZUELA. Mérida:** La Mucuy, valle de1 río Loro, entre la estación forestal y la laguna, sobre el camino a la Laguna Coromoto, 3200 m y más, *Barclay & Juajibioy 9940* (UC). - Entre las rocas de la quebrada Monte Zerpa, 2700 m, *Bernardi 657* (NY). — Distrito Libertador, Parque National Simón Bolívar, La Mucuy, formaciones leñosas al S y al E de la Laguna Coromoto, 3400 m, 22 Dec 1983, *Pipoly & Aymard 6558* (NY). - Mérida, 16 Feb 1957, Bernardi s.n. (NY).

This vining species is very similar to the preceeding one in general aspect and habitat (bushy páramos), but it is of much wider distribution (Venezuela, Colombia, Ecuador, Peru). It also reaches higher altitudes, especially farther away from the equator as in southern Peru. Its greenish-yellow petals, acuminate leaflets, more ovoid fruits, obtuse fruit ribs as well as the lack of a pronounced fragrance set it apart from *A. moschata.* The woody roots are up to 2 cm thick and spread over large areas (Figs. 17 and 18).

Fig. 17. Herbarium specimen of *Arracacia elata* collected in Pichincha, Ecuador. (Loc.: 4.5 km de San Juan a lo largo de la carretera hacia la cumbre del Atacazo, 0°18' S, 78°36' W, 3500 m asl, 16 December 1990, vern. 'sacha zanahoria', *Hermann 647,* UC.) Scale: 10 cm.

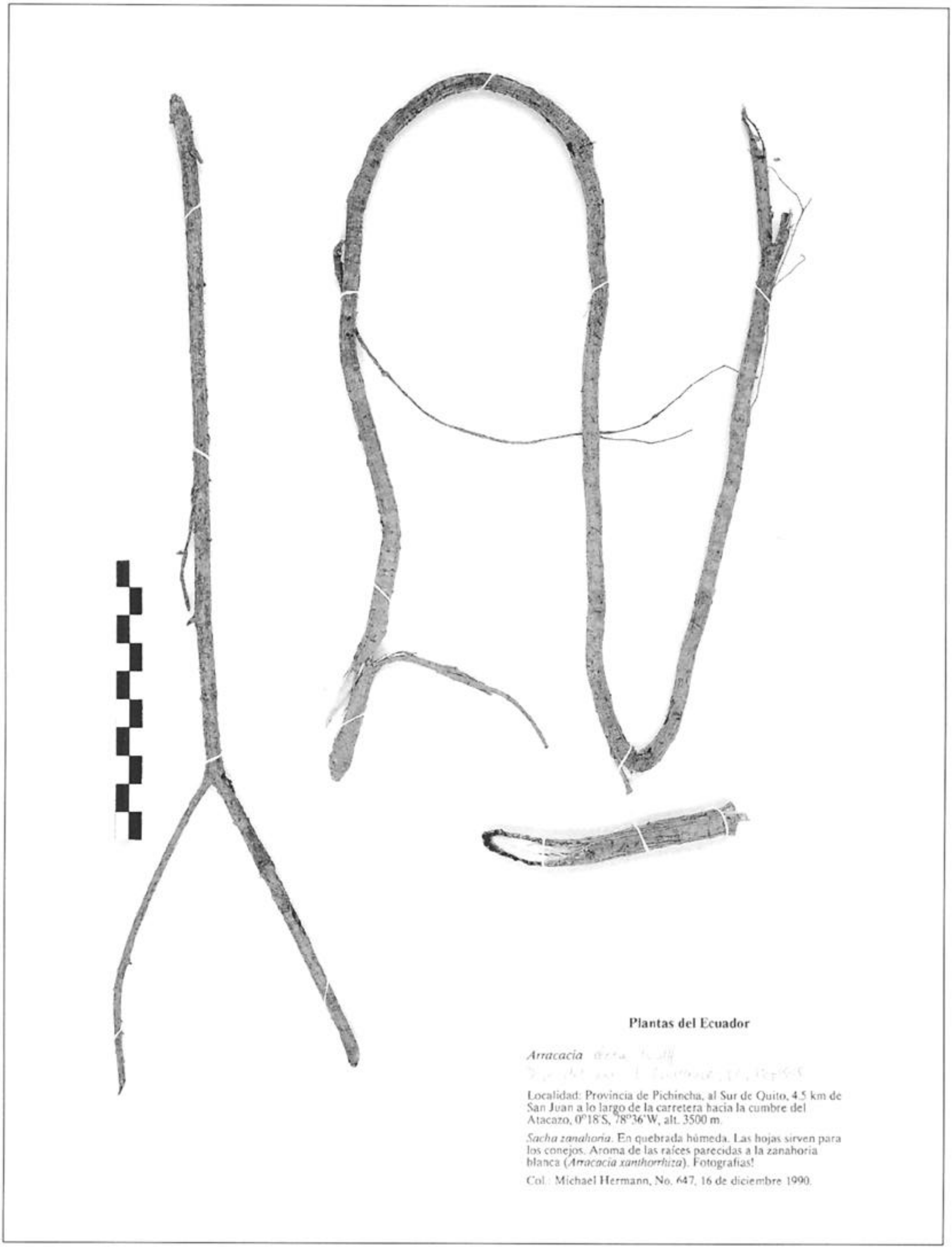

Fig. 18. Roots of *Arracacia elata* (for locality and specimen, see Fig. 17). Scale: 10 cm.

Near Quito, *A. elata* is a very common plant on the western slope of the Atacazo volcano between 3300 and 3550 m altitude, where it is associated with terrestrial orchids, Melastomataceae, Ericaceae, *Vaccinium* spp., *Ottoa oenanthoides* (Umbelliferae), *Lycopodium, Oxalis* spp., *Gunnera* sp., ferns and other plants that indicate high atmospheric humidity (Fig. 15). Here *A. elata* often trails over páramo bush and develops long shoots, often measuring 4 m and more. However, in open sites the plant assumes a bushy habit, as seen in Fig. 15, and is up to 2 m high. The plant is especially frequent in creeks and in other wet soil conditions.

6.2.1.5 *Arracacia xanthorrhiza* Bancroft, Trans. Agr. Hort. Soc. Jamaica 1825: 5 (1825)
Conium Arracacha Hook., Exot. Pl. pl. 152 (1825).
Arracacia esculenta DC., Bibl. Univ. Sci. & Arts 40: 78 (1829).
Bancroftia xanthorrhiza Billb. Linn. Samf. Handl. 1: 40 (1833).
Plants stout, caulescent, 0.5-l.2 m tall, minutely squamulose and scaberulous, from greatly swollen tuberous roots. Leaves broadly ovate, l-3 cm long and broad, biternate or bipinnate, the leaflets ovate-lanceolate to ovate, 4-12 cm long, 1.5-6.5 cm broad, acuminate, mucronate-serrate and coarsely incised or lobed, squamulose or scaberulous. Petioles 8-45 cm long. Cauline leaves with narrow sheaths. Inflorescence branching, the peduncles alternate or whorled; scaberulous at apex. Involucre 0. Rays 5-15, spreading-ascending, 1.5-4 cm long, scaberulous. Involucel of 5-8 setaceous entire bractlets 2-5 mm long. Petals purple or greenish, oval; styles slender, the stylopodium depressed. Pedicels 2-4 mm long. Carpophore 2-parted. Fruit oblong, 10 mm long, 2-3 mm broad, constricted below apex, the ribs prominent, acute; vittae solitary in the intervals, 2 on the commissure.

List of exsiccatae of cultivated or presumably cultivated material: **BOLIVIA. La Paz:** Provincia Larecaja, cultivated near Quiabaya, 55 km de Sorata hacia Consata, 3120-3280 m, 9 Sep 1989, *Hermann 285,289* (NY, LPB-foliage, roots). –Provincia Camacho, Comunidad Queñe, 15 km de Mocomoco hacia Chuma, 3000 m, 13 June 1991, *Hermann, Morales & García 835,836.* – Sorata, 9 Jan 1958, 2697 m, *Mandon 595* (GH), 22 Apr 1940, *Holway & Holway 563* (US-foliage). – Sirupaya, 1800 m, 27 July 1906, *Buchtien 5971* (US-foliage). **– BRAZIL. São Paulo:** São José do Rio Prêto, 1150 m, *Hermann 800.* **– COLOMBIA. Antioquia:** Cordillera Central, alrededores de Medellín, 1560 m, 1 May 1946, *Hodge 6861* (GH). – **Cauca:** Popayán, *Lehmann 407* (GH-flowers). – Cuesta de Tocotá, road from Buenaventura to Cali, Western Cordillera, 1500-1900 m, *Pittier 714* (US). – **Putumayo:** Valle de Sibundoy, ca. 2250 m, 18 Feb 1942, *Schultes 3267* (GH-foliage). **ECUADOR. Loja:** Vicinity of Las Juntas, *Rose, Pachano & Rose 23215* (US-foliage). – Cultivated, West Indies to Peru, and possibly Bolivia. **–Tungurahua:** Ambato, 1918, *Rose 38* (GH, US-photo of foliage). **–PERU. Cusco:** Paruro, Hacienda Araypallpa, 3100 m, 28 July 1937, *Vargas 411* (GH, CUZ). – Colinas de1 Laxaihuamán, 3600 m, Dec 1928, *Herrera 858* (F). – Ollantaytambo, ca. 3000 m, 24 June 1915, *Cook & Gilbert 282* (US-foliage). – San Miguel, Urubamba valley, ca. 1800 m, 26 May 1915, *Cook & Gilbert 934, 935* (US-

foliage). — Cultivated in chacra of Félix Huamán Zúñiga, Nogal Niyoc, Provincia de Calca, 22 km de Paucarpata hacia Colca, 2050 m, 23 Sep 1990, *Hermann, Cruz & Meza 546,547,549* (NY, MOL-foliage, roots).

List of exsiccatae of recently collected wild material (identified by L. Constance): **ECUADOR. Chimborazo:** Cantón Colta, 30 minutos a pie desde Cañihacia Corralpamba, 11 May 1994, *Tapia & Cazar* 43 (UC). — 8 km from Capzol toward Huigra, 1600 m, 17 May 1996, *Hermann & Santos 1410* (UC). — **PERU. Cusco:** Provincia Cusco, bajando de Fierroccata hacia la Granja K'ayra, 3300-3400 m, 12-13 Feb 1991, *Hermann 747, Hermann & Cruz 749,750* (UC, MOL). — Ak'o Moqo, Granja K'ayra, San Jerónimo, camino a Paruro, 3500 m, 10 Dee 1990, *Cruz 108* (MOL) . — Provincia Anta, 22 km de Ancahuasi hacia Limatambo, 2900-3100 m, 14 Feb 1991, *Hermann, Cortés & Alvarez 764* (UC, MOL).

This species is the cultivated arracacha. It is grown all across the Andes (except Argentina) and some mountain ranges in Central America, the Caribbean and southeastern Brazil (Hermann 1991, 1995). According to Friedberg (1978), arracacha is the only umbelliferous domesticate in Peru; no other native umbellifer has been domesticated or used for aromatic properties in this country.

Herbarium specimens used to describe the species are notoriously insufficient, and published descriptions are correspondingly inadequate (Constance 1949). Arracacha is vegetatively propagated and rarely flowers in the Andes, so most herbarium specimens are sterile. None of the older material used by systematists is unquestionably from the wild (see list of exsiccatae) and the species has so far been known only from cultivated material.

The specific epithet *xanthorrhiza* is Greek for 'yellow-rooted' and thus refers to the clones with yellow to yellowish orange flesh preferred in most countries. However, arracacha also has white or ivory-coloured roots; sometimes these show purplish variegations in the tissue surrounding the vascular bundles. Notably, *Arracacia* species with close affinities to arracacha *(A. andina, A. equatorialis)* have white roots only.

Undoubtedly wild collections identified by L. Constance as *A. xanthorrhiza* were only recently made, both in Peru and Ecuador. The Peruvian material (vouchers *Hermann 747; Hermann & Cruz 749,750; Cruz 10; Hermann, Cortés & Alvarez 764)* comes from two provinces in the department of Cusco (Cusco and Anta), where it is locally abundant between 2900 and 3500 m altitude in open or disturbed sites (Figs. 19 and20). Local people refer to this material in their native tongue (Quechua) as *k'ita racacha, k'ita virraca* (= wild arracacha) or *orko racacha* (= mountain arracacha, = high-altitude arracacha). I have grown this plant from original seed in Quito greenhouses and it has invariably shown its biennial nature. After initial slow development, the plant grows into a simple herb with basal leaves that emerge from a rootstock. After about 7-9 months of vegetative growth, true senescence sets in, that is, the leaves will die even under favourable growth conditions. The storage roots are about 4 cm thick

Fig. 19. Herbarium specimen of wild *Arracacia xanthorrhiza* collected in Cusco, Peru. (Lot.: Provincia Anta, 22 km de Ancahuasi hacia Limatambo, 13°28' S, 72°23' W, 2900-3100 m asl, *Hermann, Cortés & Alvarez 764,* MOL, UC.) Scale: 10 cm. This species is the same as vouchers *Hermann 747, 749, 750* and *Cruz 108* from Granja K'ayra, San Jeronimo, near Cusco. In Quechua, this biennial species is referred to as *k'ita racacha* (= wild arracacha) or *orko racacha* (= mountain arracacha, = high-altitude arracacha). Its tuberous and fetid roots are 4 cm thick and 10-20 cm long (see Fig. 21).

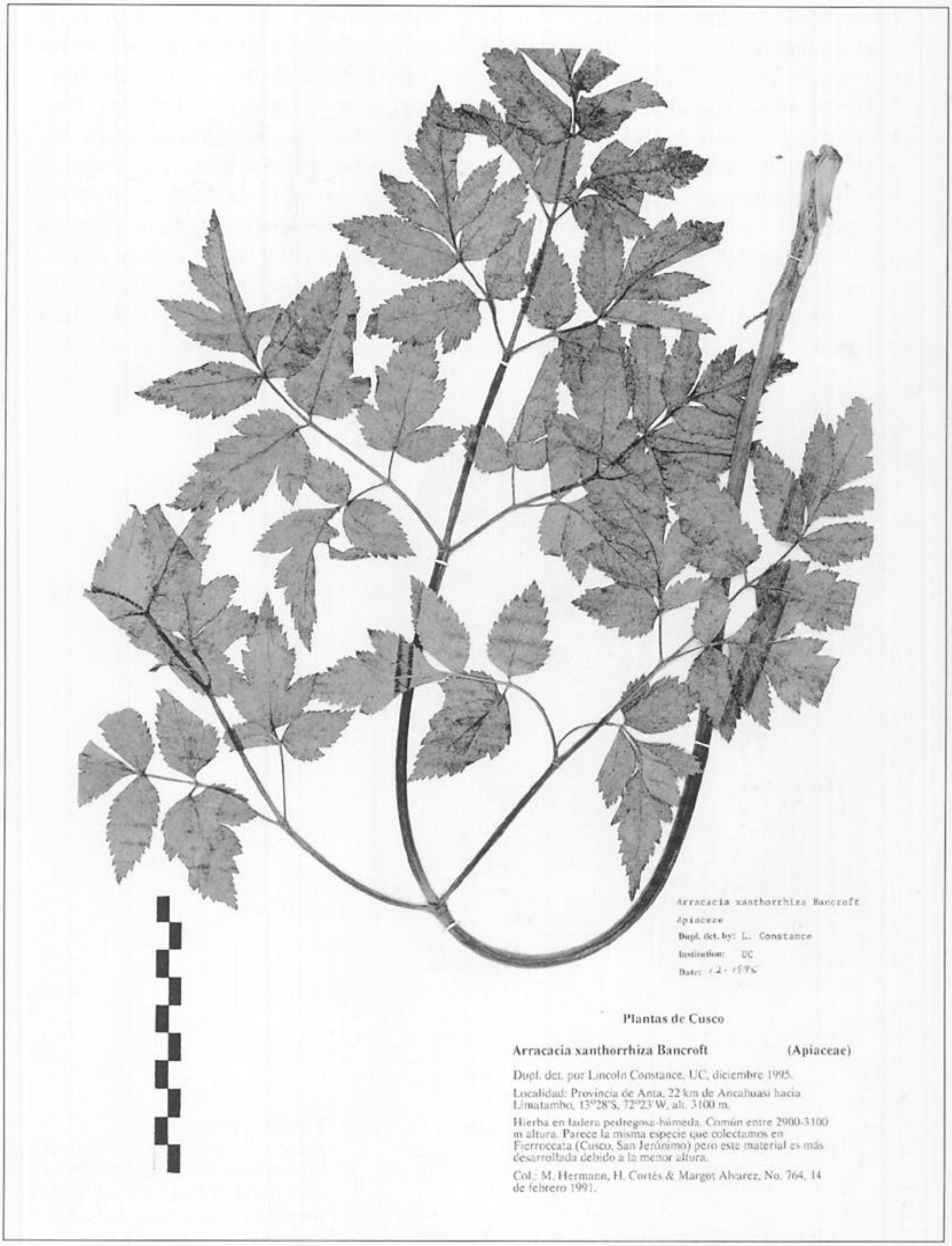

Fig. 20. Leaf of wild *Arracacia xanthorrhiza* (for locality and specimen, see Fig. 19). Scale: 10 cm.

and up to 20 cm long (Fig. 21). Following root dormancy of about 2-3 months, a vigorous generative shoot with several umbels appears from the rootstock and flowers for several months. Then the whole plant, including the rootstock, eventually dies.

The tuberous roots are yellowish and are said to be fed to pigs. However, they have a strong flavour and remain astringent after cooking. As in cultivated arracacha, but to a much higher extent, numerous vessels in the cortex contain an aromatic resin. It is hard to imagine how prehistoric people would have used the root for food, perhaps by roasting it in hot ashes to get rid of the outer and fetid cortex. Unless populations of this variant of *A. xanthorrhiza* with more palatable roots are found, it is unlikely the wild ancestor of the cultivated arracacha. Also its biennial character and the occurrence of this wild species at high altitudes set it apart from cultivated arracacha. Neither Herrera in his Sinopsis de la Flora de1 Cusco (1941) nor

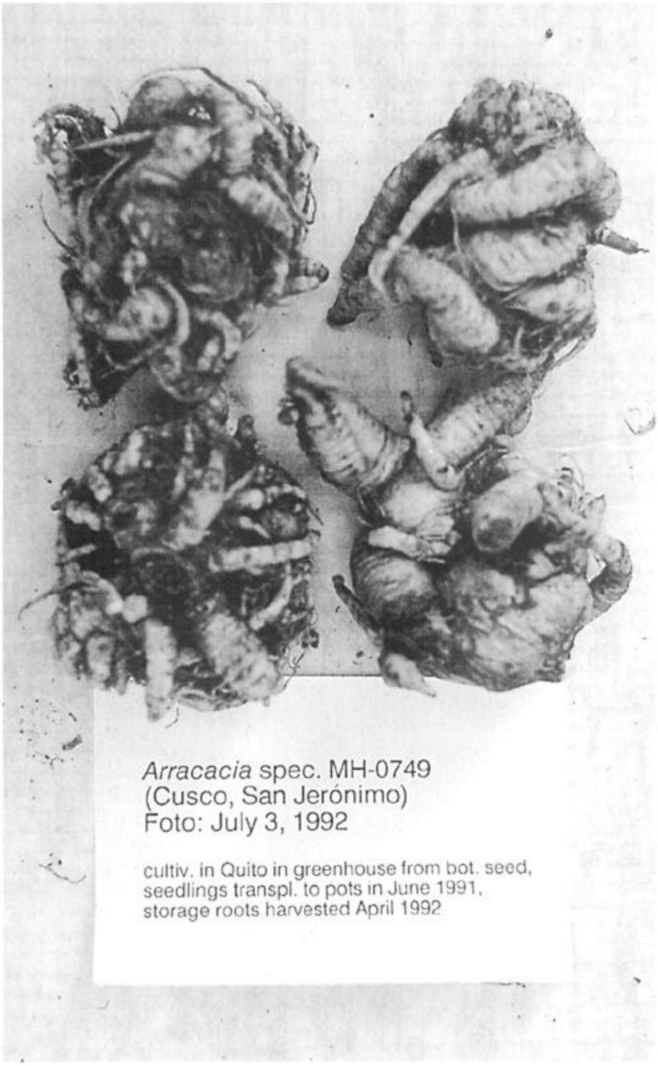

Fig. 21. Storage roots of *Arracacia xanthorrhiza* cultivated in pots from seed collected from wild plants in Cusco, Peru. (Loc.: Provincia Cusco, San Jerónimo, bajando de Fierroccata a la Granja K'ayra, 13°33' S, 71°55' W, 3300 m asl, *Hermann 747)*

Weberbauer in his classic monograph on the Peruvian flora mention this species (Weberbauer 1911). Because of its absence (or dearth) in herbaria, we must conclude that this material is rarer than the situation in Cusco would suggest.

A more likely candidate for the ancestral race from which arracacha might have been domesticated was recently found near Cañi, Chimborazo, Ecuador (voucher *Tapia & Cazar 43).* This material was identified by Dr Constance as *A: xanthorrhiza.* Material with identical root and fruit characteristics is now also available from Huigra and Sibambe in Chimborazo Province *(Hermann & Santos 1410),* and from Bolívar Province. Specimens from the Huigra and Sibambe populations (vouchers *Asplund 15452, Fosberg & Giller 22581),* however, have previously been assigned to *Arracacia andina* (Mathias and Constance 1976). This illustrates the difficulty of differentiating *A. andina* from *A. xanthorrhiza.* Indeed, Dr Constance, in a pers. comm. to me (1995), wrote: "Since publication of the Flora of Ecuador, I concluded that *Arracucia andina* Rusby is too similar to *A. xanthorrhiza* Bancroft to be regarded as specifically distinct".

Figure 22 shows a herbarium voucher of the recently made collection from the Sibambe-Huigra population *(Hermann & Santos 1410).* This population is distributed between 1450 and 2500 m altitude in the canyons of the Chanchán River and its affluent Río Sibambe. Near Chanchán, at 1600 m altitude, it is a frequent plant on road banks or other disturbed sites with sandy or stony soils of high alkalinity (pH = 8-8.8). Annual rainfall is around 500 mm, of which only 100 mm falls during the dry season from June to November. The resulting xerophytic vegetation (Fig. 23A) is classified as 'monte espinoso pre-montano' in the modified Holdridge system (Cañadas 1983). It is characterized by thorny bushes, *Agave, Opuntia* and some columnar cacti. Wild crop relatives of this vegetation include *Cyclnthera, Phaseolus vulgaris* and *Psidium.* In the cantons of San Miguel and Guaranda in Bolívar province, the plant can be found in moister habitats and soils of neutral or slightly acid pH (6-7).

This *Arracacia* species has a striking similarity with cultivated arracacha in terms of morphology (root, leaf and generative characters), life form (perennial) and altitudinal distribution, yet it is sufficiently distinct to be recognized as wild as opposed to merely escaped from cultivation. Local informants interviewed in villages in Chimborazo and Bolívar, especially women, recognized it as a medicinal, the roots or leaves of which are commonly employed in potions to induce *post partum* placental elimination, in both humans and domestic animals.

In May 1996, this wild arracacha was found above Chanchán in a variety of growth stages ranging from single-leaved seedling plants left from the preceding rainy season to juvenile-vegetative and to mature-generative plants with tubers weighing up to 3 kg, the latter presumably being several years old (Fig. 23C). The seedling forms a thick taproot from which, in the juvenile plant, several tuberous roots emerge. These swell into storage roots which taper up to 1 m in length and can be up to 8 cm thick at their base. These are difficult to recover entirely as they break easily. Apparently, taproots and storage roots are perennial as is the plant. As in cultivated arracacha, a 'crown' of cormel-like structures develops on top of the taproot (Fig. 23D). The cormels are not as pronounced as in cultivated arracacha,

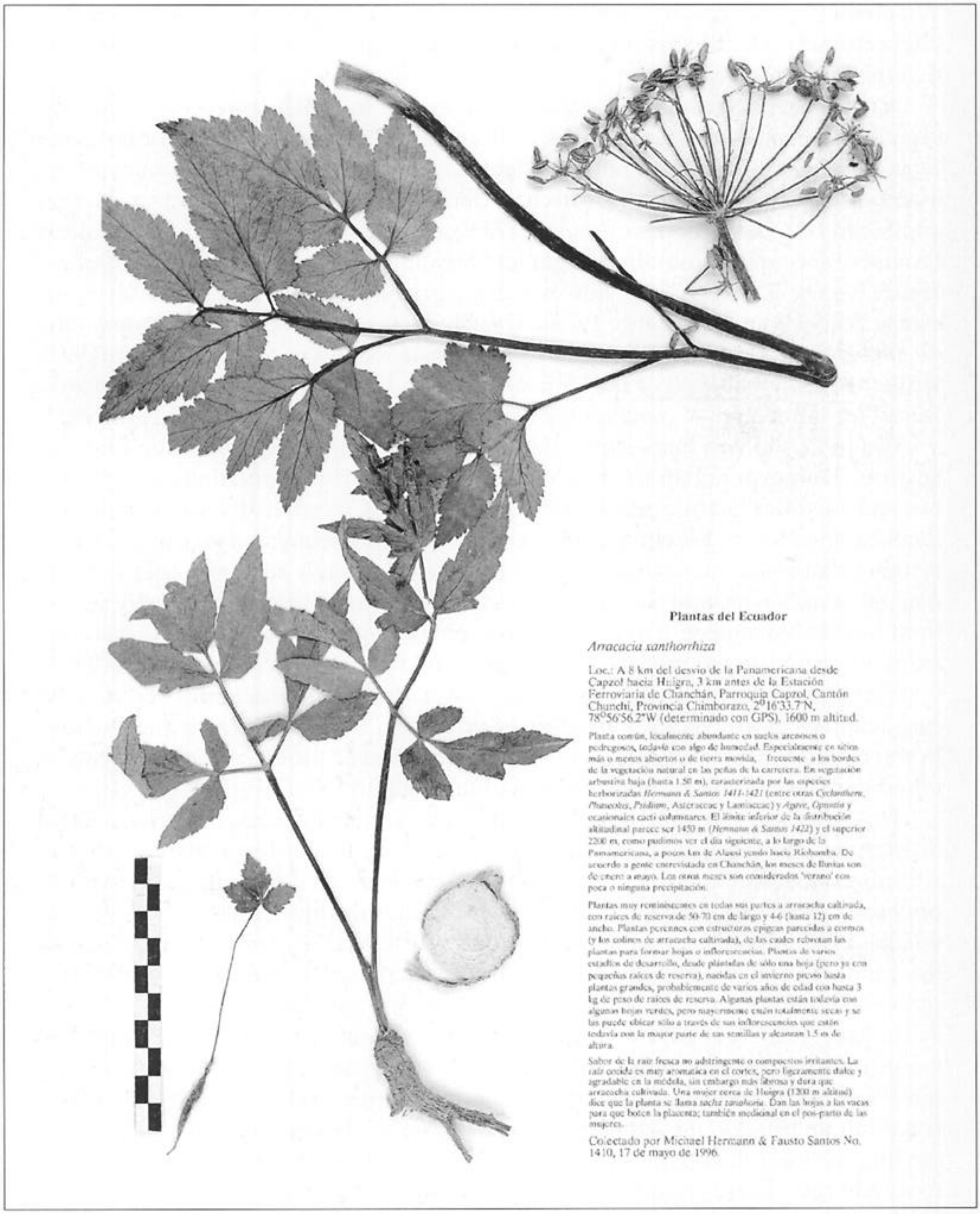

Fig. 22. Herbarium specimen of wild *Arracacia xanthorrhiza* collected in Chimborazo, Ecuador. (Loc.: Cantón Chunchi, on road Capzol-Huigra, 3 km before train station of Chanchán, 17 May 1996, vern. 'sacha zanahoria', 2°16'33.7" S, 78°56'56.2" W, 1600 m asl, *Hermann & Santos 1410,* UC.) Scale: 10 cm.

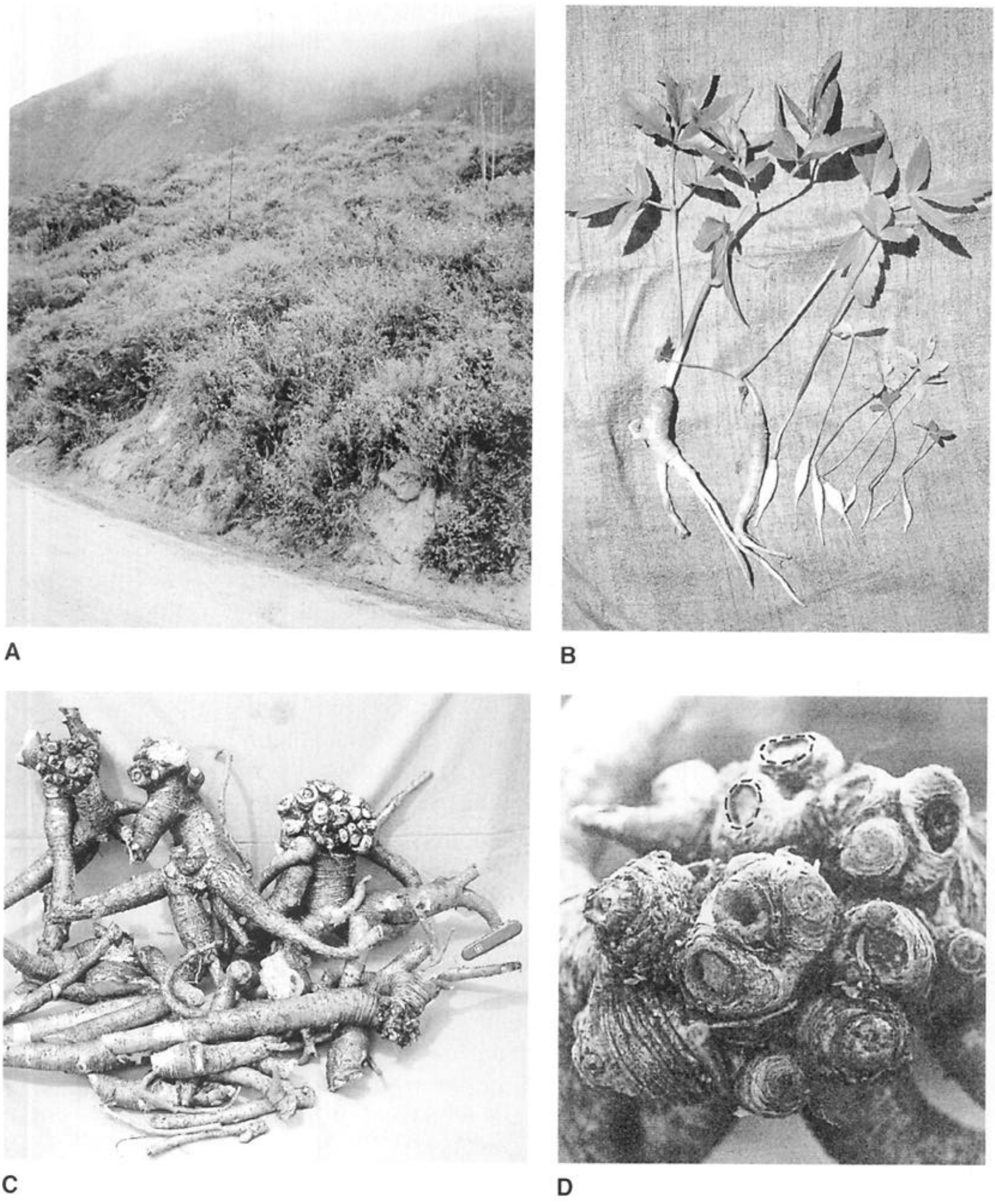

Fig. 23. Collecting site and storage root of *Arracacia xanthorrhiza* voucher *Hermann & Santos 1410.* (Loc.: Ecuador, Cantón Chunchi, on road Capzol-Huigra, 3 km before train station of Chanchán, 2°16'33.7"S, 78°56'56.2"W, 1600 m asl) **A:** collecting site on road bank, note dry bush ('estepa espinosa montano bajo'); **B:** juvenile (vegetative) plants; **C:** typical storage roots weighing 1-3 kg per plant; **D:** crown of rootstock from which the plant regenerates in the rainy season (trace drawing indicates scars left from generative shoots) (Photographs: May 1996).

but rather are depressed and rise only to the soil surface. The cormel is homologous to the propagule in cultivated arracacha, which is called *colino* or *hijuelo* in Spanish. It is a solid stem structure, consisting of starchy storage parenchyma, but it has distinct internodes and nodes at which the leaves are inserted. Some of the otherwise vegetative corms develop generative stalks, as indicated by the trace drawing (Fig. 23D), which emphasizes scars left by such stalks. Leaf shape-and generative characters, such as flower and fruit morphology, as well as seed fragrance are very similar to those of cultivated arracacha.

The cooked root is fibrous, but it has a bland, slightly sweet and umbelliferous taste. The content of physically extractable starch is 14-16% of the fresh root weight. Although not as pleasant to eat as cultivated arracacha (the flesh remains firm after extended cooking and is more fibrous), this wild arracacha does not have the astringent principles of the Peruvian material described above, and it would therefore have made an attractive caloric food source for prehistoric gatherers. The plant can easily be spotted because of its conspicuous generative shoots, which are up to 1.5 m high, and, as a rule of thumb, the larger ones are associated with bigger roots. Equipped with a digging tool, a person can harvest 10-20 kg of roots in half an hour in abundant plant populations. Human intervention might have been beneficial to maintaining or even increasing plant populations as seeds shed from harvested plants would have germinated in freshly disturbed sites, where the plant occurs naturally. Thus early people might have unconsciously maintained populations for sustainable exploitation. Such people would probably not have used the crowns, which trap dead leaves and soil and account for only 10% of total root weight. Presumably, the crown would have been discarded during food preparation. It may have sprouted on garbage heaps, thus eventually leading to the discovery of the most convenient propagation method, which is the replanting of the crown or parts of it.

To my knowledge, the Huigra-Sibambe population is an entity that resembles cultivated arracacha more than any other wild *Arracacia* germplasm described so far. It might offer potential for introgressing drought resistance, desiccation resistance of the roots and improved dry-matter partitioning (into the storage roots versus the crown) into the cultivated background. Future explorations should concentrate on mesothermic and periodically dry valleys adjacent to Chimborazo and Bolivar. Such habitats occur across the northern and central Andes, and the *Arracacia* germplasm in question here might well extend northward into southern Colombia and southward into Peru. In this context, a brief mention of wild arracacha used as emergency food and for "helping women with childbirth" in Cajamarca (adjacent to Ecuador) is most noteworthy (Seminario 1995).

6.2.1.6 *Arracacia andina* Britton, Bull. Torrey Bot. Club 18: 37 (1908). Fig. 4

Plants stout, caulescent, 0.3-1.0 m tall, the foliage and inflorescence minutely squamulose or scaberulous, from a tuberous base. Leaves triangular-ovate to ovate, l0-30 cm long, 15-30 cm broad, 1-2-pinnate, the leaflets lanceolate to ovate, acute to acuminate, 2-10 cm long, l-5 cm broad, mucronate-serrate and usually shallowly

incised or lobed, sparsely squamulose to hispidulous. Petioles 15-35 cm long. Cauline leaves with moderately inflated sheaths. Inflorescence branching, the peduncles usually whorled, scaberulous at apex. Involucre usually 0. Rays 8-25, slender, spreading-ascending, 2-8 cm long, scaberulous. Involucel of 6-9 linear entire bractlets 2-9 mm long. Petals purple, obovate; styles slender, the stylopodium depressed. Pedicels 2-10 mm long. Carpophore 2-parted. Fruit ovoid, 6-11 mm long, 4-5 mm broad, obtuse, the ribs very prominent, acute; vittae l-3 in the intervals, 4-6 on the commissure.

List of exsiccatae: **BOLIVIA.** "Plantae Bolivianae", *Bang 2839* (F, GH, MO, NY, US). - Ingenio de1 Ovo, Rusby 776 (F, NY-TYPE, US). — **ECUADOR.** — **Cañar:** Between Tambo and Suscal, valley of Río Cañar, 2000-3000 m, *Camp E-2778* (UC). — **Chimborazo:** Sibambe, canyon of Río Sibambe, affl. of Río Chanchan, 2460-2550 m, 28 Jan 1945, *Fosberg & Giller 22581* (NY, UC, US). — Huigra, *Asplund 15452* (S). — **Cañar:** Between Tambo and Suscal, valley of Río Cañar, 2000-3000 m, *Camp E-2778* (UC). — **PERU. Cajamarca:** *Sagástegui & Mostacero 9124* (MO) (specimen cited in Brako and Zarucchi 1993).

Constance maintained this as a separate species on the basis of its broader leaflets and fruit characteristics (Constance 1949), which differentiate it from its closest relative *A. xanthorrhiza.* However, the similarities between the two species have been discussed in the foregoing account. Perhaps what has to date been considered *A. andina* is the wild arracacha. Only a revision and more comprehensive material will show whether this entity is conspecific with *A. xanthorrhiza,* in which case the binomial *A. andina* would have to be reduced to synonymy.

6.2.1.7 *Arracacia equatorialis* Constance, Bull. Torrey Bot. Club 76: 46 (1949)

Plants slender, caulescent, 0.4-0.8 m tall, the foliage somewhat squamulose, from tuberous roots. Leaves triangular-ovate, 6-30 cm long, 7-18 cm broad, biternate or bipinnate, the leaflets ovate to lanceolate, 2-8 cm long, 0.5-3 cm broad, acute or acuminate, mucronate-serrate and usually deeply incised or lobed, squamulose to glabrate. Petioles 10-20 cm long. Cauline leaves with scarious, strongly inflated sheaths. Inflorescence branching, the peduncles usually whorled. Involucre usually 0. Rays 6-15, slender, ascending, 1.5-4 cm long, scaberulous. Involucel of 3-6 ovate-acuminate entire narrowly scarious-margined bractlets 2-6 mm long. Petals purple, obovate; styles slender, the stylopodium depressed. Pedicels 2-5 mm long. Carpophore 2-parted. Fruit ovoid-oblong, 7-9 mm long, 3-4 mm broad, obtuse, the ribs filiform, acute; vittae solitary in the intervals, 2 on the commissure.

List of exsiccatae: **ECUADOR. Azuay:** Cantón Cuenca, parroquia San Joaquín, barrio Parabón, 1 km W de la carretera, *Tapia & Velásquez 58.* — Cantón Cuenca, parroquia Cumbe, 28.6 km on road Cuenca-Saraguro, 3000 m, *Tapia & Velásquez 133* — 2 km N from Chordeleg on slopes of river bed on left side of road to Cuenca, 2335 m, 7 Aug 1996, *Vásconez & Montalvo 16* — **Loja:** Vicinity of Las Juntas, Rose, *Pachano &*

Rose 23215 (US, holotype; GH, NY). —S . Pedro-Chinchas (ca. 55 km W of Loja), 1600 m, 1 Mar 1947, *Espinosa 1305* (UC). —Cantón Loja, parroquia San Lucas, loc. Bucashi, a 46 km de la via Loja-Cuenca, 16 Feb 1992, *Tapia & Velásquez 51.* — Cantón Loja, 7 km on old road Loja-Catamayo, 3000 m, *Tapia & Velásquez 140* — Above San Pedro de Vilcabamba, 2000 m, Feb 1995, *Herrmann 1573.* — **PERU.** — **Apurímac:** Provincia Andahuaylas, quebrada Posoconi, 2650 m, *Vargas 8795.* — **Cusco:** San Sebastian, grassy place on summit of bluff, 3300-3400 m, *Pennell 13628.* Prov. Cusco, Cerro Sape, frente a Sacsahuamán, cerca a la ciudad de Cusco, 3400 m, *Ferreyra 2675.* Prov. Paruro, Araypallpa, 3100 m, *Vargas 411.* — **Junín:** Prov. Tarma, Huasahuasi, *Ruiz & Pavón,*

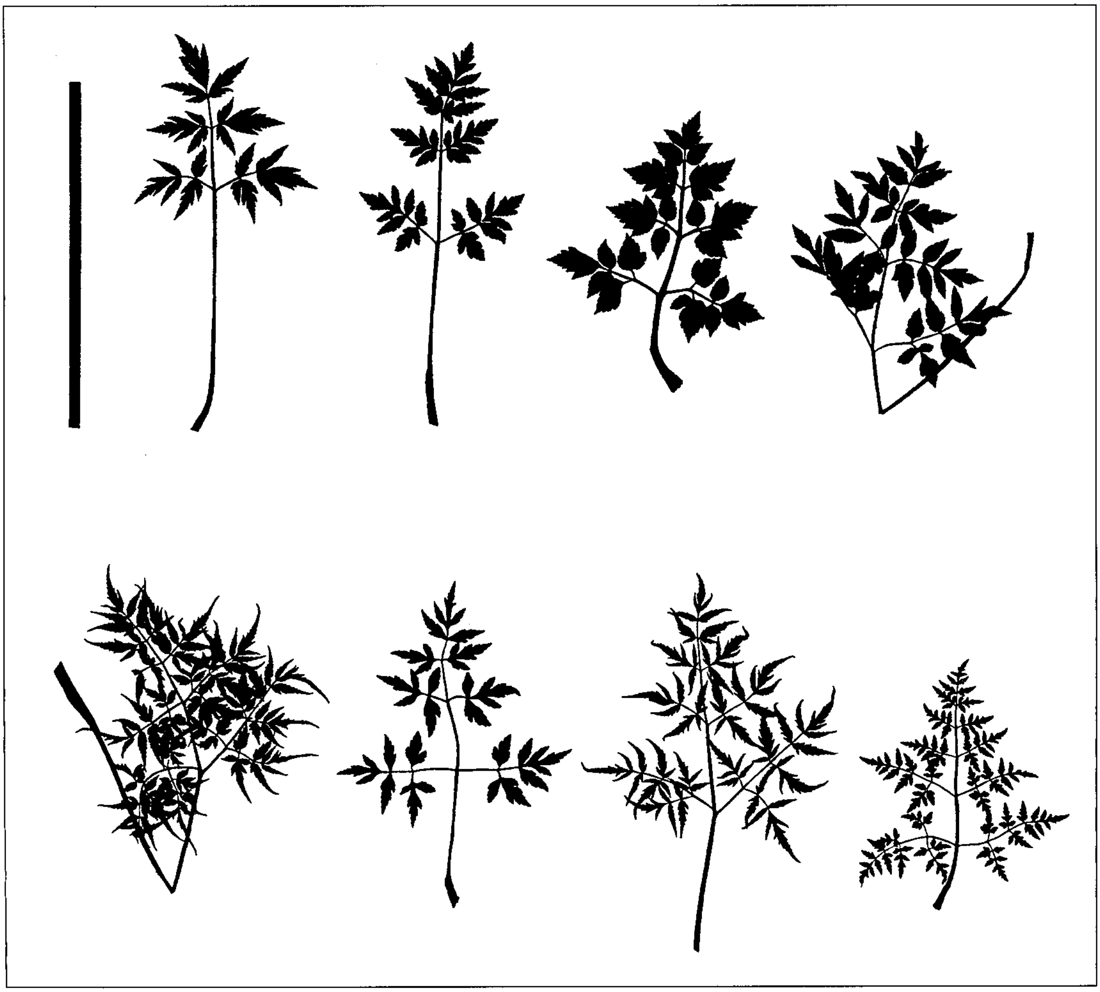

Fig. 24. Leaf variation of *Arracacia andina* (upper row) and *Arracacia equatorialis* (lower row). Herbarium specimens in upper row from left to right: *Hermann 1523* (Bolivar), *Vásconez & Velasco 4* (Bolivar), *Hermann 1522* (Chimborazo), *Vásconez & Velasco 1* (Chimborazo). Herbarium specimens in lower row from left to right: *Vásconez & Montalvo 17* (Loja), *Hermann 1543* (Loja), *Hermann 1573* (Loja), *Hermann 1520* (Azuay). All specimens from Ecuador. Scale: 30 cm.

— Entre Palca y Huacapistana, 2400-2700 m, *Weberbauer 1745* — Entre Palca y Carpapata, 2500 m, *Cerrate 929* — Carpapata, 2500 m, *Cerrate 2806* — Quebrada pedregosa, 2300-2500 m, *López 802* — Huacapistana, Valle de Tarma, 2400 m, *Velarde 722* — Chanchamayo, *Isern (Cuatrecasas 2417)* — Prov. Huancayo, Huancayo, alrededores, *Soukup 3579.*

This species is known from southern Ecuador and Peru. It has high overall resemblance with *A. xanthorrhiza* and *A. andina* but has been maintained as a separate species because of differences in its fruit, leaf, involucel and oil tube characters (Constance 1949; Mathias and Constance 1976). Also the gracile growth habit and the highly dissected leaf sets the species apart from both *A. xanthorrhiza* and *A. andina* (see Fig. 24). I have observed material from Azuay *(Vásconez & Montalvo 16)* and from Loja *(Hermann 1573),* southern Ecuador (Fig. 25). The storage roots (diameter up to 3 cm) are smaller than those of *A. xanthorrhiza* or *A. andina;* however, the skin of the roots of this material is very thin and easily rubbed off in

Fig. 25. *Arracacia equatorialis* from Loja, cultivated in Quito greenhouse (Herbarium voucher *Hermann 1573)* (Photograph January 1997).

contrast to the paper-like skin of *A. andina* which can be peeled off entirely. This feature and proximal constrictions of the roots (the 'necks' that connect them to the rootstock) suggest close affinity of *A. equatorialis* with cultivated arracacha. There is probably too little material available to decide whether *A. equatorialis* merits species status and what its biosystematic relations with other *Arracacia* species are.

6.2.1.8 *Arracacia incisa* Wolff, Bot. Jahrb. 40: 305. 1908

Stout, caulescent, branching, 0.3-1.2 m high, the foliage squamulose; leaves triangular-ovate to ovate-lanceolate, 10-25 cm long, ternate-pinnate or bipinnate, the leaflets triangular-ovate to ovate-oblong, acute, cuneate or truncate at base, the lower distinct and short-petiolulate, the upper sessile and the larger pinnately incised, squamulose on margins and along veins on both surfaces, the lower surface paler and reticulate, a squamulose tuft on the upper side of the sulcate rachis at the base of the larger leaflets; petioles 8-16 cm long, narrowly sheathing at base, the sheaths scaberulous on the veins; cauline leaves with wholly sheathing, inconspicuously inflated petioles; inflorescence branching, the peduncles arising axially and terminally, 2-12 cm long, squamulose at apex; involucre wanting, or of 1 or 2 sheathing bracts; fertile rays 4-8, stout, spreading-ascending, 1-4 cm long, scaberulous at least at apex; involucel of 4-8 obovate to lanceolate, scarious, denticulate-margined, unequal bractlets, 5-10 mm long, the green central portion projecting as an acuminate point, exceeding flowers but shorter than fruit; fertile pedicels 2-6, stout, spreading, usually 2-5 mm long, scaberulous; flowers dark purple or greenish, the petals obovate; stylopodium depressed, the styles slender, divaricate; carpophore 2-parted to base, lax; fruit ovoid, 5-8 mm long, 3.5-6 mm broad, the ribs very prominent and corky, acute; vittae small, 2-3 in the intervals, 3-6 on the commissure, frequently some accessory ones under the ribs or in the intervals; seed scarcely channeled under the intervals, the face deeply sulcate.

List of exsiccatae: **PERU. Ancash:** Prov. Bolognesi, Capillapunta, Cerro al Sur de Chiquián, 3560 m, *Ferreyra 5712, Cerrate 155.* — **Cusco:** Prov. Paucartambo, Paucartambo Valley, Hacienda Churu, 3500 m, *Herrera 1391* — Kencumayo 3300 m, *Woytkowski 199* — Prov. Cusco, Cusco, *Rose & Rose 19034.* — **Huánuco:** Prov. Pachitea, steep rocky open grassy slope, Huacachi, estación near Muña, 6500 ft, *Macbride 4163.* — **Lima:** Prov. Huarochirí: "in declivibus rupestribus prope Tambo, ad viam ferream inter oppida Lima et Oroya," 2650 m, *Weberbauer 165,* type — Viso, sandy hillside, 2800 m, *Goodspeed, Stork & Horton 11540* — Valley of Rio Rimac near Lima-Oroya highway at km 90 east of Lima, 3000 m, *Goodspeed & Weberbauer 33059* — Matucana, 8000 ft, *Macbride & Featherstone 326, 2949* — Rio Blanco, 12,000 ft, *Macbride & Featherstone 730* — Prov. Canta: cerca a Culluay entre Canta y La Viuda, 3600-3700 m, *Ferreyva 12964* — Pasco: Prov. Daniel Carrion, in shrub on southwestern canyon slope, Yanahuanca, 10 000 ft., *Macbride & Featherstone 1244.*

This species, which is known only from Peru, and *A. peruviana* have been generally confused, largely because of the inadequacy of the original description. The involucels of the two species are entirely distinct. *Arracacia incisa,* with its conspicuous scarious involucels, deep purple flowers, and blunt, prominently ribbed fruit, is one of the most distinctive species of the genus. The taproot is fleshy and has a fragrance of anise (Mathias and Constance 1962).

6.2.1.9 *Arracacia peruviana* (Wolff) Constance Bull. Torrey Club 76: 45 (1949)

Velaea peruviana Wolff, Bot. Jahrb. 40: 303 (1908).
Slender, branching, 0.6-0.9 m high, squamulose to scaberulous throughout, the stem base clothed with dry sheaths, from a branched taproot; leaves ovate-lanceolate, 20-30 cm long, bipinnate, the leaflets ovate to lanceolate, acute, cuneate at base, the lower distinct and short-petiolulate, the terminal sessile and confluent, 2-5 cm long, 1-4 cm broad, coarsely sinuately lobed and mucronulate-serrate, squamulose on veins and margins, the lower surface paler and reticulate; petioles 10-30 cm long, sheathing below; cauline leaves pinnate, the uppermost with short, wholly sheathing petioles; inflorescence of alternate axillary peduncles, 7-15 cm long, squamulose at apex; involucre wanting, or of a single leaf sheath; fertile rays 5-10, slender, spreading, 4-8 mm long, squamulose especially at apex; involucel of 6-10 entire linear bractlets 5-9 mm long, exceeding flowers but shorter than fruit; fertile pedicels 2-6, spreading, 5-6 mm long, squamulose or scaberulous above; flowers reddish-brown, the petals obovate; stylopodium depressed, the styles slender, spreading-erect; carpophore unknown; fruit ovoid, 4-6 mm long, 3-4 mm broad, glabrous, the ribs filiform; vittae large, solitary in the intervals, 2 on the commissure; seed face deeply and narrowly sulcate.

List of exsiccatae: **PERU. Ancash:** Prov. Cajatambo, infra Ocros, 3000-3200 m, *Weberbauer 2748,* type. – **Ayacucho:** Prov. Huanta, mountains northeast of Huanta, *Weberbauer 7513.* – **Lima:** Prov. Yauyos: Cuchapaya-pampa, cerca (arriba) a Tupe, 2830 m, *Cerrate 1027.* – **Moquegua:** Prov. Mariscal Nieto: Carumas, *Weberbauer 7269.*

This is a species from Peru separable by its conspicuous linear bractlets and reddish-brown flowers. Little is known about its distribution and roots.

7 Variation of cultivated arracacha

7.1 Morphological variation

There appears to be little morphological variation in the cultivated genepool of arracacha. Because of the dearth of experimental data, however, this is difficult to prove. Clearly, the storage root is the most variable plant part; three horticultural forms are generally recognized: yellow-rooted and white-rooted material and cultivars with additional purplish pigmentation (probably anthocyanins) in the outer cortex or in the region of the vascular bundles. Cultivars of the latter type are particularly frequent in collections of Peru. The former classification, however, is an artificial one, and, in reality there is a continuous range between the three 'extremes'. Figure 26 shows root shapes in an Ecuadorean germplasm collection. The variation in root shape is modest compared with that of other roots and tubers. From the comparative richness of varietal names (Arbizu and Robles 1986; Meza 1995) and available descriptions, it is reasonable to assume that Peru has the greatest morphological diversity in arracacha of all countries.

The only segregating population known is one that resulted from (self-pollinated) seed progenies of the commercial Brazilian clone. This progeny shows a wide range of white to intensely yellow root colour, but purple genotypes also occur at a low frequency. The Brazilian clone is therefore highly heterozygous.

Fig. 26. Variability of arracacha storage root variability in Ecuadorean germplasm collection (Photo courtesy INIAP).

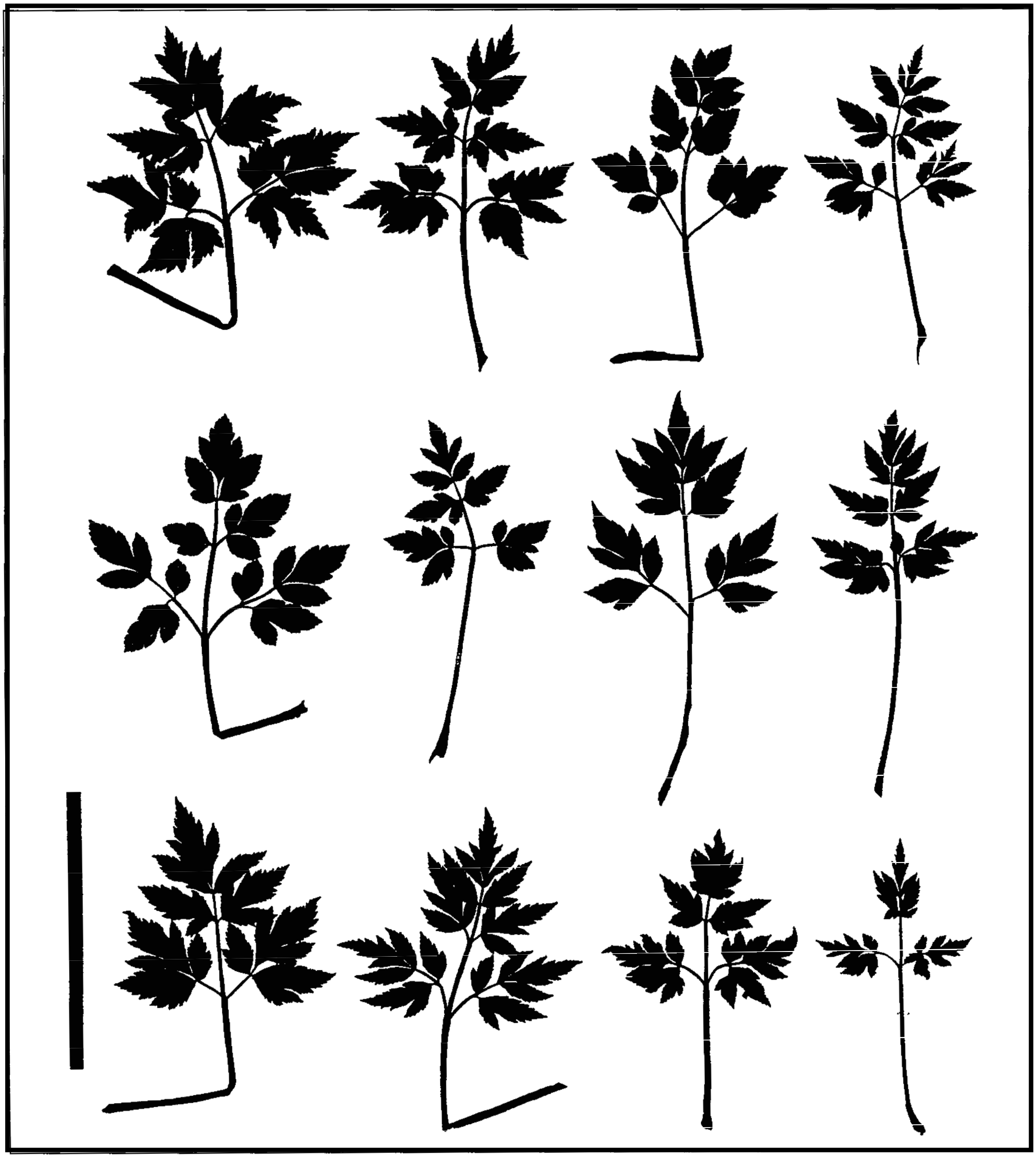

Fig. 27. Leaf variation of cultivated arracacha across species range. All leaves are from plants of the same age and growth conditions (cultivated in pots in greenhouses). Provenance of accessions used (from left to right and top to bottom): Colombia: MH1358 (Cundinamarca, 4°18'N), MHIF1342 (Huila, 2°05'N); Ecuador: ECU1155 (Imbabura, 0°13'N), ECU1232 (Cotopaxi, 0°47'S), ECU1168 (Cotopaxi, 1°04'S), ECU1206 (Bolívar, 1°32'S), ECU1186 (Cañar, 2°43'S); Peru: CA5026 (Lima, 12°20'S), MH546 (Cusco, 13°00'S); Chile MHCN1250 (Arica, 18°50'S); Brazil: MH800 (São Paulo, 20°40'S), CNPH90437 (Distrito Federal, approx. 16°S); note the leaf of MH800 shows virotic leaf deformation. This is the commercial clone used all across Brazil and CNPH90437 is an F_1 genotype resulting from selfing MH800. Scale: 30 cm.

Figure 27 presents the leaf variation found in arracacha cultivars across the species range. By comparison with Fig. 24, it becomes clear that leaf variation in wild *Arracacia* species is much greater. Leaf shape of arracacha may vary as much within one accession as between accessions of a collection. Mazón (1993) struggled to describe leaf characters but concluded that only the degree of (purple) petiole pigmentation is a suitable and consistent leaf descriptor.

Future germplasm evaluations should consider the allocation of dry matter to the rootstock, which appears to be variable (see Table 4). Also, the variation of generative plant parts holds potential for the development of germplasm descriptors (see Section 4.2.2).

7.2 Chromosome number

Chromosome counts in root tips of cultivated arracacha have consistently shown a mitotic number of 44, both in Peruvian (Blas and Arbizu 1995; Blas 1996; 65 accessions) and Ecuadorean material (Mr J.J. Vásconez, 1996, pers. comm.). Blas and Arbizu report the same number for two "wild arracacha" accessions from Peru. Apioid genera have mostly haploid series of 11 chromosomes (Darlington and Wylie 1955) and it therefore seems likely that arracacha is a tetraploid. Tetravalent pairing in meiosis was recently observed in Ecuadorean arracacha (Mr C. Salazar, 1996, pers.

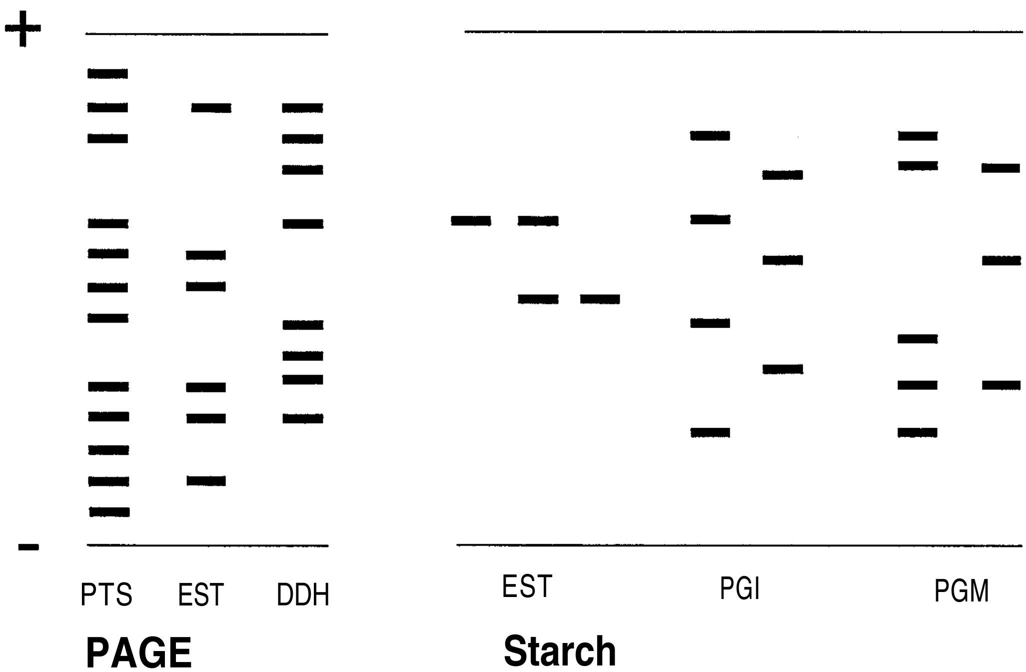

Fig. 28. Electrophoretic isozyme patterns of cultivated arracacha. (Sources: Mazón 1993 (Starch), Erazo *et al.* 1996 (PAGE)). PAGE: in polyacrylamide gels; Starch: in starch gels. EST=esterases, DDH=dihydrolipoamide dehydrogenase, PGI=phosphoglucoisomerase, PGM= phosphoglucomutase, PTS=total proteins.

comm.). Constance *et al.* (1976) report 44 chromosomes for 15 specific taxa of Mexican *Arracacia* and the same number in the closely related genus *Tauschia.*

7.3 Molecular variation

To overcome the difficulties involved in differentiating arracacha cultivars morphologically, Mazón (1993) and Erazo *et al.* (1996) conducted studies aimed at finding isozyme polymorphisms. Although both authors used a range of plant tissues, extraction procedures and buffer systems, little or no isozyme variation was found in a collection comprising Bolivian, Brazilian, Chilean, Ecuadorean and Peruvian germplasm (see Fig. 28). Of 20 isozyme systems showing enzymatic activity, only three (esterases, phosphoglucoisomerase and phosphoglucomutase) showed modest polymorphisms in starch gels (Mazón 1993).

Preliminary work using PCR-amplified DNA from random-sequence decamer primers has yielded promising results in terms of molecular polymorphisms for application in fingerprinting of arracacha cultivars. Thus Blas *et al.* (1997) and Castillo (1997) report the occurrence of DNA polymorphisms in 48% and 85% of primers assayed, respectively. Castillo (1997), however, concludes from his work that overall molecular diversity in his (Ecuadorean) material is low.

8 Conservation and use

8.1 Genetic erosion and germplasm collecting

Undoubtedly, countless generations of farmers, especially the more diversity-minded individuals who share with the modern plant collector a fascination about variation in crop plants, have brought upon us the extant diversity of arracacha and other traditional crop plants. This should not be mistaken with the recently evolving and increasingly popular belief that farmers per se are germplasm conservationists, and that crop germplasm can be conserved *in situ,* in complementarity with genebanks, as it were. Andean farmers indeed use germplasm, whether for economic, medicinal, culinary, aesthetic or other purposes, but chiefly for the diversification of diets that often cannot be supplemented, or only insufficiently so, from markets for lack of integration in the money economy. The fact that one still finds amazingly diverse crop germplasm in poor areas of the Andes is not necessarily proof of the curatorial attitude of farmers, but rather a sign of their dependence on genetic diversity in their fields as an insurance against famine and disease. As farmers are (successfully) integrated into national market economies and have access to external food sources, education and health, an objective that all Andean societies aspire to, dependence on native food sources decreases, and germplasm inevitably is lost to some extent. This is an incremental process and farmers will retain what they still consider useful. I have traveled widely across the Andes and gathered local evidence for the loss of cultivars of arracacha and other crops, particularly in those countries that have lower overall indices of poverty and seem to 'progress' economically faster than other countries (Argentina, Chile, Colombia, Ecuador). In light of this experience, the vigorously promoted view on *in situ* crop conservation would appear highly objectionable.

The conservation of germplasm, as opposed to its use, is a conscious effort to preserve what is today obsolete or currently not needed, in the belief that such material will be valuable at a later stage for the extraction of interesting traits from 'undesirable' genetic backgrounds. This is what farmers cannot and will not do.

Little is known about the disappearance of arracacha genotypes. This process is commonly referred to as genetic erosion, but strictly speaking, what is meant is the loss of genes or unique linkage groups of genes. Whether genotypes or genes, for that matter, are actually disappearing would require knowledge of the structure of genetic diversity, which, in the case of arracacha, we do not have.

There is, however, indirect evidence for the loss of genotypes in some areas. During germplasm-collecting trips, farmers interviewed often recall clones that are no longer around. Much of the production destined for commerce is from a limited number of genotypes and these tend to replace varieties that, for one reason or another, are less attractive to produce. It has been argued that potatoes and other clonally propagated tuber crops of the Andes have not suffered the extent of genetic erosion as previously thought, and that, in spite of the introduction of modern cultivars, many of the rarer genotypes are still used. This argument overlooks the

economic dimension of the problem. Even if a genotype survives in some remote location, it might become unreasonably costly to spot and collect it. It is therefore a good precautionary principle to preserve this material now, which has also been the rationale behind the collecting of arracacha germplasm in the past.

Since arracacha cannot be propagated from the storage root, which is the economic product, germplasm collections are not possible from markets, unless the rootstock is on offer which seems to be exceedingly rare and restricted to parts of Colombia (see Section 5). Collecting localities given in catalogues (Arbizu and Robles 1986; Tapia *et al.* 1996), therefore, nearly always represent actual growing sites. Cormels are available from arracacha plants in all stages of development and this in combination with the year-long crop duration ensures accessibility to cormels year-round. Even when the crop has been harvested, its crowns (aboveground plant parts) are stored and farmers are normally willing to derive cormels for the visitor. The crowns are not eaten and, since they are stored far in excess of re-planting needs, they are not as highly valued as other (edible) tubers upon which poor people rely in periods of food scarcity. Obviously, collecting at harvest time is more rewarding to germplasm collectors as they can observe root and plant morphology and record uses. Once collected, the cormels can be stored conveniently in paper bags for several weeks at ambient temperatures. On arrival at the genebank, the cormels should be cleaned and surface-sterilized. It is also possible to excise meristems or shoot-tips from the cormels for tissue culture.

Herbaria will be of virtually no help to map out promising areas for arracacha germplasm explorations because of the scarcity of herbarium specimens both in Latin America and in collections known for their New World holdings (for example Missouri and New York Botanical Gardens). Sexual seeds are rarely available from fields and they are of little significance to the germplasm collector.

8.2 Arracacha in genebanks

Efforts to collect arracacha germplasm date back to the early 1970s when both Peruvian institutions, aided financially by the Interamerican Institute for Cooperation in Agriculture (IICA), established arracacha field collections. In 1977, the first of eight international congresses on Andean crops was held and subsequently other field genebanks of arracacha and other Andean root crops were started in the Andean countries, particularly in Peru. The 'lost decade' of the 1980s brought civil strife to Peru, and much of what had been collected was lost owing to political instability, the lack of financial resources and even terrorist threats to genebank curators (Dr C. Arbizu, 1989, pers. comm.). Also, the funding of international agencies was channeled mostly to collecting, but little incentive for follow-up activities, especially for the maintenance and characterization, was provided. Ironically, germplasm scientists in the region generally derive more prestige from the size of their holdings than from a small but well-curated collection. Inflated collections and lacking financial resources proved thus to be a fatal combination that caused some of the loss that occurred. The only two collections

that have essentially kept their holdings are in Quito (INIAP) and Cajamarca (University). Unfortunately, collecting missions during recent decades did not yield herbarium material. This is a source of particular regret when germplasm collections were lost. Informative germplasm catalogues with good location data are available for Peru (Arbizu and Robles 1986) and Ecuador (Tapia *et al.* 1996).

Table 7 provides an overview on current collections as they have been reported in genebank catalogues or other documents. A total of about 700 clonal accessions of arracacha are currently available from genebanks. Ecuador, northern Peru and parts of southern Peru have been comparatively well covered by collecting missions, but there are no significant collections from Bolivia, Colombia and Venezuela.

Table 7. Reported germplasm holdings of arracacha

Institution†	Country	No. of accessions	Origin	Source of information	Status
University Ayacucho	Peru	88	All of Peru	Arbizu and Robles 1986	Mostly lost
University Cusco	Peru	104	Apurímac, Cusco, Puno	Ortega 1995	Recently collected
University Cajamarca	Peru	110	Cajamarca, Amazonas	Seminario 1995	Collected over the past 25 years
INIA	Peru	180	Northern Peru	C. Arbizu, 1996, pers. comm.	Characterization
INIAP	Ecuador	94	All of Ecuador	Tapia *et al.* 1996	Collected over the past 15 years, characterization
EMBRAPA-CNPH	Brazil	35 11	Brazil Ecuador	F.F. Santos, 1996, pers. comm.	Characterization, breeding
International Potato Center	Peru, Ecuador	66	Brazil, Colombia, Ecuador, Peru, Bolivia, Chile	International Potato Center,1996, germplasm databases	In quarantine, RAPD fingerprinting

† INIA = Instituto Nacional de Investigaciones Agrarias, Peru; INIAP = Instituto Nacional Autónomo de Investigaciones Agropecuarias, Quito, Ecuador; EMBRAPA-CNPH=Empresa Brasileira de Pesquisa Agropecuária, Centro Nacional de Pesquisa de Hortaliças, Brasilia DF, Brazil.

Most collections are well documented in terms of passport data, but from the available genebank documentation the status of characterization and evaluation is unclear except for the INIAP holdings in Quito. Yield or other plant performance data from this collection, however, are not very meaningful as they come from a field genebank at 3050 m altitude, where arracacha is poorly adapted. Even by conservative estimates, INIAP's arracacha collection is highly redundant, with 57% duplicated accessions (Mazón 1993). Based on a study involving the analysis of 75 polymorphic RAPD markers, Blas *et al.* (1997) estimated the clonal duplication of CIP's arracacha collection to be 51%. We must assume that other collections have similar degrees of duplication, although there are few data to support this.

The arracacha collection of the International Potato Center is an opportunity collection assembled during multi-tuber crop missions to Chile, Colombia, Bolivia and Peru. It is not the result of systematic explorations of the arracacha genepool.

EMBRAPA-CNPH in Brazil currently holds some 2000 clones, of which 35 have been identified as promising material for distribution within Brazil. All this material was selected from self-set seed progeny of the only commercial Brazilian clone (see Section 8.4). In addition, CNPH conserves 11 Ecuadorean accessions donated from INIAP some years ago.

CATIE in Costa Rica had for some time a collection of 6 accessions, but it appears to have been lost because of poor adaptation to the tropical climate of Turrialba (600 m altitude, approx. 10° N) (Mr J.A. Morera, 1996, pers. comm.).

8.3 Conservation strategies

The foregoing section illustrates the effort of many institutions in the Andean countries to preserve the genetic heritage of their countries, but it also shows the infant stage of the conservation of arracacha genetic resources. Mere amassing of materials with little regard for geographical representation or conservation needs is typical for any germplasm collection in its early stages and is a product of our ignorance of the structure and geographical distribution of crop genepools. Even the best-researched collections of global crops are plagued by this syndrome to some extent.

Arracacha, however, is a minor crop and only minor resources can justifiably be allocated to the preservation of its genepool. Also, the clonal diversity in a vegetatively propagated crop is a finite quantity and increasing collecting efforts inevitably result in diminished increments of captured diversity in analogy to the economic law of diminishing returns. It follows then that clonal comprehensiveness of arracacha collections should not be the aim but rather 'lean' collections that encapsulate a maximum of diversity in a minimum number of accessions.

The first step to achieve this is to identify clonal duplicates by the use of a number of conventional and molecular techniques, which have become available. The wealth of information that is gained in this process can be used to enhance our understanding of variation in the genepool and gaps in collections, geographic or otherwise, can be identified and targeted.

In my experience, the clonal conservation of arracacha is cumbersome and prone to losses. To meet the crop's ecological requirements in the Andes, field collections often have to be located far away from genebank headquarters, where they are difficult and costly to monitor. Although protocols for tissue culture storage of arracacha have now become available (Landázuri 1996), their application cannot always be recommended, as tissue culture laboratories are very vulnerable to the withdrawal of external funding necessary to sustain them. Where institutions have shown a capability to preserve field collections over many years, tissue culture undoubtedly becomes a valuable adjunct to increasing germplasm safety.

In addition to clonal collections, arracacha germplasm should increasingly be stored as sexually reproduced seed. The crop has retained the ability to produce seed and research should be undertaken to better understand the factors that induce flowering. From evidence presented in Section 4.3.1, drought stress and vernalization would appear to be factors involved and research is needed to elucidate the effectiveness of such treatments.

8.4 Crop constraints and breeding

Plant breeding is all too often seen by its practitioners as the panacea for overcoming crop constraints. This approach tends to overlook productivity gains from improved cultivation, particularly from applying standard horticultural techniques to arracacha (transplanting, sanitation of planting stocks, improved post-harvest handling). The potential of horticultural intensification probably exceeds the benefits to be had from breeding arracacha with the limited resources available for a minor crop. Also, breeding requires a clear understanding of crop constraints, whether they are related to factors that limit production or consumption. In the absence of meaningful germplasm evaluations and consumer statistics, such an understanding is not available for most arracacha-producing areas.

It is with these reservations that I turn to plant breeding as a means of increasing arracacha's competitiveness with other crops. The two single most important issues emerging in discussions with growers, extensionists and users are long crop duration and limited post-harvest life. Even when arracacha propagules are pre-cultured (to facilitate rooting and crop establishment), the crop needs 7-8 months from transplanting to harvest (see Section 4.5.1). This limits the crop's diffusion in two ways. First, entrepreneur farmers aware of the significance of the opportunity cost of land and factor productivity give preference to other vegetables with shorter durations. Second, arracacha does not fit into the tight cropping cycles of densely populated areas, nor can it be expected to expand into more temperate climates unless more precocious cultivars are available (see Section 4.6). Unfortunately, the evidence points to limited variability of crop duration in the cultivated genepool and it is likely that only a combination of genetic improvement or selection with improved crop management will produce the desired results.

There are no data on the extent of genetic variation of root perishability in arracacha collections, but the ubiquity of the problem would suggest that possibilities

of selecting or breeding cultivars with dramatically improved shelf-life are low. Again, the potential of improved post-harvest handling (see Section 4.5.5) should not be overlooked.

Arracacha root characteristics are the subject of regional or even local preferences (for details see Section 2). It seems that preferences for yellow and intensely flavoured roots in Brazil and for white and weakly flavoured roots in other countries or regions are ingrained in local culinary customs and these need to be taken into account in breeding programmes. On the other hand, no singular cultivar is likely to satisfy the needs of different market segments. For example, some processing companies are mainly concerned about intense and evenly distributed root pigmentation while others place emphasis on high dry matter contents and strong aroma. Yet for direct consumption, weakly flavoured roots may appeal to consumers who find the strong umbelliferous aroma undesirable.

As outlined in Section 4.5.4, arracacha is affected by a number of parasitic organisms but there is no single disease or pest known to limit production across growing areas. Even if the area devoted to arracacha was to expand significantly, it would remain comparatively small and long rotations, known to control diseases and pests, would remain an effective option for phytosanitary control. Therefore, pests and diseases rank low in overall priorities and they should not unnecessarily compound the complexity of breeding programmes.

The breeder also will have to struggle with the practical problems involved in cross-pollinating arracacha. The plant has tiny flowers (see Section 4.2.2), and magnifying aids are necessary to emasculate them. Also the scarcity of pollen makes pollinations a tedious task, and hardly more than 20-50 manual pollinations can be done per hour. Moreover, a fruit develops only a maximum of 2 seeds.

The narrow variation found in the arracacha genepool would have to be widened by the use of wild *Arracacia* species. These, however, are presently too little known and no germplasm collections are available.

To my knowledge there is only one arracacha breeding programme. It was started in 1987 at EMBRAPA-CNPH in Brasilia and motivated by the need to breed cultivars with adaptations to different environments. All Brazilian arracacha is derived from one clone, but researchers noted that this cultivar releases much useful diversity when reproduced from sexual seed (Dr F.F. Santos, 1992, pers. comm.). Since the plant does not, or rarely so, set seed under the hot and dry conditions of Brasilia, self-set seed has been collected every year between November and January from farmers' fields in the cooler states of Paraná, Santa Catarina and Minas Gerais. The established seedlings are transplanted into the field and the first screening takes place at plant maturity after a lo-month crop duration. The only genotypes retained are those that show superior vigour and have strong yellow root pigmentation similar or more intense to the commercial clone and cylindrical roots which are preferred for packing. Of many thousand genotypes thus evaluated (2000-20 000 per year) only some 50-100 are further evaluated for agronomic performance, nematode resistance, post-harvest behaviour and reduced crop duration. Only about

10% of the genotypes will survive this (second) screening cycle and eventually 5-10 new genotypes are added to the collection as advanced materials ready for multilocation trials. However, other materials that are of no immediate interest to Brazil, such as white genotypes, also are retained, or others with exceptional yields, pigmentations, etc. As a result, CNPH has accumulated a collection of 2000 clones including 35 promising accessions, the latter for cultivation in Brazil.

Giordano *et al.* (1995) report significantly increased yields of several new clones which are distributed to a wide range of environments across Brazil. Also, clones with somewhat reduced crop duration but otherwise similar characteristics to the traditional clone have been identified and are being tested in multilocation trials (Dr F.F. Santos, 1995, pers. comm.).

8.5 Research needs

As with so many other minor crops, there is a plethora of possible research questions surrounding arracacha. Previous chapters have highlighted a number of issues that could be approached in only a speculative fashion because of the dearth of data. Among the most under-investigated topics is certainly the biosystematic relationships of arracacha to its closely related wild relatives. If the ancestry of arracacha could be solved, then an interesting model for the domestication of a unique umbelliferous plant would be at hand.

In the context of this monograph, the following research needs have been identified to back-up the conservation effort: studies of the factors inducing flowering, better understanding of the breeding system, germplasm conservation by sexual seed and the sanitation of planting stocks.

From a production viewpoint, two issues appear to be of utmost importance. First, how can the crop duration be reduced and what role would a crop model play in achieving this goal? Second, the storage life of the root needs to be improved, by either genetic improvement or better storage technologies.

Finally, processing research and development of new products will be instrumental in promoting this crop for urban consumption. Pilot trials should explore the potential to introduce arracacha outside Latin America.

8.6 Crop prospects

In closing this monograph, one might ask what the future will bring for arracacha. With about 30 000 ha dedicated to its cultivation and an annual production value well in excess of US$100 million, arracacha is actually not a neglected crop. Given its versatility in cuisine, productivity, peculiar aroma and fine starch, will it ever establish itself as a global, albeit secondary crop? Or has it reached its peak distribution and will it stay within the confines of Latin American highlands?

Arracacha has not shared the stunning global success of a number of New World crops. Sweetpotatoes spread into Polynesia before the advent of the great European sea voyages. Maize was widely known in many parts of the Old World by the end of the 16th century. Potatoes, cassava and New World cucurbits became worldwide

staples long before the invention of research institutes and the surge in mass communication and travel. The failure of arracacha to conquer its niche in Africa and Asia cannot thus be explained in terms of deficient research, promotion or any other single cause.

While this recognition should be the basis for a realistic appreciation of arracacha's potential, it should not discourage us from addressing specific crop constraints. Eventually, research and, perhaps more importantly, the application of existing technology will lead to incremental improvements of the crop's competitiveness and this, aided by the increasing demand for processed arracacha products, will provide opportunities for crop expansion, both in traditional areas and beyond.

In Section 8.4, the possibilities for breeding or selecting improved arracacha cultivars were outlined. A much bolder (but infinitely costlier) approach would be the attempt to 're-design' or 're-domesticate' arracacha. We must remember that arracacha is essentially still a neolithic crop brought into cultivation thousands of years ago. Today's varieties reflect the crop's adaptation to nutrient-poor soils and rain-fed agriculture. Selection for vigorous vegetative propagules and the historic utilization of the central rootstock for food led to a plant architecture which ensures the survival of the crop in harsh conditions, but also one that compromises much of the dry matter in non-commercial storage organs, delays early plant development and results in long crop duration. Would it be possible to breed arracacha into a crop with only one central rootstock or tuber analogous to that formed by the closely related celeriac *(Apium guaveolens* var. *rapaceum)?* Could eventually, by the use of wild *Arracacia* germplasm, biennial and seed-propagated arracacha cultivars be bred with production characteristics similar to those of fast-growing Old World umbellifers? Research budgets needed to answer these questions are probably not available today, but undoubtedly, such research would provide credentials to our modern claim of 'plant improvement'.

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Maca

(*Lepidium meyenii* Walp.)

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Contents

1 Species classification

The Cruciferae (Brassicaceae) family contains many important crop plants and comprises approximately 3000 species. According to Rehm and Espig (1991), crops of economic importance are:

- starch plant - maca *(Lepidium meyenii)*
- oilseeds - rapeseed *(Brassica napus)* and crambe *(Crambe abyssinica)*
- vegetables-cauliflower, common cabbage, Brussels sprouts, etc. *(Brassica olevacea* var. *botrytis,* var. *capitata,* var. *gemmifera);* Chinese cabbage *(B. rapa* subsp. *chinensis);* garden rocket *(Eruca vesicaria* subsp. *sativa);* watercress *(Nasturtium officinale);* radish *(Raphanus sativus);* garden cress *(Lepidium sativum)*
- spices - mustard *(Brassica nigra, Brassica juncea* and *Sinapis alpa)*
- fodder - fodder kale *(Brassica* spp.), fodder radish *(Raphanus sativus).*

The species in the Brassicaceae are classified in three large cosmopolitan sections — Dileptium, Monoploca and Lepidium — and three minor sections restricted to the Old World — Lepia, Lepiocardamon, Cardamon (Thellung 1906; Mummenhoff *et al.* 1995).

The genus *Lepidum* belongs to tribe Lepidieae and section Monoploca of the Brassicaceae family (Thellung 1906) and consists of approximately 175 species (Mummenhoff *et al.* 1992) being the largest genus in the Brassicaceae (Hewson 1982). Maca *(Lepidium meyenii* Walp. in Nov. Act. Nat. Leopold. Carol. 19, Suppl. 1 (1843) 249) is the only species cultivated as a starch crop. In the genus three other species are cultivated (Hanelt 1986; Mabberley 1993):

1. the garden cress or land cress *(Lepidium sativum* L.) is grown worldwide and is used at the cotyledon or seedling stage as a salad component
2. dittander *(L. latifolium* L.) was a cultivated salad plant of the Ancient Greeks and is used as a medicinal plant in the Canary Islands to alleviate renal lithiasis. According to studies of Navarro *et al.* (1994), this species has diuretic action
3. poor man's-pepper *(L. virginicum* L.) is used as a leafy vegetable (weed in maize) by the Tarahumara Indians in Mexico.

The taxonomic status of maca, the Andean cultivated species of *Lepidium,* has been questioned by Chacón (1990), who proposed to change its name *L. meyenii* Walp. to *L. peruvianum* Chacón sp. nov., based on morphological observations and comparative analysis of herbarium specimens in Germany and the USA. Additionally, the original collections of *L. meyenii* were done outside the present range of distribution of maca, namely Puno in Peru. Although it is believed that in Inca times maca was cultivated in Puno, there is no evidence of this crop being cultivated there at the present time (M. Holle, pers. comm.). Later, other accessions collected in Bolivia and Argentina were also classified as *L. meyenii.* After superficial morphological inspection, however, no resemblance to maca can be seen in these early herbarium specimens, which in many cases are not in optimal shape. Therefore the species name change seems justifiable, although further taxonomic research is required to solve this problem.

Common names of the species are (National Research Council 1989):
English: maca, Peruvian ginseng
Quechua and Spanish: *maca, maka, maca-maca, maino, ayak chichira, ayak willku.*

At least seven wild species of *Lepidium,* including the cultivated one, have been reported in Peru by Brako and Zarucchi (1993) from the departments of Ancash to Puno. In addition, other Andean species have been collected in Ecuador, Bolivia and Argentina (M. Hermann, pers. comm.). Practically nothing is known about the origin of these species and even less about their possible relationship to maca. Although maca is an octoploid, the Andean wild species of *Lepidium* surveyed so far include both tetraploid and octoploids (Quirós *et al.* unpublished). A survey of approximately 30 different cultivars of maca and 21 wild species from Ecuador, Peru and Bolivia, with Randomly Amplified Polymorphic DNA (RAPD) and Restriction Fragment Length Polymorphism (RFLP) markers for rDNA, cruciferins, napins and a self-incompatibility sequence (Kianian and Quirós 1991), disclosed very low polymorphism among cultivars. Phylogenetic distances calculated on the basis of 75 RAPD markers indicate that none of the wild species so far screened is closely related to maca (Quirós *et al.,* unpublished). Tentatively three wild species could be identified by one of us (CFQ) when comparing them with herbarium specimens at the UC Berkeley Jepson herbarium, Berlin-Dahlem Herbarium in Germany, Museo de Historia Natural Javier Prado in Lima and Cesar Vargas Herbarium at the Universidad del Cusco. The species' identities in the collection were confirmed by Dr I. Al-Shahbaz at the Missouri Botanical Garden. These species are *L. bipinnatifidum* Desvaux, *L. kalenbornii* C.L. Hitchcock and *L. chichicara* Desvaux. Tetraploid and octoploid forms were found for *L. bipinnatifidum* and *L. chichicara. Lepidium kalenbornii* consisted only of tetraploid accessions. In 1996 we collected in the departments of Cusco and Apurimac at 3600 to 3950 m asl and found the same wild species. No cultivated maca was detected in this region.

2 Botanical description and reproductive biology

The maca plant is a rosette of frilly leaves with an enlarged fleshy underground organ formed by the taproot and the lower part of the hypocotyl (Leon 1964; Tello *et al.* 1992). These parts of the plant swell during growth, forming a storage organ resembling a turnip. For simplicity, we will call this organ 'hypocotyl', which is the economic product of maca (Fig. 1). The foliage forms a mat, growing in close contact with the ground. The leaves exhibit dimorphism, being larger in the vegetative phase and reduced in the reproductive cycle (Tello *et al.* 1992). The 'hypocotyls' display a variety of colours from purple to cream and yellow (Leon 1964) (Fig. 2). This species is an octoploid with $2n=8x=64$ chromosomes (Quirós *et al.* 1996), considering that the basic genomic number of Lepidieae is $x=8$ (Fig. 3). Its meiosis is normal, with the chromosomes associating predominantly as bivalents. This type of association

Fig. 1. Mature maca plants grown in Nununhuayo, Junín.

Fig. 2. Range of maca hypocotyl colours. Longitudunal sections show the arrangement of vascular tissue in the root and hypocotyl (Photo, courtesy of M. Hermann, CIP).

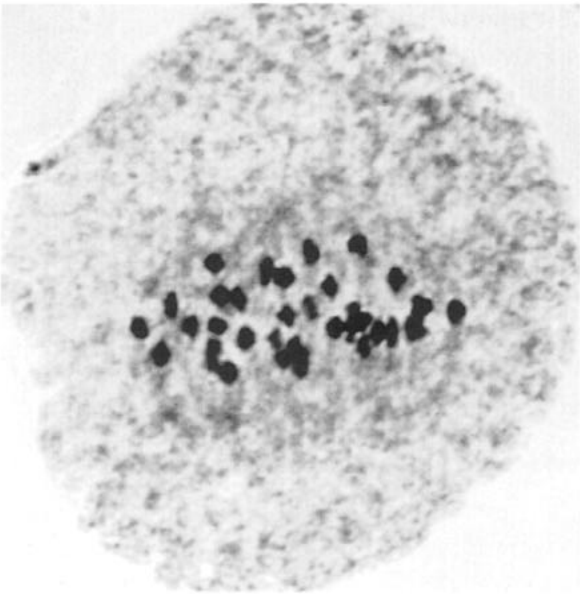


Fig. 3. Pollen mother cells in metaphase I showing 32 bivalents (100X oil immersion objective, phase contrast).

Fig. 4. Initial flower cluster appearing at the initiation of generative shoots.

Fig. 5. Generative branch bearing mature siliques.

indicates that maca is a disomic polyploid. Polyploidy is a common event among the species in the tribe *Lepidieae* to which maca belongs (Darlington and Wylie 1945). Most of the pollen collected from the flowers is fertile, as measured by pollen stainability. Consistent with other cruciferous species, pollen grains are trinucleated.

Maca is an annual crop completing its life cycle within a year when climatic conditions are favourable (Quirós *et al.* 1996). However, often maca considered a biennial plant (Tello *et al.* 1992) because it has a vegetative cycle followed by a reproductive phase. Furthermore, in the Junín area maca is grown as a biennial by holding the 'hypocotyls' underground during the dry season. However, during favourable years, when there is enough moisture in the soil and an absence of killing frosts, plants left in the field complete their life cycle within a year. The vegetative phase includes the expansion and growth of the 'hypocotyl' and root. These organs are fully enlarged approximately 7 months after planting. At this time the plants initiate their reproductive phase. Often the first floral buds will appear in a small cluster at the centre of the rosette (Fig. 4), or as solitary flowers in some of the leaf axils, announcing the initiation of the generative shoots, the main reproductive structures. Only a few of the first flowers will produce fruit. Almost at the same time, at the base of the plant, radially and under the leaves, generative shoots will rapidly grow, producing secondary branches. These will generate most of the seed of the plant. Approximately 20 primary generative branches are produced per plant, and each of these will produce approximately 13 secondary branches (Aliaga-Cárdenas 1995). The generative branches will produce profuse flowering racemes for the next 3 months. Each secondary branch will yield racemes with 50-70 flowers each. Therefore, a primary branch will bear close to 1000 flowers. Fruits will set in most of these flowers throughout this period, maturing in approximately 5 weeks (Fig. 5). At this time, the fruits will initiate dehiscence and the mature seed will be released. During the long period of flowering, it is possible to observe both fruits and flowers in the generative branches.

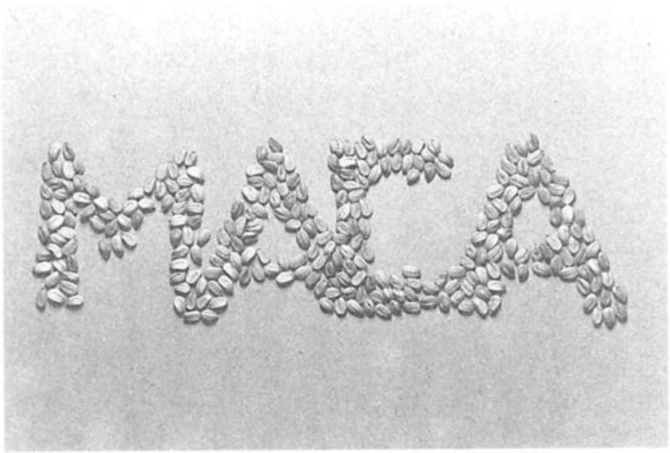
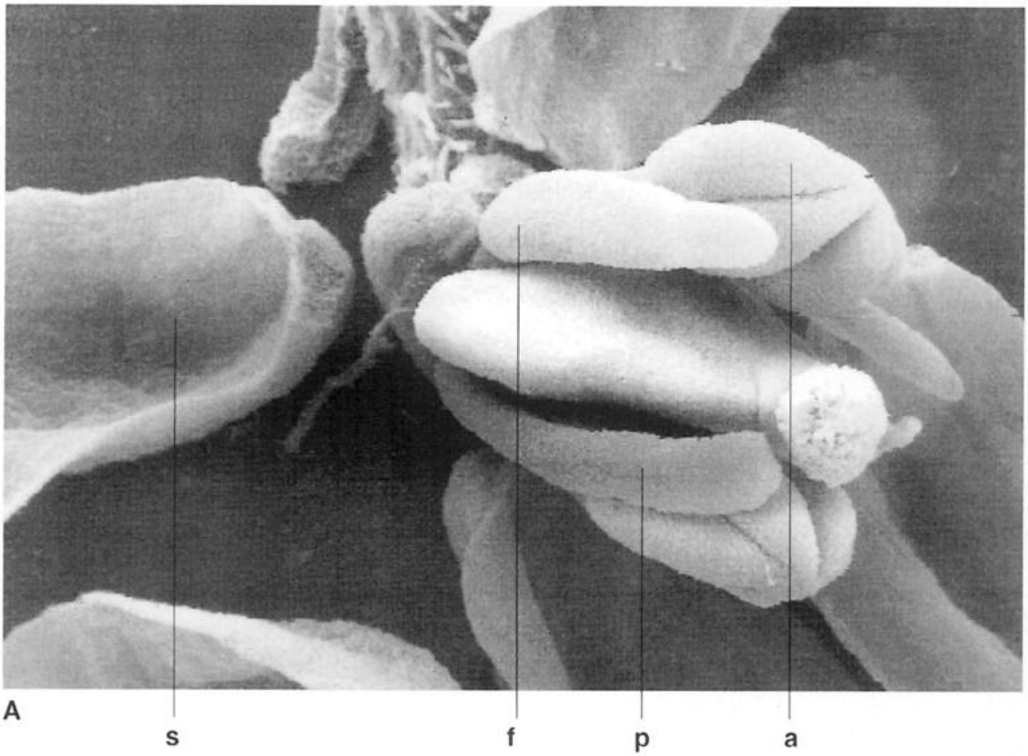


Fig. 6. Maca seed.

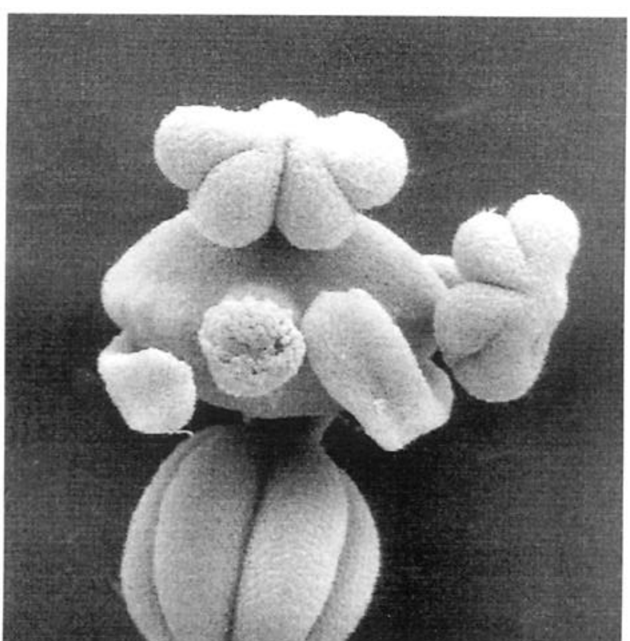
Approximately 85% of the fruits will bear seeds. Apparently seeds do not have dormancy, germinating in 5-7 days at 25°C and good moisture conditions. A single plant of maca produces approximately 14 g of seeds. One gram contains approximately 1600 seeds. Seeds are small, measuring 2 mm in length, and are light tan to brown in colour (Fig. 6) (Aliaga-Cárdenas 1995).

The flowers of maca are inconspicuous and arranged in axillar racemes. They have four erect, concave sepals, and four small white petals. The ovary is oval and bicarpelar with a short style, which develops into a dehiscent silique of two locules, carrying one seed per locule. Only two stamens (Fig. 7a), or seldom three (Fig. 7b), with well-developed anthers are present in the flowers. A variable number of rudimentary stamens consisting only of filaments is also present (Fig. 7a). The normal number of functional stamens in the family *Brassicaceae* is six, four larger than the other two. However, androeceum variation reflected in number of complete stamens is a common feature of the genus *Lepidium* (Thellung 1906). Small nectaries at the base of the stamens are also present. It is unknown, however, whether these are functional. Aliaga-Cárdenas (1995) found that maca is primarily an autogamous species. Pollination is initiated 4-5 days after the flower bud is first visible to the naked eye, and continues for another 3 days. The anthers and petals wither for the next 2 days while the ovary starts to enlarge initiating fruit development. Part of the anthesis takes place while the flower is still closed, thus indicating that the maca flowers are partially cleistogamous. Further evidence of autogamy is provided by spontaneous fruit-setting of flowering plants in growth chambers, where insects were excluded (Quirós *et al.* 1996). In Junín, the native area of maca production, no insect pollinators working the flowers were observed. Only sporadic visitation by two or three species of Dipterae which landed in the leaves and flowers have been seen (Quirós, unpublished).

In the field at Davis, California, only a few syrphid flies were observed visiting the foliage and seldom the flowers. Plants grown from different accessions are morphologically alike, with a few exceptions. All these observations suggest that maca reproduces predominantly by self-pollination.



A



B

Fig. 7. Scanning microscope photographs of maca flowers. **A:** normal flower with two complete stamens supporting anthers (a), a filament lacking the anther (f), petals (p) and ovary showing the stigma. The sepals (s) lie on the side, separated to show the rest of the organs. **B:** flower showing three complete stamens.

3 Origin and geographical distribution

3.1 Origin

The genus *Lepidium* is widely distributed throughout the world in all continents except Antarctica. The genus probably originates in the Mediterranean basin where most of the diploid species are found (Thellung 1906; Mummenhoff *et al.* 1992). Little is known about the time of origin of the genus and the mechanisms responsible for its worldwide distribution. However, most of the existing evidence indicates that long-distance dispersal during the late Tertiary or Quaternary, rather than continental drift, was responsible for the colonization of these species to the Americas and Australia. This seems to be the prevalent mechanism of distribution of other genera in the family such as *Capsella* and *Cardamine* (Mummenhoff *et al.* 1992). Common genetic features observed in the immigrant species of *Lepidium* are autogamy and polyploidy, which helps their establishment in new habitats. Although there are extensive taxonomic treatments of the *Lepidium* species of Australia (Hewson 1982) and North America (Al-Shehbaz 1986a, 1986b) as well as a general monograph on the genus (Thellung 1906), information is scarce on the species endemic to South America, and in particular about Andean *Lepidium* species, which belong mostly to the sections *Dileptium* and *Monoploca* (Thellung 1906). These species are interesting because they grow at high-altitude habitats, up to 4500 m asl, and include the cultivated species maca. Probably maca was domesticated in San Blas, Junín, between 1300 and 2000 years ago, but little is known about its origin (Matos 1978; Rea 1992). It is believed that in the 16th and 17th centuries maca had a wider range of cultivation than today. The existence of wild species of different ploidies, in some cases sympatric with the cultivated taxon, indicates that extinction of possible ancestral species has not proceeded too far to prohibit understanding of the evolutionary history of the group. Consequently, taxogenetic studies may disclose the ancestral species of the cultivated taxon. The identification of related wild species could be applied to the genetic improvement of maca, if these carry useful genes that could be transferred by hybridization.

3.2 Geographical distribution

Maca is an Andean crop of narrow distribution. It is restricted today to the suni and puna ecosystems (Bonnier 1986) of the Departments of Junín and Cerro de Pasco of Peru (Fig. 8a) at elevations above 3500 m and often reaching 4450 m in the central Andes of Peru (Fig. 8b) (Leon 1964; Tello *et al.* 1992). The largest cultivated area is found around Lake Junín at Huayre, Carhuamayo, Uco, Ondores, Junín, Ninacana and Vicco. Apparently maca occupied wider areas of cultivation in the past (Johns 1981). In addition to Junín and Cerro de Pasco, presumably, it also was grown in Cusco and in the Lake Titicaca watershed. Some of the writers of the time mention that many natives did not have any other food but maca. It was also used as payment of taxes to the Spanish administrators (Castro de Leon 1990). Its restricted cultivation today indicates that maca may have been in danger of being phased out as a crop.

At the present time less than 50 ha are being dedicated to the production of maca in Peru and presumably in the world (Tello *et al* 1992). However, the popularity of this crop is steadily increasing, not only in its area of production but also in large cities because of its putative medicinal properties.

Fig. 8. Geographic distribution of maca in Peru. **A:** maca cultivation is restricted today to the Departments of Cerro de Pasco and Junin. In the past, it is believed that it was cultivated much more widely, covering from Junin to Puno. **B:** altitude profile of the main maca production area.

4 Uses

Maca is cultivated for consumption of its root-hypocotyl axis, and is used extensively for medicinal purposes.

The maca 'hypocotyls' are eaten fresh, cooked in *pachamancas* (cooking of meat and vegetables in underground ovens lined with hot stones) or stored dried for later consumption. The dried roots are eaten after boiling in water or milk, and are sometimes mixed with honey and fruit for preparation of juices, and addition of sugarcane rum for cocktails and other alcoholic beverages (Johns 1981; Tello *et al.* 1992) (Fig. 9). Flour is also prepared from the dried roots for making bread and cookies. Maca is mixed with *chuño* (freeze-dried potatoes), oca, quinua and soyabeans to prepare different dishes and dessert. Toasted and ground 'hypocotyls' are used to prepare "maca coffee" (Castro de Leon 1990).

Local consumers close to the production sites prefer medium size and yellow maca roots. This is because larger roots take longer to cook and the colour preference is due to the belief that yellow roots are sweeter than those of other colours. Apparently any root shape is acceptable. In general, however, there are no established quality characteristics for this crop. The pharmaceutical industry is now a main consumer of maca, and processes practically any roots that are in acceptable sanitary condition. The main centres of commercialization of maca are in La Oroya, Junín and Huancayo. The total production of maca is estimated to be approximately 320 t/year, and it is possible that the demand is twice as much. In 1995, the cost of 1 kg of dried maca hypotocotyls was between US$1.5 and $2 in the Junín market. There are now efforts by pharmaceutical laboratories to promote the cultivation of this crop and expand its production (F. Tamayo, pers. comm.).

According to folk belief, maca is an aphrodisiac which enhances sexual drive and female fertility in humans and domestic animals, which tends to be reduced at higher altitudes (León 1964). Sanchez León (1996) presents an interesting account of the role of maca in the conquest of the Inca Empire. The Spaniards when arriving in a hostile environment, such as the puna of Junín, were afraid of losing their horses because of the lack of conventional pastures and their inability to reproduce at high altitudes. They soon learned about the nutritious and fertility-enhancing properties of maca, allowing their horses to pasture in fields of this crop. The conquerors found "well fed babies and tall adults" in the high Andes, which was attributed to their diet based on maca. Owing to these beliefs, maca had a prominent place as a crop used to enhance the reproduction of pigs, chickens and horses. During the times of the Tawantinsuyo, the legend says that before going to war the Incas used maca to feed the warriors to increase their energy and vitality. However, after conquering a city the soldiers were prohibited to consume it as a measure to protect women from their sexual impulses.

Beliefs of fertility-enhancing properties of maca have been partially substantiated by limited experiments in rats, which indicate that gains in fertility are due to the probable increase in the development of the Graaf follicles (Chacón 1990; Rea 1992). Chemical analysis by Johns (1981) suggests that the fertility-enhancing properties of

maca may be due to the presence of biologically active aromatic isothiocyanates, and specifically due to benzyl isothiocyanate and p-methoxybenzyl isothiocyanate. The latter is also found in mashua (also know as *añu and isaño) (Tropaeolum tuberosum* Ruiz and Pavon). This species, however, is reputed to be an antiaphrodisiac and antireproductive agent in males, but a promoter of female fertility (Johns 1981). The putative aphrodisiac powers of maca also can be attributed to the presence of prostaglandins and sterols in the 'hypocotyls' (Dini *et al.* 1994). In early times, maca was appreciated not only as nutritious food, but also as a gift to the gods along with corn and potatoes. Mountain Raco in Junín was considered the god of stewed food. In its honour, the natives buried potatoes and maca there among other offerings. Maca also was used in beverages with hallucinogenic products in dances and religious ceremonies (Castro de León 1990). Today in the local markets it is advertised as an aphrodisiac, stamina-builder and ferility-promoter. It is also often promoted as a cure for rheumatism, respiratory ailments and as a laxative. Dried maca roots are ground to power and sold in drugstores in capsules as a medicine and food supplement to increase stamina and fertility. One of the leading pharmaceutical laboratories in Peru has started an aggressive advertising campaign promoting maca capsules as a magnifier of sexual potency. Other medicinal properties attributed to maca are regulation of hormonal secretion, stimulation of metabolism, memory improvement, antidepressant activity and effectiveness in combating anemia, leukemia, AIDS, cancer and alcoholism among others. None of these properties, however, has been substantiated by scientific research. Because of these putative virtues, maca is also known by the name of Peruvian ginseng (Rea 1992).

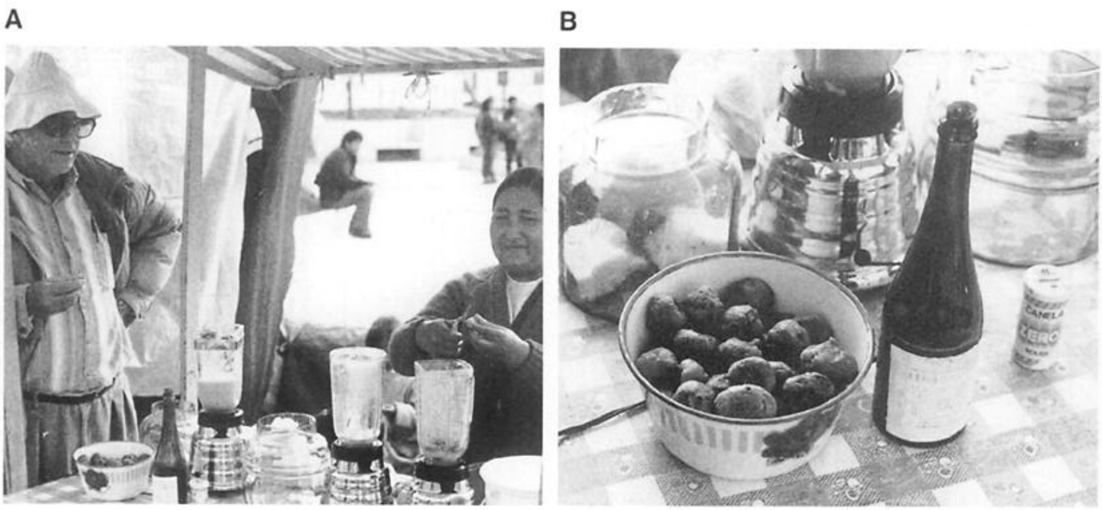


Fig. 9. Market stand in Junín offering maca cocktails. **A:** preparation by cutting boiled roots in small pieces. **B:** blending maca roots with milk, honey, pineaple, cinnamon, algarrobina and other components.

5 Properties

The nutritional value of the dried 'hypocotyl' of maca is high, resembling that found in cereal grains such as maize, rice and wheat. Fresh hypocotyls contain 80% water. Dry maca hypocotyls have the following composition: 59% carbohydrates, 10.2% proteins, 8.5% fiber and 2.2% lipids among a few other compounds (Dini *et al.* 1994). Maca has a large amount of essential amino acids and higher levels of iron and calcium than the white potato. In addition, it contains important amounts of fatty acids, of which linoleic, palmitic and oleic acids are the most prominent. Maca is also rich in sterols and has a high mineral content, in particular Fe, Ca and Cu. Alkaloids are also present, but these have yet to be determined (Dini *et al.* 1994) (Table 1). Maca has a strong and peculiar flavour which is not acceptable to many people. In most cases, this is disguised by other components used in preparation of juices and other concoctions. The compounds responsible for maca flavour are unknown and may be other than glucosinolates (T. Johns, pers. comm.).

Table 1. Summary of the most prominent chemical components of maca 'hypocotyls' (after Dini *et al.* 1994)

Component	Content
Protein (% of total dry weight)	10.2
Hydrolyzable carbohydrates (% of total dry weight)	59.0
Amino acids (mg/g protein)	
Aspartic acid	91.7
Glutamic acid	156.5
Serine	50.4
Glycine	68.3
Arginine	99.4
Valine	79.3
Fatty acids (% of methyl ester mix)	
Palmitic acid	23.8
Linoleic acid	32.6
Saturated fatty acids	40
Unsaturated fatty acids	52.7
Sterols (% of sterol mix)	
Campesteryl acetate	27.3
Sitosteryl acetate	45.5
Minerals (mg/100 g dry matter)	
Fe	16.6
K	2050
Ca	150

6 Genetic resources and breeding

The largest collection of cultivated maca and wild species of *Lepidium* is maintained at the Universidad Nacional Agraria, La Molina, in Lima, Perú. This collection is the product of four expeditions to the Departments of Pasco, Junin, Huancavelica, Ayacucho and Cuzco. It consists of 93 accessions of maca and 41 of wild species. In addition, 38 experimental lines, mostly progenies from single plant selections, are maintained in the collection (Table 2). Most of the maca accessions come from Pasco and the eastern side of lake Junín and higher part of the Mantaro valley around Huancayo. It includes the whole range of morphological types for 'hypocotyl' shape and colour (Table 3). The majority of the accessions have yellow or purple 'hypocotyls'. The curator of the collection is Ing. Rolando Aliaga. At the present time a controlled-temperature facility is being built at the university campus for long-term storage. The collection is being evaluated *in situ* in Junin and Pasco. A smaller collection consisting of approximately 33 accessions, mostly duplicates of the first one, is located in the International Potato Center at the station in Lima. The curator of this collection is Dr Michael Hermann. Details of accessions can be retrieved through the web site of the System-wide Information Network on Genetic Resources (SINGER) of the Consultative Group on International Agricultural Research (CGIAR) on the world wide web (http: / / www.cgiar.org, then click on "Inter-Center Initiatives", then on "SINGER").

Table 2. Number of accessions of maca and other *Lepidium* wild species maintained at the Universidad Agraria, La Molina

	Place of collecting				
Species	Junin	Pasco	Huancavelica	Ayacucho	Cuzco
Cultivated	58	32	3	0	0
Wild	17	14	4	3	3
Experimental lines	38	0	0	0	0

Table 3. 'Hypocotyl' colour distribution in the maca germplasm collection

Colour	No. accessions	%
Yellow	36	39
Purple	27	29
White	2	2
Grey	2	2
Black	3	3
Yellow/Purple	12	13
White/Purple	11	12

The seed is stored in commercial freezers at approximately -15°C on silica gel, which assures germination close to 95%, based on a 5-year observation period. Prior to introducing the seed in the freezer, it is dried on silica gel for 2 weeks. Seeds of maca are maintained by growing 20 plants per accession, until they produce enlarged 'hypocotyls'. These are then vernalized at 5-7°C for 2 months in moist peat. Seed germination tests are recommended every 2 years (M. Hermann, pers. comm.).

No official descriptors have been published for maca; however they are in preparation as part of the research activities of the programme "Raíces y Tuberculos Andinos" based at the International Potato Center in Lima.

In other institutions, the collections are fairly new and therefore regimes for renovation and maintenance are not well established yet, which in many cases is due to lack of funding and resources. There are areas of maca production which are not represented yet in the existing collections. These include the western side of lake Junín and the Department of Huancavelica, where there are a few reports of cultivated maca. Wild species are poorly represented in the existing collections. A systematic collecting effort needs to take place from Huanuco to Puno and Bolivia.

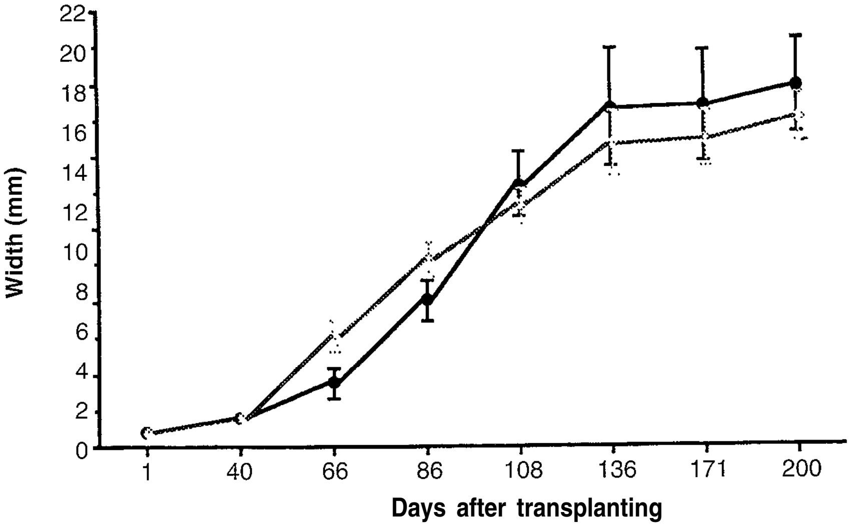
Genetic improvement of maca is restricted at the present time to root selection for colour, size, shape and other desirable attributes. Selected roots are replanted later for seed collection. The small size of the flowers and the large numbers of flowers per cluster at different stages of development, which approaches 50, make quite difficult the emasculation and elimination of flowers not appropriate for this procedure because of their different ages. The oldest flowers in the raceme are on the outside whereas the youngest are at the centre. These difficulties are aggravated by the cleistogamous nature of the flowers which need to be emasculated using magnifying aids while they are still closed but before there is any evidence of pollen shedding. Furthermore, emasculated flowers do not seem to survive well, probably because of damage to other floral structures during the delicate procedure.

7 Ecology

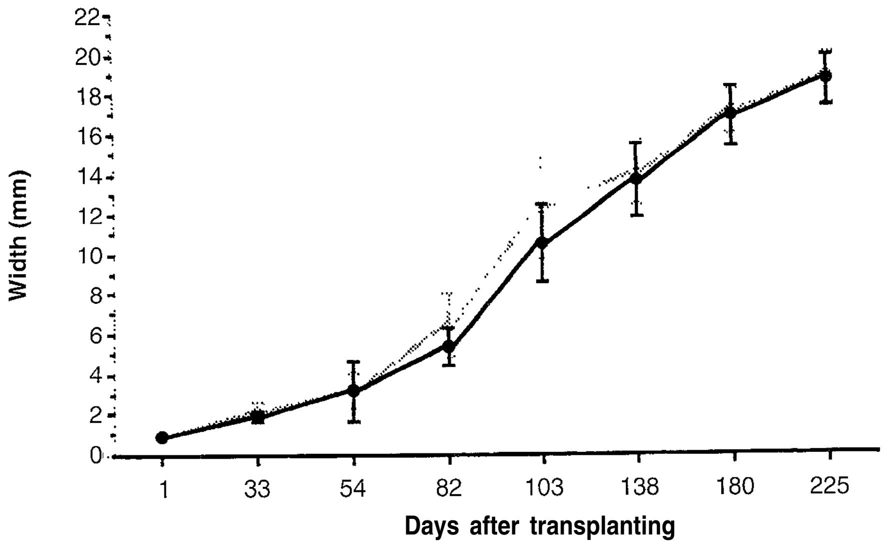
Maca has one of the highest frost tolerances among other native cultivated plants, since it is able to grow in the puna where only alpine grasses and bitter potatoes thrive (Bonnier 1986). The natural habitat of highland Peru where maca is grown has an average minimum temperature of -1.5”C and an average maximum of 12°C (Tello *et al.* 1992). Frost is frequent and temperatures can get as low as -10°C. The relative humidity is high, with an average of 70%. The natural soil in the maca production area is acidic, having a pH of 5 or less (Tello *et al.* 1992).

Although production of maca is restricted primarily to the central Andes of Peru, it can be grown successfully in other parts of the world. Field experiments in Davis, California indicate that this crop can be grown during the winter in this area as an annual crop if irrigation is available throughout its whole life cycle. At Davis, 4 to 6-week-old seedlings transplanted in the field at the middle of September initiated hypocotyl development in 6-8 weeks. At this time of the year daylength is approximately 10 hours and mean soil temperature approximately 12°C. The ‘hypocotyls’ reached a maximum size of 35-50 mm in diameter 7 months after transplanting, when daylength was over 13 hours and mean soil temperature was approximately 20°C. By the middle of March, at the end of the rainy season, irrigation water was supplied as needed. Floral stems developed at this stage at the base of the stem, reaching anthesis and fruit-setting 8-9 months after sowing the seed. Therefore, most of the plants completed their seed-to-seed cycle in 10-11 months.

Experiments on photoperiod response in growth chambers demonstrate that maca does not require short days for general development, hypocotyl enlargement or flowering. Hypocotyl enlargement takes place at similar rates under either short (12 hours) or long days (14 hours) (Fig. 10). Similarly, flowering takes place independently of daylength and without need of a vernalization period (Quirós *et al.* 1996). It is unknown, however, whether vernalization will promote more profuse and coordinated flowering in this species. From the results of these experiments, maca can be considered photoperiod-neutral and can be grown as an annual or biennial species, depending of water availability and optimal temperatures. Low temperatures and water availability during the growing season seem to be more important than daylength in the development of the maca plant. Therefore, with adequate water supply to the plants and cool temperatures, *in situ* as well as *ex situ* germplasm conservation activities can be carried out for maca without much impediment. Maca may be grown outside its native habitat, the Andean highlands of Junín, and therefore its range of adaptation is not as narrow as previously believed (Tello *et al.* 1992).



A



B

Fig. 10. 'Hypocotyl' width (mm) based on four accessions, five plants per accession grown under long (light line) and short day (dark line) conditions for 29-32 weeks at two temperature regimes. **A:** 18°C maximum and 8°C minimum temperatures; **B:** 22°C maximum and 12°C minimum temperatures. Error bars are shown at each point (Quirós *et al.* 1996).

8 Agronomy

Maca is sown in small plots in empty grazing fields by broadcasting the seeds still containing floral debris mixed with soil. In the Junín area sowings with seed stored for 4 years are common. However, the viability of these seeds may be only 50%.

One kilogram of seed with 15 kg of soil is used for high-density planting or 1 kg of seed and 25 kg of soil for low density. Then sheep are released to the field to trample the seed. This will result in 700 000-400 000 plants/ha depending on the sowing density used. Sowing takes place from September to October starting at the initiation of the rainy season, usually in the morning to avoid winds. The soil is well prepared, with clods broken up, and is fertilized with sheep manure. Often the plants are thinned out 2 months after sowing to obtain uniform and larger hypocotyls. Weeds, if present in the field, are removed by hand. The seed is commercialized as *charpu,* which is the amount of seed and floral debris mix contained in an l8-cm diameter dish (Tello *et al.* 1992). The pastures lie fallow for as many as 10 years before maca is again planted in the same plot. This is because maca seems to exhaust the soil by extracting nitrogen and other nutrients (Tello *et al.* 1992). Also, fallow plots will result in less incidence of weeds, pathogens and pests when the crop is produced. The main pests and diseases, which are just a few, include a root borer called *gorgojo* de los Andes *(Premotrypes* spp.) and a leaf fungus causing mildew *(Peronospora parasitica).* Other fungal pathogens causing diseases present in the area are *Fusarium* graminium and *Rhizoctonia solani* (Tello *et al.* 1992; Aliaga-Cárdenas 1995).

The hypocotyls are harvested from May to July when they are at their maximum size, about 5 cm in diameter (Leon 1964; Tello *et al.* 1992). At this time, most of the leaves in the plants are still growing, without showing signs of senescence. A local hand hoe called a *cashu* is used for digging the plants one by one (Fig. 11). The curved

Fig. 11. Utilization of a *cashu* for maca harvesting in Junín.

blade of this tool avoids damage to the roots. Estimated yields of fresh hypocotyls are 14.7 t/ha and 4.4 t/ha of dried hypocotyls with a harvest index of approximately 0.77 (Tello *et al.* 1992). After harvesting, the whole plants are dried during the day under the sun for 10-15 days, and covered during the night to avoid rain and frost damage. The leaves are left on the plant during drying because the local farmers believe that this will result in sweeter roots. After drying, the leaves are removed and the hypocotyls are taken to the market or stored dry in layers of less than 10 cm thick in well-ventilated sheds protected from the rain. Some of the freshly harvested plants are replanted for seed production during the following spring when the first

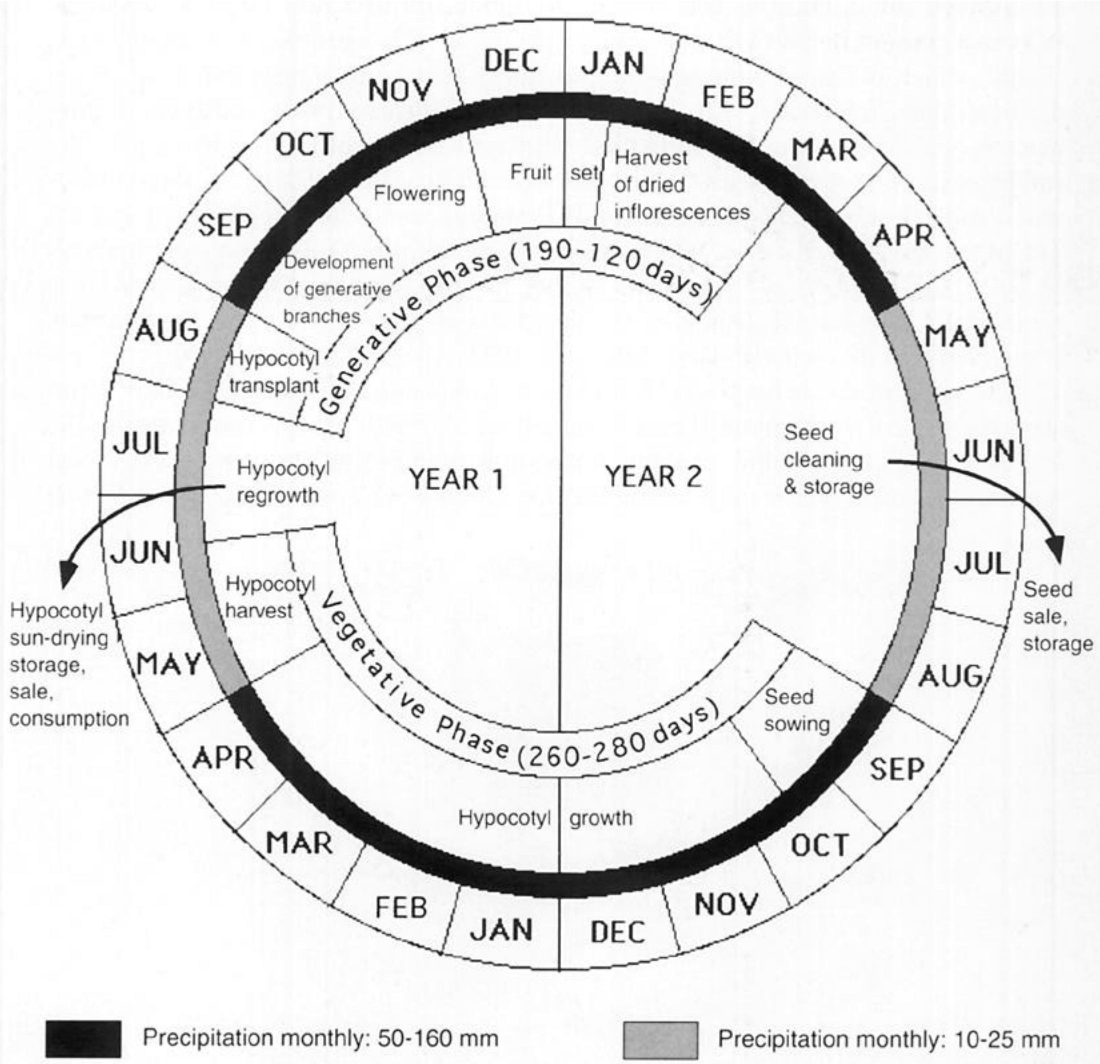


Fig. 12. Maca production biennial cycle in Junin coordinated with rainy season (redrawn from Tello *et al.* 1992).

rains appear (Tello *et al.* 1992). For this purpose, the whole plants are stored in pits covered with soil for approximately 45 days to allow root regrowth and initiation of generative shoots. This practice results in the loss of many plants due to rotting of the foliage. After this period, when the generative shoots are about to appear, the hypocotyls are dug out and transplanted 0.6-0.7 cm apart in empty sheep stables where plenty of manure is available in the soil. Therefore, maca is handled as a biennial crop because of water limitation in the region. Each cycle, vegetative and reproductive, is coordinated with the beginning of the rainy season in the central Andes, as illustrated in Fig. 12. After approximately 4 months the whole plants are lifted, when the siliques begin to turn yellow before dehiscence to avoid seed shattering. The plants are then dried and the seed is thrashed by rubbing the dry inflorescences with both hands (Tello *et al.* 1992).

9 Limitations, research needs and prospects

9.1 Limitations

The main limiting factors of maca production are availability of good-quality seed, adequate weed control, acid soils in the present area of cultivation and post-harvest handling. Seed is often sufficient for planting only small plots, sincelarge quantities are hard or impossible to find from a single source. The presence of floral debris and soil mixed with the seed makes it difficult to know how much actual seed is really available. Other limitations are lack of information on soil management practices as well as weed, insect and disease control.

9.2 Research needs

- Better seed-cleaning methods must be adopted.
- The seed bulked from many plants of different characteristics makes it impossible to determine the root colours that will be obtained in the crop. This makes necessary the systematic selection of plants of different traits to generate cultivars possessing predictable traits. Simple breeding and selection schemes along with good seed-production practices will rapidly solve this limitation.
- Effective practices for weed control are necessary to increase yields.
- Soil acidity could be solved by application of amendments to increase the pH. Little research has been done on this problem, whose solution could result in substantial yield increases (Quirós *et al.* 1996). At the present time, it is possible that maca is not being grown to its full potential because of the lack of optimal soil in the production areas.
- The current practice of drying the plants after harvesting needs improvement. Often it results in losses of 30-50% of the harvest due to rotting caused by overheating of foliage still present in the plants. Research is necessary to determine the optimal practices for root drying to minimize losses.

9.3 Prospects

Maca is one of a few crops that can be grown at high altitudes. It has gained great popularity as a nutritious food and its reputed medicinal properties open up the opportunity to grow it on a larger scale in the highlands of the Andean region. Its amenability for processing in a large number of products, including health supplements, makes this crop quite attractive for regions where other crops cannot be grown. Further, the unmet demand of maca at the present time provides the challenge to expand the area dedicated to this crop and to work toward the solutions of its present limitations.

Acknowledgements

We are indebted to M. Holle and Francisco Delgado de la Flor for supporting research on maca, to Vincent D'Antonio and Francisco Jarrín and Judith Toledo for technical assistance, to Michael Hermann for supplying seeds of some of the wild species and to Dr I. Al-Shahbaz for species identification. Research was supported in part by a grant from the Consortium for the Sustainable Development of the Andean Ecoregion at the International Potato Center (CIP-COTESU).

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Yacon

Smallanthus sonchifolius (Poepp. & Endl.) H. Robinson

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Contents

1 Introduction

The Andean region has been the cradle of a surprisingly wide range of edible tubers and roots. Most of them have been used by the Andean inhabitants as food energy, while two - ahipa *(Pachyrhizus ahipa)* and yacon *(Smallanthus sonchifolius)* -have been considered 'fruits'. That perception is particularly strong in the case of yacon, which despite its juiciness and sweet taste, has been recognized as a food of relatively low energy value since early times.

Some medicinal attributes may have increased the attractiveness of yacon to the ancient Andean people. However, its high productivity and other attractive agronomic traits could not counterbalance its low nutritive value. This likely led to diminished interest on the part of the old Andean agronomists, who presumably did not work on yacon as they did on potato *(Solanum tuberosum),* oca *(Oxalis tuberosa)* or ulluco *(Ullucus tuberosus).* Furthermore its reduced nutritive value may have contributed to the disappearance of yacon landraces in 'many areas at different historical stages, in times of crisis or famine. This process has probably accelerated significantly in the present century, owing to the profound political, social and cultural changes happening in the Andes. In recent decades, improved transport has increased the availability of fruits in the region, which may be competing with yacon in the local markets.

In modern times, the human view of yacon could be radically different from in the past. Certainly, calories are still limited and critical in many regions of the earth and the Andes themselves. In contrast, on a global scale, starch, glucose and fructose are comparatively common commodities, with relatively low prices, and are available to certain sectors of the human population in quantities well above their dietary requirements and even beyond their physiological tolerance. Under these conditions, yacon may provide the low calories and fiber necessary to survive the stress of sedentary lifestyles combined with overconsumption of carbohydrates and fats.

The productivity and other valuable agronomic traits of yacon strongly suggest that it is a species with a great potential. With limited testing and fine tuning, addition of conventional fertilizers to the clones developed by the old Andean agronomists has produced annual yields of up to 100 t/ha (fresh weight). It is easy to speculate on potential yields if modern breeding techniques, hybridization or genetic engineering were applied. But perhaps the challenge of the future will be not only to breed yacon into a very productive multipurpose crop and to satisfy several aspects of modern life requirements, but also to pay back to the descendants of the old Andean agronomists a fair share for their invention.

2 Vernacular names

The species has received common names in the dominant Andean languages, Aymara and Quechua (Cárdenas 1969). *Aricoma* and *aricuma,* the Aymara terms, are used in certain areas of Bolivia. *Llaqon, llacum, llacuma* or *yacumpi* are the Quechua words that evolved into 'yacon', perhaps after the Spanish conquest. In the Quechua language, *yacu* and *unu* are words meaning water, while *yakku* is an adjective meaning watery or insipid. 'Yacon', with subtle regional differences in the pronunciation of the 'y' and the 'c' or 'k', is commonly used from Peru to northwestern Argentina. Much less frequent is the term *ipio,* used by the Chiriguano groups in the lowlands of Southern Bolivia. In Ecuador, *jicama, chicama, shicama, jiquima* or *jiquimilla* are the common names of the species (Tittel 1986). These terms closely resemble and probably derive from *xicama,* the Mexican term applied to *Pachyrhizus erosus* and extended to the other members of the genus *Pachyrhizus.* This word was presumably introduced by the Spanish invaders, who began their Andean conquest in Ecuador after arriving from Central America. The term *arboloco,* used in Colombia, suggests very strongly a Spanish background. Yacon has also received names in other European languages, coined probably by researchers or growers: *poire de terre* (French) and yacon strawberry (English).

3 Taxonomy

3.1 The genus

Yacon and its relatives were originally placed in *Polymnia* (Compositae, Heliantheae, subtribe Melampodinae), a genus founded by Linnaeus in 1751. De Candolle (1836) produced the first comprehensive treatment of the group. Later, important contributions were made by Blake (1917, 1930). In the first modern revision of the genus, Wells (1967) maintained yacon and its relatives within *Polymnia.*

A different perspective was adopted by Robinson in a more recent study (1978). Robinson re-established the genus *Smallanthus,* proposed by Mackenzie in 1933.

Robinson separated the species previously considered within Polymnia by Wells into two genera — *Smallanthus* and *Polymnia* — keeping both within the subtribe Melampodinae. One North American species, most Central American species and all South American species were placed in *Smallanthus,* while a few North American species remained in *Polymnia.* According to Robinson, there are important differences separating *Polymnia* from *Smallanthus* (e.g. striation on the cypsela surface, presence of a whorl of outer involucral bracts, absence of glands on the anther appendages, lack of a particular feature in the lobes of the disk flower corollas). Some of those characters place *Polymnia* as the most isolated genus within the subtribe, while *Smallanthus* is closer to other genera in the group, such as *Melampodium* and *Espeletia,* than to true *Polymnia.* Robinson's point of view is formally sound, it has gained acceptance by the North American authors and it is being used in the North American herbaria. *Smallanthus* also has been adopted by Brako and Zarucchi (1993) in their catalogue of plants of Peru, and by Jørgensen and León (1997) in their catalogue of vascular plants of Ecuador.

It is important to point out that both Wells and Robinson principally, or perhaps only, studied herbarium specimens of the South American species. Moreover, herbarium material of these species is scarce, frequently poorly preserved and rarely includes underground organs, which in this case would be of particular interest. These limitations have certainly affected the work of Wells and Robinson. This fact may explain why Wells' key to the species is of limited value for identifying the South American taxa.

Smallanthus sensu Robinson includes at least 21 species, all American, ranging mostly through southern Mexico and Central America and the Andes. They are perennial herbs, less frequently shrubs or small trees and only rarely annuals.

3.2 The species

Smallanthus sonchifolius (Poepp. & Endl.) H. Robinson, Phytologia 39:51. 1978.
Synonyms: *Polymnia sonchifolia* Poepp. & Endl. Nov. Gen. Sp. Pl. 3:47. 1845.
Polymnia edulis Wedd., Ann. Sci. Nat. Bot. IV. 7:114:1857.

3.3 The other Smallanthus species

Smallanthus apus (Blake) H. Robinson
This is a poorly known Mexican species.

Smallanthus connatus (Spreng.) H. Robinson
An annual herb up to 2 m tall, widely distributed, present in southeastern Brazil, Paraguay, Uruguay and eastern Argentina to 35°S. It is the southernmost species, closely related to S. *macroscyphus.*

Smallanthus fruticosus (Benth.) H. Robinson
It is a shrub or tree to 12 m tall, distributed in southern Colombia, Ecuador and northern Peru.

Smallanthus glabratus (DC.) H. Robinson
A shrub or tree up to 8 m tall, closely related to *S. fruticosus* and placed by Wells together with *S. parviceps* and *S. microcephalus* within the *glabrata* complex. Its main area of distribution is the Peruvian mountains. It also has been reported in Ecuador and Chile.

Smallanthus jelksii (Hieron.) H. Robinson
A shrub or tree up to 8 m tall, described only for Peru, related to S. *pyramidalis,* both with characteristic small flower heads.

Smallanthus latisquamus (Blake) H. Robinson
Considered a synonym of *S. quichensis* by Wells (1965), *S. latisquamus* is treated as a separate species by Robinson (1978). Stems up to 3 m tall, present in Costa Rica.

Smallanthus lundellii H. Robinson
This species proposed by Robinson (1978) is a herb up to 1 m tall, related to *S. latisquamus* and *S. quichensis,* found in Guatemala.

Smallanthus macroscyphus (Baker ex. Martius) A. Grau, comb. nov.
A perennial herb up to 3 m tall, present in Bolivia and northwestern Argentina, where it is known as *yacon del campo* (wild yacon). It has a well-developed root system with storage roots that can reach 2-5 cm diameter. *Smallanthus macroscyphus* and *S. connatus* were treated as synonyms by Wells (1965) and Robinson (1978). On the contrary, Cabrera (1978) and Zardini (1991) consider them different species (Fig. la, b).

Smallanthus maculatus (Cav.) H. Robinson
A coarse herb up to 5 m tall. Several varieties of the species have been described for Mexico, Guatemala, Honduras, El Salvador, Nicaragua and Costa Rica.

Smallanthus macvaughii (Wells) H. Robinson
A herbaceous species up to 5 m tall, present in Mexico and related to *S. oaxacanus.*

Smallanthus meridensis (Steyerm.) H. Robinson
A herb with stems up to 3 m tall, distributed in Venezuela and Colombia.

Smallanthus microcephalus (Hieron.) H. Robinson
A shrub or small tree up to 8 m tall, found in Ecuador.

Smallanthus oaxacanus (Sch.Bip. ex Klatt) H. Robinson
A herb up to 2 m tall, distributed in Mexico, Guatemala and Honduras.

Smallanthus parviceps (Blake) H. Robinson
Another shrub or tree up to 8 m tall with stems of 15 cm diameter. It occurs in southern Peru and northern Bolivia.

Smallanthus pyramidalis (Triana) H. Robinson
A tree up to 12 m tall and 20 cm diameter at the base, distributed in Venezuela, Colombia and Ecuador.

Smallanthus quichensis (Coult.) H. Robinson
Closely related to *S. latisquamus* and present in the same region, Costa Rica and Guatemala.

Smallanthus riparius (H.B.K.) H. Robinson
A herb or shrub up to 4 m tall, with a very wide latitudinal range, from southern Mexico to northern Bolivia.

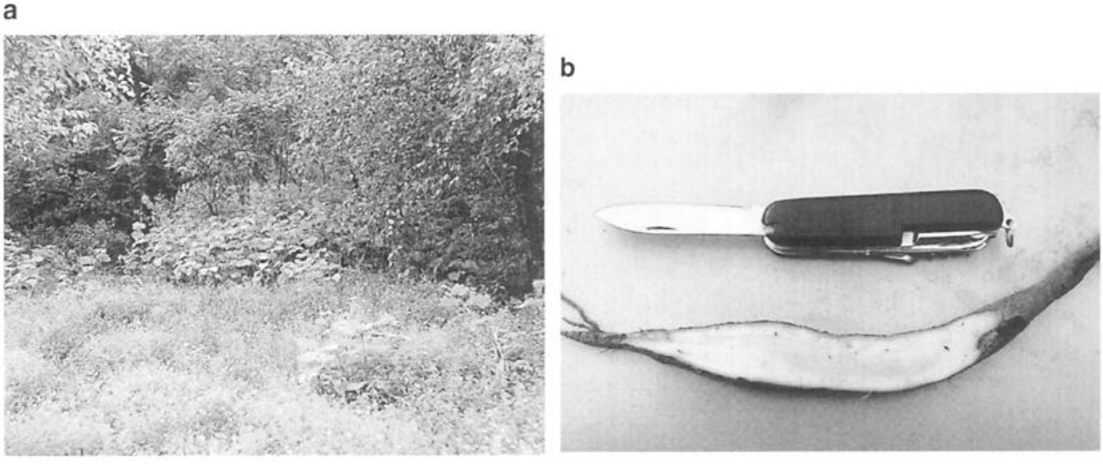


Fig. 1. Yacon del campo *(Smallanthus macroscyphus)* growing on a landslide at 1400 m asl in the cloud forest of Tucumán province, Argentina (a); storage root, detail (b).

Smallanthus siegesbeckius (DC.) H. Robinson
Described as an annual herb by Wells (1965). However, observations by Lizárraga and Grau (unpublished) on material responding to the description of *S. siegesbeckius* indicate that this species is perennial, up to 5 m tall, possessing a well-developed underground system, with many tuberous roots very similar to yacon, 20 cm long and 6 cm diameter or more (Fig. 2a, b). This species has been described for Peru, Bolivia, Brazil and Paraguay. It is possible, however, that the Brazilian and Paraguayan material actually belongs to a different species.

Smallanthus suffruticosus (Baker) H. Robinson
A shrub or herb up to 2 m tall adapted to the lowlands of Venezuelan Amazonia.

Smallanthus uvedalius (L.) Mackenzie
A perennial herb up to 3 m tall, distributed in the eastern United States of America from New York to Florida and Texas.

3.4 Relationships between species

No comprehensive taxonomic study has been carried out beyond Wells' perspective (1965) and Robinson's rearrangement (1978). Following, in part, Wells' guidelines it is possible to distinguish some species groups.

The best-studied group includes the North American-Mexican-Central American species. Owing to the availability of herbarium material this group was thoroughly analyzed by Wells, who recognized several varieties in some of the species. These species are herbs and some of them are related: *S. maculatus* is hard to distinguish from *S. uvedalius; S. macvaughii* is close to *S. oaxacanus; S. quichensis* is related to *S. latisquamus* and *S. lundellii.* While geographically distant from yacon, some of the Central American species may be taxonomically close to the 'yacon

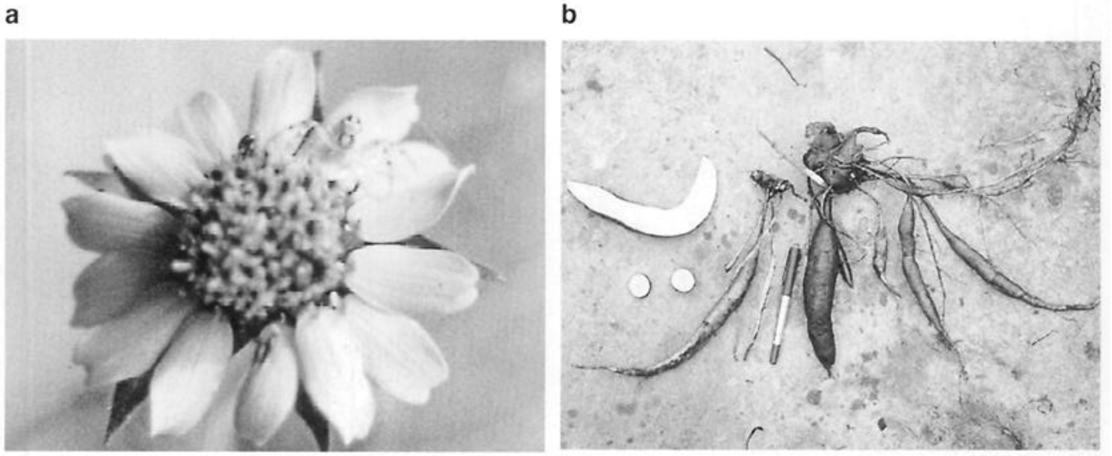


Fig. 2. *Smallanthus* cf. *siegesbeckius* collected by L. Lizárraga and A. Grau at 1900 m asl, Ahuabamba, Cusco region, Peru: flower (a), underground organs (b).

group' (see below). *Smallanthus riparius,* the only Central American species that extends to the Andean region, is indeed a member of that group.

Considering geographical distribution, growth habit and morphology of the aerial parts, six species appear to be close to *S. sonchifolius,* forming a sort of 'yacon group': *S. connatus, S. macroscyphus, S. riparius, S. meridensis, S. suffruticosus* and *S. siegesbeckius. Smallanthus riparius* is considered very close to *S. siegesbeckius* by Wells (1965), to the point that he reported intermediate herbarium specimens. *Smallanthus riparius* also closely resembles *S. macroscyphus.* It is likely that at least two of the species in this group have contributed to the yacon genome. It is also possible that at least some of the material present in different germplasm collections as 'wild yacon' is actually *Smallanthus* species of this group, other than *S. sonchifolius.*

Wells placed four species *(S. glabratus, S. microcephalus, S. parviceps* and *S. fruticosus)* into a *'glabrata* complex', a group formed by shrubs or small trees reaching sometimes 10 m or more. *Smallanthus jelksii* and the related *S. pyramidalis* also reach tree size. Nevertheless, they appear to be more related to the yacon group than to the *glabrata* complex.

4 Species description

4.1 Botanical/morphological description

The yacon is a perennial herb, 1.5-3 m tall. The root system is composed of 4-20 fleshy tuberous storage roots that can reach a length of 25 cm by 10 cm in diameter, and an extensive system of thin fibrous roots. Storage roots are mainly-fusiform, but often acquire irregular shapes due to the contact with soil stones or the pressure of neighbouring roots. Roots have an adventitious nature, growing from a developed and ramified stem system formed by short, thick sympodial rhizomes or rootstock ('corona', crown) (Fig. 3).

Storage root growth is caused by the proliferation of parenchymatous tissue in the root cortex and particularly in the vascular cylinder. The parenchyma accumulates sugars and, in some cases, pigments typical of certain clone groups. According to pigments, flesh colour varies considerably: white, cream, white with purple striations, purple, pink and yellow. The tuberous root bark is brown, pink, purplish, cream or ivory white, thin (l-2 mm) and contains resin conduits filled with yellow crystals.

The aerial stems are cylindrical or subangular, hollow at maturity with few branches in most clones or ramified in others, densely pubescent, green to purplish. Lower leaves are broadly ovate and hastate or subhastate, connate and auriculate at the base; upper leaves are ovate-lanceolate, without lobes and hastate base; upper and lower surfaces are densely pubescent. Lower and upper epidermis have trichomes (0.8-1.5 mm long, 0.05 mm diameter) and glands which contain terpenoid compounds (Fig. 4a, b).

Inflorescences are terminal, composed of 1-5 axes, each one with 3 capitula; peduncles densely pilose. Phyllaries 5, uniseriate and ovate. Flowers are yellow to bright orange; ray flowers are 2 or 3-toothed, depending on the clone, to 12 mm long x 7 mm broad, pistillate; disc flowers about 7 mm long, staminate. Immature cypselas are purple, and turn dark brown or black at maturity (Fig. 5).

4.2 Reproductive biology

Flower production is more reduced in yacon than in other wild *Smallanthus* species. Reduced flowering and fruit set are features commonly present in other clonally propagated tuber crops. During yacon evolution, continued vegetative propagation and selection for root yield may have impaired flowering and fruit set.

Flowering is strongly dependent on the environment of the growing area. In some regions, such as northwestern Argentina, flowering happens very late in the growing cycle or not at all. On the contrary, flowering is intense in most clones in northern Bolivia, the growing areas around Cusco, southern Peru and Cajamarca, northern Peru. In the Cajamarca region flowering begins 6-7 months and peaks 8-9 months after planting. But even in the areas where flowering is abundant, seed set is frequently poor or nonexistent and a high proportion of the seeds are non-viable or show low vigour.

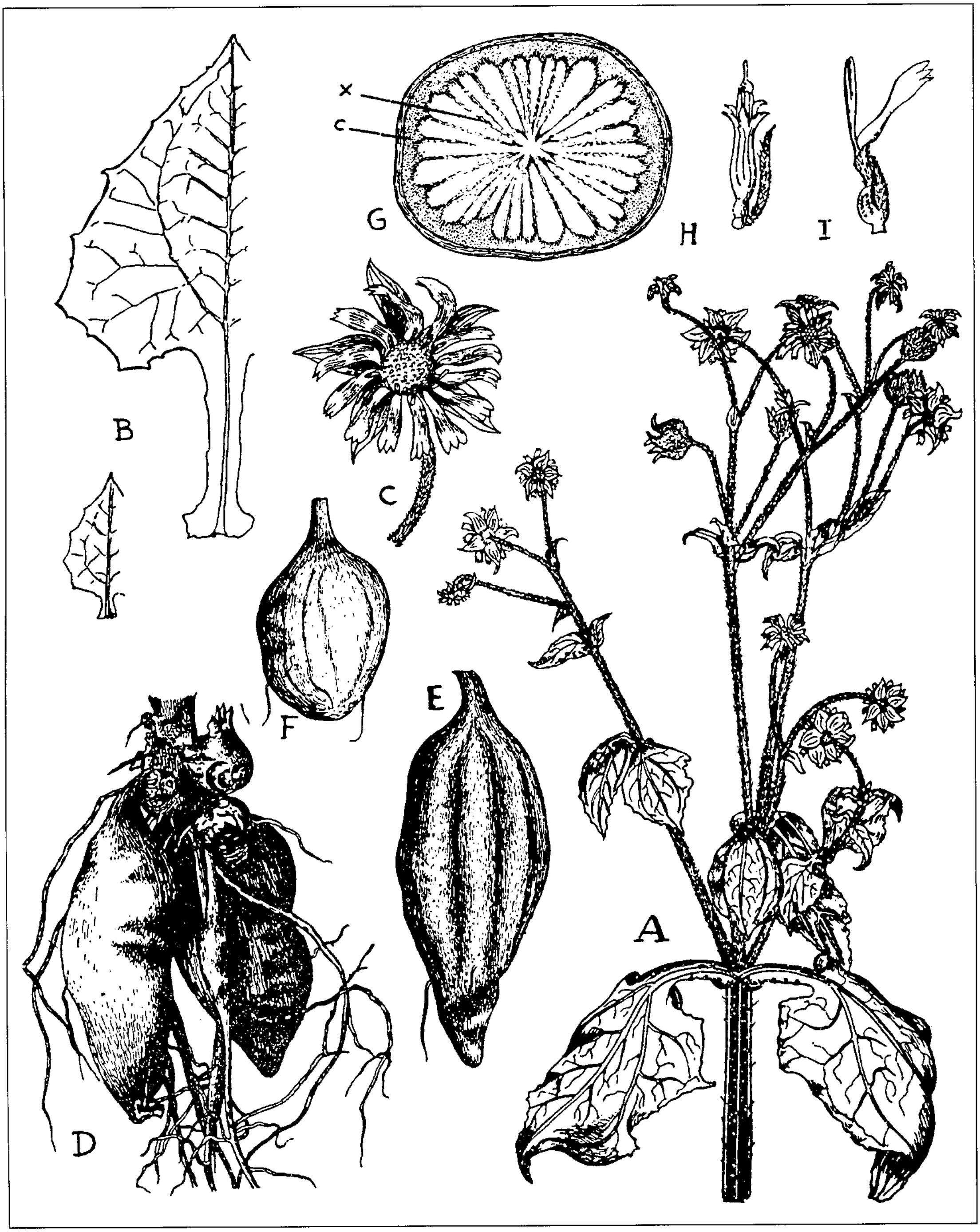
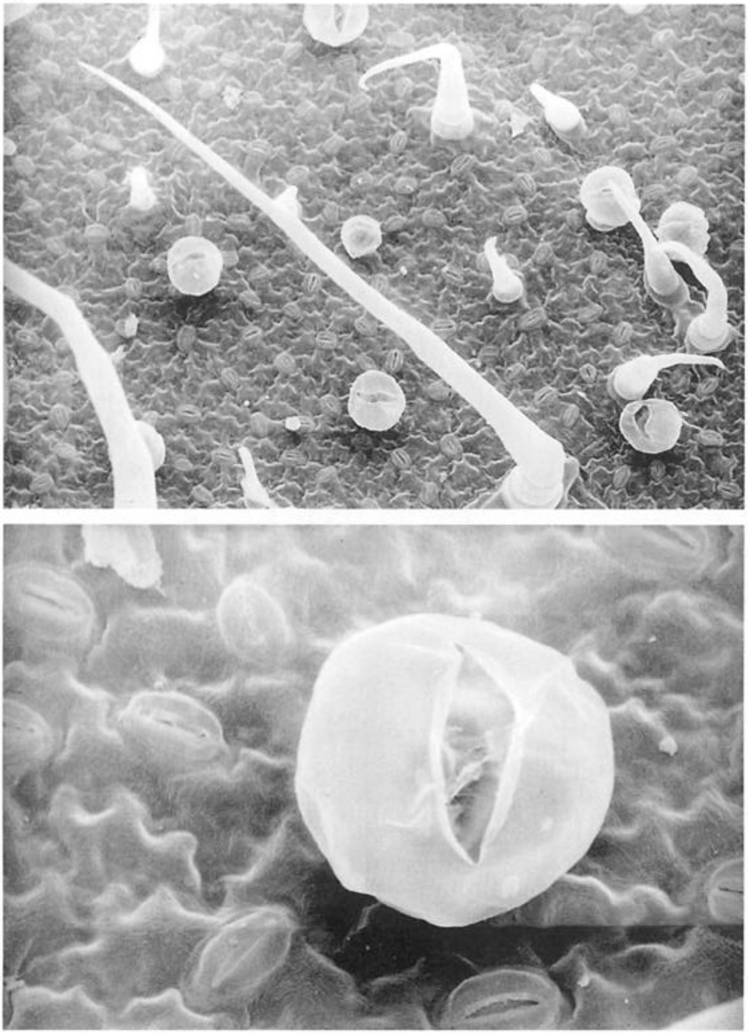


Fig. 3. Yacon *(Smallanthus sonchifolius)* morphological aspects (from León 1964). A: flowering branches. B: leaves. C: flowerhead. D-F: tuberous roots. G: transverse section of the tuberous root (x, xylem; c, cortex tissues). H: staminate disk flower. I: pistilate ray flower.

Poor seed set and low seed vigour can be the result of problems at different levels. One factor is high pollen sterility. Grau (1993) failed to obtain viable seeds under glasshouse conditions working with a single clone grown commercially in New Zealand. Artificial pollination was tried, but pollen was highly sterile and no filled fruits were produced. Low pollen fertility (0-30% fertility) also was observed in Argentine (Grau and Slanis 1996) and Ecuadorian clones (Grau, unpublished, material supplied by Dr R. Castillo, INIAP). In these cases pollen was stained using the Alexander methodology. Aberrant pollen grains have been observed in other species of *Smallanthus* (Fisher and Wells 1962; Wells 1971). Abnormal pollen development arises in many cases from irregular meiosis. However, meiosis appears



a

b

Fig. 4. Scanning microscope image of the upper epidermis showing epidermal trichomes (a) and epidermal glands (b).

be normal in yacon (Frías *et al.* 1997b), in spite of its high ploidy level and likely hybrid origin (see Section 4.3).

Lizárraga *et al.* (1997) analyzed seed set using paper bags, mesh bags and open-pollination. Open-pollination yielded twice as many seeds as mesh bags, which showed slightly better performance than paper bags. These results indicate that pollinators are very important, probably because pistillate ray flowers mature earlier than staminate disk flowers. In northwestern Argentina bumblebees (*Bombus* sp.) have been observed actively pollinating yacon and *S. macroscyphus.* Unidentified Hymenoptera have been observed playing the same role in Bolivia.

Other results point to inadequate germination conditions, dormancy or hard coat. Hard coat inhibiting germination is a trait present in *S. macroscyphus,* a wild species with high pollen fertility and high seed production (Grau and Slanis 1996), and may also be present in yacon. Experiments by Rea (1995a) yielded unfilled and filled cypselas, but he failed to germinate the filled ones. Low germination temperatures (12-15°C) may be partly responsible for this result. Meza (1995) obtained only one seedling out of about 300 seeds sown under glasshouse conditions. Chicata (1996, pers. comm.) obtained better results by selecting the filled cypselas from a sample containing empty and half-filled ones and germinating them at 28°C.

Fig. 5. Typical yacon flowerhead, photographed at Bárcena, Jujuy province, Argentina.

At present there are still many important gaps in the knowledge of yacon reproductive biology. Most perennial crops are outbreeders and this behaviour is also present in sunflower *(Helianthus annuus)* and topinambur *(Helianthus tuberosus),* two crop species in the same tribe as yacon. But there is no experimental report on the yacon mating system. It is also unknown whether yacon seeds are orthodox or recalcitrant. Flowering can be artificially induced in yacon by grafting onto sunflower (Nakanishi and Ishiki 1996), and this technique may represent a useful tool in future reproductive biology studies.

4.3 Chromosome numbers

The first report on yacon chromosome number (2*n*=60) was published by Heiser (1963), working with Ecuadorian material. A year later Leon (1964) reported 2*n*=32 using material grown at the La Molina University in Peru. Recent reports by Talledo and Escobar (1996) indicated 2*n*=60 in Peruvian material. However, more detailed studies (based on 1256 cell counts) by Salgado Moreno (1996) and Ishiki *et al.* (1997) on 15 clones from Ecuador (1), Peru (8), Bolivia (4) and Argentina (1) showed that all but one had 2*n*=58. The remaining clone had a somatic number of 87. A somatic value 2*n*=58 has also been observed by Frías *et al.* (1997b) in material from northwestern Argentina (Fig. 6).

Talledo and Escobar (1996) suggested that yacon is a tetraploid. Grau and Slanis (1996) speculated with the possibility of yacon being an allotetraploid, with

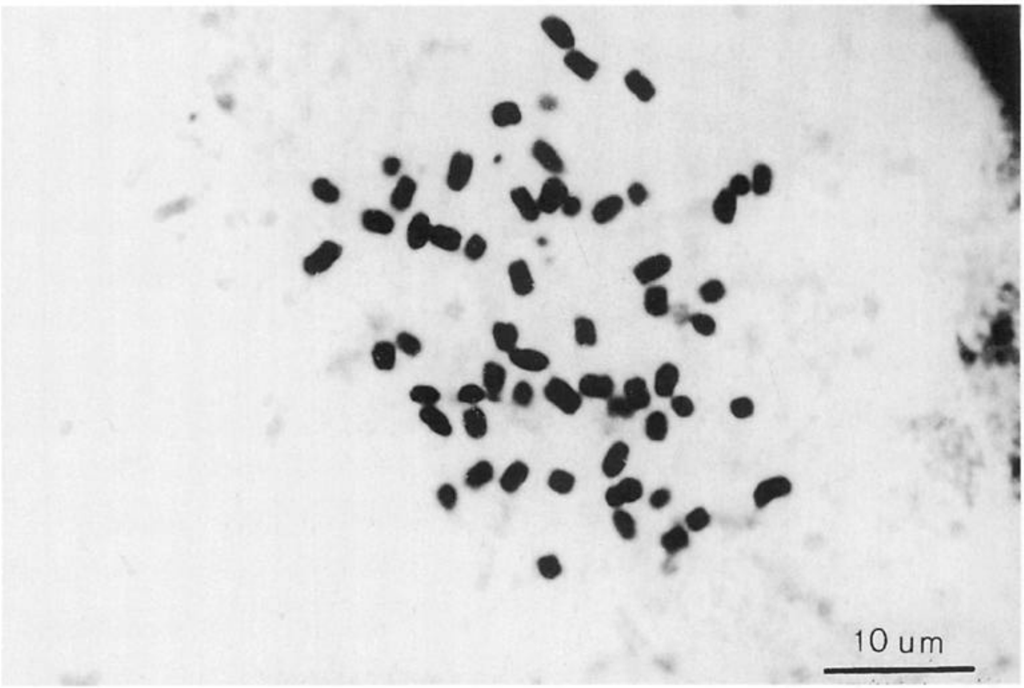


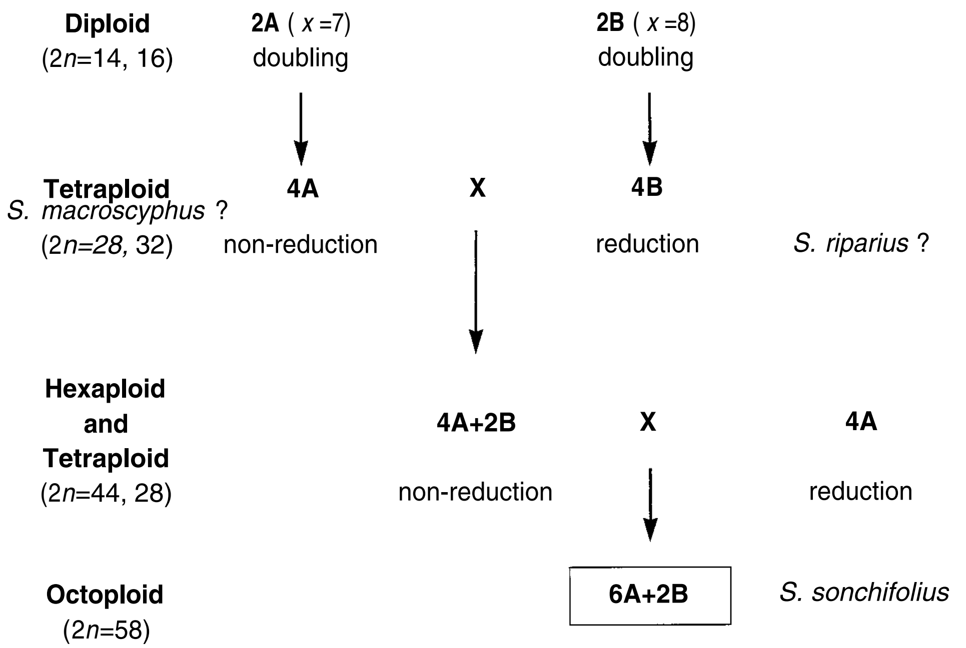
Fig. 6. Typical yacon caryotype with 2*n*=58 chromosomes (from Frías *et al.* 1997b).

S. macroscyphus as one of the putative parents, a role that could also be played by *S. riparius.* The studies of Ishiki *et al.* (1997) are consistent with allopolyploidy, suggesting a yacon caryotype composed by two genomes. They propose an octoploid 6A+2B structure as the dominant in most yacon clones 2*n*=58, while a dodecaploid 9A+3B structure would explain the 2*n*=87. Box 1 shows the hypothetical crossings that occurred during the evolution of yacon.

The studies of Salgado Moreno (1996) and Ishiki *et al.* (1997) are the most detailed and comprehensive so far. Nevertheless more studies are necessary to assess the validity of the reports indicating different chromosome counts. As a clonal crop, yacon could exhibit considerable diversity in chromosome numbers. Another aspect to consider is the presence of B chromosomes, reported in other *Smallanthus* taxa (Wells 1971; Ishiki *et al.* 1997), which may be an important factor affecting results. Further studies are also needed to accept, improve or reject the hypothesis of yacon hybrid origin.

Wells (1967) published the first review of *Smallanthus (Polymnia)* chromosome numbers, and the most common value listed is 2*n*=32 *(S. apus, S. oaxacanus, S. maculatus, S. uvedalius).* The same value has been obtained for *S. riparius* (Robinson

Box 1. Hypothetical evolution of yacon (by Ishiki *et al.* 1997, modified by A. Grau)



et al. 1981), *S. connatus* (Wulff 1984) and *S. macroscyphus* (Rozenblum *et al.* 1985; Frías *et al.* 1997a). However, the general picture is still blurred because of the different results reported for the same species by different authors and sometimes the same authors (Table 1). *Smallanthus jelksii* and *S. pyramidalis* share the $2n$=58 value with yacon. However, they are shrubs or small trees and seem unlikely ancestors.

Table 1. Chromosome numbers of *Smallanthus* species

Taxon	Somatic chromosome number	Reference
S. apus	32	Wells 1967
S. connatus	32	Wulff 1984
S. fruticosus	>50	Heiser 1963
S. jelksii	58	Sundberg *et al.* 1986
S. macroscyphus	32	Rozenblum *et al.* 1985
	32	Frías *et al.* 1997a
S. maculatus	32	Wells 1965
	66	Wells 1967
	32 and 68	Robinson *et al.* 1981
S. microcephalus	54 and 60	Robinson *et al.* 1981
S. parviceps	58	Jansen *et al.* 1984
S. pyramidalis	60	Heiser 1963
	58	Hunziker *et al.* 1989
S. oaxacanus	32	Turner *et al.* 1962
S. riparius	30	Heiser 1963
	32	Robinson *et al.* 1981
S. sonchifolius	60	Heiser 1963
	32	León 1964
	60	Talledo and Escobar 1996
	58	Salgado Moreno 1996
	87	Ishiki *et al.* 1997
	58	Frías *et al.* 1997b
S. uvedalius	32	Wells 1967
Smallanthus sp.	37 (32+5B)	Ishiki *et al.* 1997

5 Origin, evolution and history

Several wild *Smallanthus* species *(S. glabratus, S. riparius, S. siegesbeckius, S. macroscyphus* and *S. connatus)* show a clear preference for disturbed habitats, like riverbanks, landslides and roadsides. The growth habit of *Smallanthus* is well adapted to take advantage of vegetation gaps (Fig. la). The strategy of colonizing areas free of vegetation may be the reason why yacon became associated with humans in the first place. Agriculture in the steep eastern slopes of the Andes, particularly slash-and-burn agriculture practised by the Andean people since prehistoric times, may have provided an ideal niche for yacon relatives. In present times this behaviour can be observed in the Vilcanota river basin, Peru, where *S. siegesbeckius* is a common invader of abandoned fields and a weed in coffee plantations. The same strategy is used by *S. macroscyphus* in northwestern Argentina, invading abandoned sugarcane fields and shrubby vegetation patches between cultivated fields. It seems highly possible that a hybrid of two or more *Smallanthus* species colonizing disturbed habitats gave rise to a species ancestral to yacon.

It is likely that in a very early stage the Andean peasants discovered yacon properties and changed its status from weed to a managed plant, and later to a cultivated plant. The most probable area where these early events took place is the eastern humid slopes of the Andes, in the region extending from northern Bolivia to central Peru, the area with the largest clone diversity, and where native Quechua and Aymara names are used. Diversity of clones is more reduced in Ecuador, where modifications of the Mexican word *xicama* dominate. Both facts may indicate that the species was introduced there at later stages, perhaps with the Inca conquest of Ecuador, only decades earlier than the Spanish invasion.

Although the mountain forests of central Peru and northern Bolivia are evergreen and supplied with abundant rainfall and mist during most of the year, they are subjected to a relatively dry winter period lasting 2-4 months. This drier and slightly cooler interval may have played a critical evolutionary role, generating the conditions under which large tuberous roots could have an adaptive advantage.

From the humid mountain forests of Peru and Bolivia, yacon may have expanded to the north and south along the humid slopes of the Andes, to the dry inter-Andean valleys and to the Peruvian coast. It is in the coastal archeological sites of Nazca (500-1200 AD), Peru that the oldest phytomorphic representations of yacon have been identified, depicted on textiles and ceramic material (Safford 1917; Yacovleff 1933; O'Neal and Whitaker 1947). Further south, putative remains of tuberous yacon roots have been recovered at a site of the Candelaria culture, which developed between 1 and 1000 AD in the Salta province, south from the present area of cultivation in Argentina (Zardini 1991).

The first written record on yacon *(llacum)* is by Felipe Guaman Poma de Ayala (1615) in a list of 55 native crops cultivated by the Andeans, including eight crops introduced from Spain. The chronicler priest Bernabé Cobo (1653) produced a more detailed description, pointing out its use as a fruit and its capacity to withstand several days of transport by sea.

In the 19th century Weddell (1857) called attention to the qualities of yacon roots, named the species *Polymnia edulis* and collected the herbarium type. According to Perez Arbeláez (1956), yacon was exhibited for the first time in Europe at the Paris exhibition at the beginning of the century. European interest was not very significant though. In Italy there was a serious cultivation attempt in the late 1930s, which faded during World War II (Calvino 1940).

Affected by deep cultural changes, yacon cultivation has declined slowly and steadily throughout the Andes during most of the present century, to the point that the German researcher and Andean crop enthusiast H. Brücher mentioned it in his excellent monograph of useful Neotropical plants (1989), “for the sole reason of completeness.” Fortunately a drastic change in the international awareness of the crop has occurred during the 1980s, particularly after the publication of Lost Crops of the Incas (National Research Council 1989). The growing interest in the crop outside the Andes has stimulated a new wave of attention and research on yacon in the Andean countries.

6 Geographical distribution and centres of diversity

Yacon is being grown in many localities scattered throughout the Andes, from Ecuador to northwestern Argentina. In most cases just a few yacon plants are cultivated for family consumption (Fig. 7a). Less frequently yacon is grown as a cash crop to be marketed at the local level (Fig. 7b). Even in this situation, farmers rarely cultivate yacon as the main crop and seldom dedicate a high-proportion of their arable land to it.

Yacon is a rare crop in northwestern Argentina, present only in a few localities in the Salta and Jujuy provinces, where it was reported close to extinction by Zardini (1991). Cultivation was probably more widespread in the past, but at present the number of clones available in the area is reduced to two or three, and at risk of further losses.

While genetic erosion has probably also happened in Bolivia, cultivation of the species is still very common in most Andean departments[1] of the country, Tarija, Chuquisaca, Cochabamba and La Paz. La Paz department, particularly the Camacho and Sud Yungas provinces, is most likely the one with the largest cultivated area and the largest germplasm diversity. However, Cochabamba, Chuquisaca and Tarija departments have been poorly researched up to now and may hold valuable material.

Fig. 7. The different scales of yacon cultivation: small home garden at 2700 m asl, Leon Cancha, Tarija department, Bolivia (a), medium size (large size for Andean standards) yacon parcel at 2000 m, Erquis, Tarija department, Bolivia (b), large size yacon farm at 600 m, Capão Bonito, São Paulo state, Brazil (c).

Yacon is grown in many localities throughout the Peruvian Sierra. The largest germplasm diversity is found in southeastern Peru, in the valleys around Cusco and east of Puno. Another region of diversity and widespread cultivation is located in northern Peru, particularly the province of Cajamarca and the area close to the Ecuadorian border.

Within Ecuador, yacon is predominantly grown in the southern provinces of Loja, Azuay and Cañar. The crop is also present in the central highland provinces, such as in Bolivar and Chimborazo and in the north of the country, namely in Pichincha, Imbabura and Carchi.

Cultivation of yacon in Venezuela and Colombia has been reported in the literature (National Research Council 1989; Zardini 1991; Rea 1992). In his monograph Wells (1965) indicates its presence in Cauca, Colombia, presumably because he studied specimens from that region. Three decades ago yacon traditional use appeared to be restricted to the eastern Colombian mountainous range (Patiño 1964, cited in Debouck and Libreros Ferla 1995). However, recent explorations have not confirmed the presence of yacon in Colombia, specifically in Boyaca, Cundinamarca, Huila, Nariño (Dr M. Hermann, 1997, pers. comm.).

A strip stretching along the eastern Andean slopes, from the Apurimac river basin (12ºS) in Peru to the La Paz river basin (17ºS) in Bolivia, encloses the area richest in yacon germplasm. This is also an area where at least three wild *Smallanthus* species, taxonomically very close to *S. sonchifolius,* occur spontaneously *(S. macroscyphus, S. riparius* and *S. siegesbeckius).* Thus, this area seems to be the most likely 'origin centre' of the species (Fig. 8).

In the last three decades yacon cultivation has extended to other continents. There are reports of cultivation in several states of the USA (National Research Council 1989), but not at a significant commercial level. An interesting experience is underway in the North Island of New Zealand, where the crop has reached the supermarkets as a specialty vegetable (Grau 1993). From New Zealand yacon has been introduced into Japan, where approximately 10 ha are being grown by several small farmers (Dr K. Ishiki, 1997, pers. comm.). From Japan it was distributed to Korea and Brazil. In Brazil the crop is being cultivated commercially in São Paulo state. The crop has apparently failed in the Czech Republic (Matejka 1994) and it is likely to fail in most of Central Europe because of the long winter period.

[1] **Provinces** in Argentina and Ecuador are formally equivalent to **departments** in Bolivia and **regions** in Peru (where they replaced departments in 1987). They are the main political divisions of the state. Departments in Bolivia and regions in Peru are subdivided into provinces.

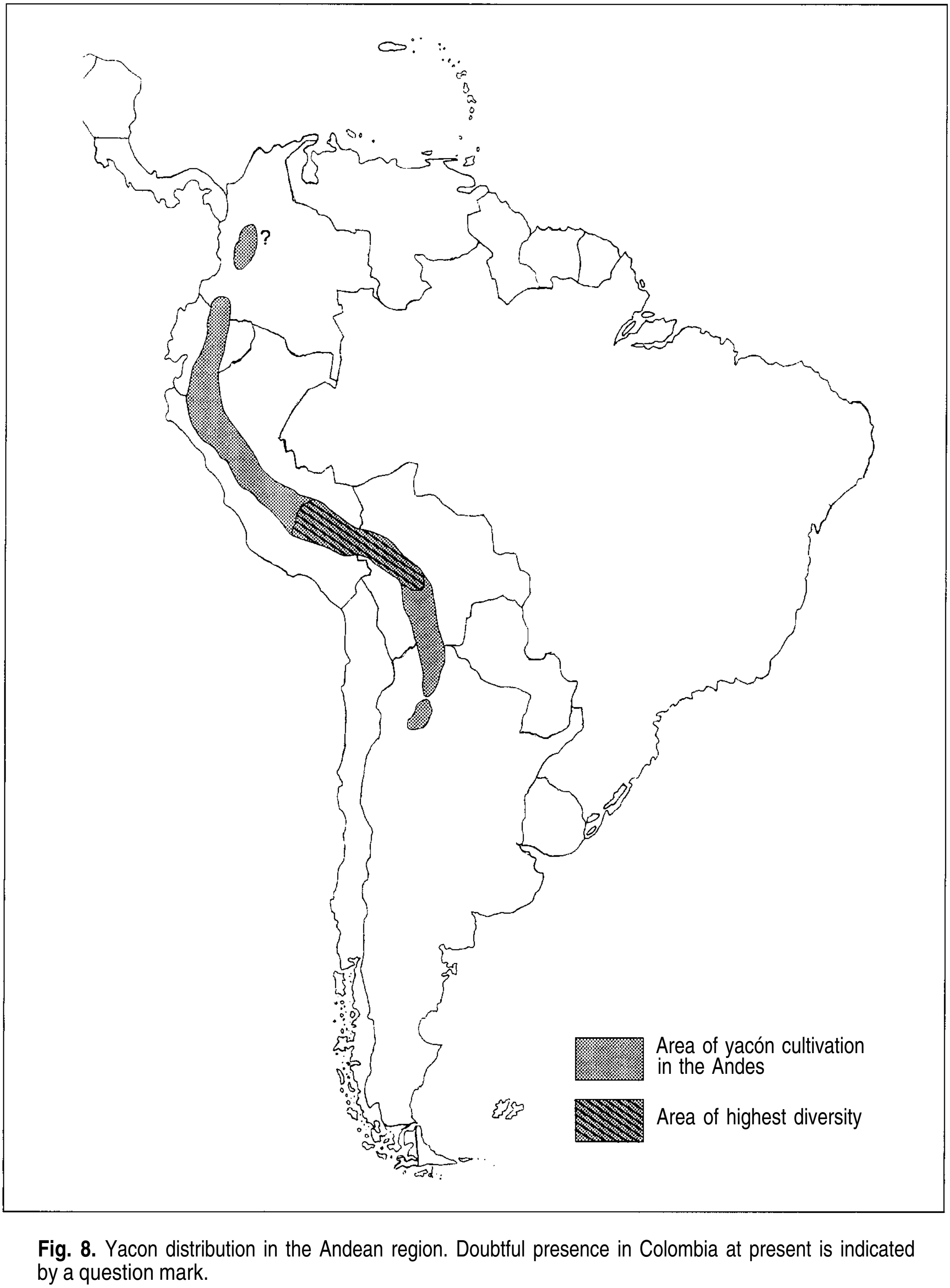


Fig. 8. Yacon distribution in the Andean region. Doubtful presence in Colombia at present is indicated by a question mark.

7 Properties and uses of the species

7.1 Chemical composition

Several carbohydrates are stored in the roots of yacon: fructose, glucose, sucrose, low polymerization degree (DP) oligosaccharides (DP 3 to 10 fructans), and traces of starch and inulin (Asami *et al.* 1989; Ohyama *et al.* 1990). Inulin, a high-DP oligofructan with DP of about 35, is a main storage compound in many plants of the Compositae family, such as *Helianthus tuberosus* and *Dahlia* sp. However, in yacon inulin appears to be only a minor component. On the contrary, oligofructans with a lower DP (average 4.3) may account for up to 67% of the dry matter content at harvest (Asami *et al.* 1991). Oligosaccharides purified from yacon have been identified as beta-(2→1)-fructooligosaccharides with terminal sucrose (inulin type oligofructans; Goto *et al.* 1995). The relative proportions of oligofructans and monosaccharides fluctuate significantly during the growing cycle and after harvesting (Asami *et al.* 1991; Fukai *et al.* 1995), leading to apparently contradictory results. For example a detailed analysis of yacon root carbohydrates has been published by Ohyama *et al.* (1990) (Table 2) indicating that oligofructans account for just 20%, instead of 67% as reported by Asami *et al.* (1991). However it is important to note that Ohyama and coworkers used material after more than 3 months in cold storage, while Asami's team utilized roots immediately after harvest. Unfortunately, a significant amount of information concerning storage sugars in yacon has been published only in Japanese, and it is not intelligible to most readers.

Table 2. Content of soluble carbohydrates in yacon tuberous roots, 96 days after harvest, maintained under cold conditions (Ohyama *et al.* 1990)

Carbohydrate	Content (mg/g dry wt.)
Fructose	350
Glucose	158
Sucrose	74
GF_2	60
GF_3	47
GF_4	34
GF_5	21
GF_6	16
GF_7	13
GF_8	10
GF_9	7
Total $GF_{2\text{-}9}$	201

GF_n= fructosylsucrose; n indicates depolymerization degree.

Besides storage carbohydrates, the tuberous roots contain small amounts of fiber, vitamins and minerals (Table 3). Interesting protein levels have been reported for stems (11% DW) and leaves (17% DW) (Calvino 1940).

Table 3. Chemical composition of yacon roots (summarized from Lizárraga *et al.* (1997), a compilation from different sources)

	Fresh weight basis	Dry weight basis
Water (%)	93 - 70	-
Ash (%)	0.3 - 2.0	1.1 - 6.7
Protein (%)	0.4 - 2.0	1.3 - 7.3
Fat (%)	0.1 - 0.3	0.4 - 1.0
Fiber (%)	0.3 - 1.7	1.0 - 5.7
Calcium (mg/g)	23	-
Phosphorus (mg/g)	21	-
Iron (mg/g)	0.3	-
Retinol (mg/g)	10	-
Carotene (mg/g)	0.08	-
Thiamin (mg/g)	0.01	-
Riboflavin (mg/g)	0.1	-
Niacin (mg/g)	0.33	-
Ascorbic acid (mg/g)	13	-

7.2 Uses

In the local markets of the Andes yacon is classified as a fruit and sold together with chirimoyas, apples, avocados, pineapples, etc. and not with potatoes, oca, ulluco or mashua *(Tropaeolum tuberosum),* as a foreign observer would expect.

Yacon tuberous roots possess an agreeable sweet flavour, an attractive crunchiness and are commonly eaten raw, usually after a period of exposure to the sun. The drying time varies from site to site, being shorter in the dry inter-Andean valley than in the cloud forest region. This procedure, called *ckochascca* (Herrera 1943), increases the sweetness of the roots, and they are considered ready for consumption when the skin is slightly wrinkled. They are eaten peeled, as the skin has a somewhat resinous taste, and they are particularly tasty chopped up in fruit salads mixed with bananas, oranges, pawpaws, etc. Tuberous roots also can be stewed, retaining in part their crispiness, or grated and squeezed through a cloth to obtain a sweet refreshing drink.

In an extended area from Peru to northwestern Argentina yacon is consumed particularly during the 'Corpus Christi' festival, which displaced the K'apac Raymi

feast of Inca times (Cárdenas 1969). In Ecuador, yacon roots are especially consumed during the 'Todos los Santos' and 'Day of the Dead' festivals (National Research Council 1989). These current practices may indicate old religious values, modified after the advent of the Catholic religion.

In Bolivia yacon is commonly consumed by diabetics and persons suffering from digestive problems. Properties to treat kidney problems and skin-rejuvenating activity also have been mentioned. Medicinal (antidiabetic) properties have been attributed to yacon leaves (Kakihara *et al.* 1996) in Brazil, where the dried leaves are used to prepare a medicinal tea. Dried yacon leaves are used in Japan, mixed with common tea leaves. Hypoglycemic activity has been demonstrated in the water extract of dried yacon leaves, feeding rats with induced diabetes (Volpato *et al.* 1997).

Yacon can be processed in different ways. The juice obtained from pressing the tuberous roots can be boiled and concentrated to produce solid dark-brown blocks called *chancaca* (National Research Council 1989), similar to the product obtained from concentrating sugarcane juice. The juice also can be concentrated at low pressure, with the addition of sodium bisulphate to inhibit enzymatic darkening. The final product is a dense syrup similar to sugarcane syrup but with significantly lower energy value for humans (Chaquilla 1997). Another promising processing technique is the production of dry chips. In this case yacon tuberous roots are peeled and cut in thin slices. The slices are first dried in a plastic tunnel, then oven-dried at 60°C (Kakihara *et al.* 1996). Dried yacon chips can be stored indefinitely.

Yacon pulp can be preserved after heating at 89°C for 10 minutes and washing with sodium bisulphate (0.5%) for 5 minutes, by adding potassium sulfate (0.1%), ascorbic acid (0.3%) and adjusting the pH to 4.5. The heated and washed material can also be added to sugar syrup and made into 'glacé' fruit. Yacon pickles are produced and marketed in Japan (Dr K. Ishiki, 1997, pers. comm.).

All yacon carbohydrates including oligofructans can be rapidly metabolized by ruminants, so tuberous roots can be used to feed cattle or sheep. The foliage, with a protein content of 11-17% (dry weight basis) has been suggested as forage (National Research Council 1989). However, there is no experimental information on the subject. Terpenoid lactones produced by epidermal glands may affect the palatability of the foliage.

8 Genetic resources

8.1 Genetic variation

Although yacon is a clonal crop, there is some morphological and physiological variation. However, this variation may reflect to some extent the phenotypic plasticity expressed in the contrasting environments where it is grown rather than genetic variation. Dr M. Hermann (1997, pers. comm.) found it very difficult to differentiate yacon clones from a wide geographical range, from Ecuador to Argentina, when they were grown in the same environment.

Even if the traits available can be exploited, yacon could gain significant variation by incorporation of genes from its wild relatives. Thicker root bark, looser storage root arrangement (which would reduce deforming pressures), reduced sweetness (which may indicate higher oligofructans level) and tuberous roots with sprouting capacity that could be used as propagules are some of the traits that could be incorporated from wild relatives.

A number of morphological descriptors have been proposed by Seminario (1995a). The variation of characters of potential breeding value is presented below.

- **Morphological characteristics:** erect and semi-erect plant type; internode length (8-25 cm); stem colour (purple, green, pale green); stem and leaf pubescence (dense, medium); number of flowerheads (0-70); colour (pale yellow, yellow, orange); shape and teeth number (2-3) of the corolla; root grouping (compact, lax); root shape; root skin colour (white, cream, pink, purple, brown); root flesh colour (white, cream, white with purple striation, purple, pink and yellow); number of tuberous roots per plant (5-40); root size (6-25 cm length).
- **Physiological characteristics:** flowering habit and duration (6-9 months until flowering); tuberous root yield (1-15 kg/plant) and quality; dry matter content (10-30%); oligofructan content; reducing sugar content; changes in sugar patterns during post-harvest period.

8.2 Geographical distribution of important traits

Considerable variability for tuberous roots yield has been found by Castillo *et al.* (1988) in Ecuador (30-73 t/ha), Seminario (1995b) in northern Peru (1.5-9.5 kg/plant) and Lizárraga *et al.* (1997) in southern Peru (<1.7 to > 3.3 kg/plant).

Variability for flesh colour is higher in southern Peru (Meza 1995; Lizárraga *et al.* 1997) and northern Bolivia, where clones with white, cream, yellow and purple flesh can be found, than in Ecuador or southern Bolivia and northwestern Argentina, where only white and yellow clones have been reported.

8.3 Importance of wild relatives as a source of diversity

The possibility that some of the wild relatives may have contributed to the yacon genome makes them good candidates for future breeding attempts, as part of introgression programmes. However, wild *Smallanthus* species are still poorly

known and only a few potential useful traits that could be introduced into yacon have been mentioned in Section 8.1.

8.4 Institutions holding germplasm

Systematic collecting of yacon germplasm began in the 1980s, sponsored by the IBPGR. It focused mainly on crops of global importance such as potato. However, some work was diverted to secondary crops such as the other Andean tubers and yacon. The collecting effort lasted about 5 years and concentrated on Ecuador and Peru.

A second collecting period began in 1993, guided by the Programme of Roots and Tubers in the Andes (RTA), administered by the CIP and funded by COTESU (Cooperación Técnica Suiza - Swiss Technical Cooperation) for a 5-year period. More emphasis was placed on secondary Andean crops and the collecting activities were expanded to Bolivia, aiming mainly at *in situ* conservation.

8.4.1 Ecuador

Ecuadorian Andean root and tuber germplasm is managed by the INIAP (Instituto Nacional Autónomo de Investigaciones Agropecuarias) at the Santa Catalina Research Station, located in Pichincha Province, Mejía Canton, at 3058 m (Tapia *et al.* 1996). The station keeps 777 accessions of Andean roots and tubers (November 1995), of which 32 correspond to yacon (jícama). Material is planted in the field once a year and duplicates are maintained *in vitro,* stored at 5°C. The provinces of Cañar, Azuay and Loja in Southern Ecuador have yielded the largest number of accessions for the Santa Catalina collection.

8.4.2 Peru

Peruvian researchers are the ones in Latin America who dedicated most attention to yacon. Collecting efforts were initiated by Arbizu and Robles (1986) and several germplasm collections have been established in different sites of the country, holding a total of about 200 accessions. However, it is likely that many duplicates are included in this figure.

In the north of the country yacon material is maintained at the Los Baños del Inca research station, Cajamarca, where 45 accessions are being characterized and evaluated (Franco and Rodriguez 1997). The northern departments, Cajamarca and Piura, have been explored by Seminario (1995b), who collected 62 accessions in 1993-94.

The International Potato Center (CIP, Centro Internacional de la Papa) in Lima holds 44 accessions, including 37 from Peru, 4 from Bolivia and 1 from Argentina (Dr C. Arbizu, 1997, pers. comm.).

In the Ayacucho department, collections are kept by the University of Ayacucho (10 accessions) and the Instituto de Investigaciones Agrarias at the Canaan center (6 accessions) (De la Cruz 1995). Material is being maintained under field conditions and *in vitro* (De la Cruz and Jiménez 1997).

Material from southern Peru is concentrated in Cusco. The CICA (Centro Internacional de Cultivos Andinos) of the University of Cusco maintains 33

accessions at the Kayra research station (3249 m). A collection of 87 accessions is maintained by the CERGETYR (Centro de Recursos Genéticos de Tubérculos y Raíces) of the Cusco University at Ahuabamba (2000 m), in the Vilcanota river valley (Lizárraga *et al.* 1997). The University of Cusco has also initiated an *in situ* program at five localities ranging from 3000 to 3500 m asl (Meza 1995).

8.4.3 Bolivia

Very little yacon material is held in *ex situ* collections in Bolivia. Just two accessions are reported at Toralapa (3400 m asl), Cochabamba. Much more important is the amount of material maintained within an *in situ* strategy (Rea 1995b). The conservation network involves 17 families in the La Paz department, which are currently managing 32 different morphotypes. The sites are distributed along a wide altitudinal gradient from 900 to 3600 m, with the largest concentration at 3100-3200 m asl. Information summarizing the experience is shown in Table 4.

8.4.4 Argentina

The Cerrillos research station in Salta (INTA, Instituto Nacional de Tecnología Agropecuaria) has collaborated with CIP during collecting campaigns of Andean tubers in northwestern Argentina, but maintains only one yacon accession. A small *in situ* conservation project for several Andean crops including yacon is being set up in the Santa Victoria area, Salta province, northwest Argentina by the LIEY (University of Tucumán).

8.4.5 Availability of data on individual accessions

Data available on individual accessions vary considerably from institution to institution. They usually indicate origin, collector and a few observations. In general little or no information is available on climatic, edaphic, ecological and agronomic data associated with the accessions, a fact that could constrain future evaluations.

8.5 Gaps in existing collections

An important deficiency in the existing germplasm collections is the limited amount of wild forms available. One 'wild' yacon accession from Ecuador is held by CIP (Ishiki *et al.* 1997) and three more are at the CICA center, Kayra, Cusco. However, these are most likely wild *Smallanthus* species other than *S. sonchifolius*. Positively wild *S. sonchifolius* material would provide not only valuable information on the phylogeny of the species but may be useful in future breeding programmes. Furthermore, wild species may represent an interesting source of valuable genes.

Material from the dry inter-Andean valleys is better represented in the collections than material from the humid eastern slopes. Assuming that yacon evolved in the forested slopes of the Andes, diversity is presumably higher in that region. Communities in the humid slopes are generally more isolated and less connected to the main road systems; this increases the likelihood of finding rare clones in these areas.

Table 4. Material held *in situ* in the La Paz Department, Bolivia

Province	Canton	Altitude (m)	Community	Family	Type[†]	Destination[‡]
Caranavi	Caranavi	1200	Colonia Sabaya	Calle	Y, 1	A
		1300	Colonia Uchumachi	Mamani	Y, 1	A
Sud Yungas	Quiquibey	880	Colonia Cascada	Ayma	W, 1	A
	Irupana	1950	Chica, Choropata	Apaza	W, 1	A
	Pariruayan	2720	Pariguaya	Cuentas	W, 1	A
					P, 2	A
Camacho	Ambaná	3400	Ambaná	Mantilla	W, 2	B
					Y, 2	C
					P, 1	C
		3100	Stgo. Pampa	Aliaga	Y, 1	C
					W, 2	B
		3150	Mojsahuma	Kamasa	Y, 1	C
		3200	Kapahuaya	Villca	W, 2	B
				Catacora	Y, 2	C
	Moco-Moco	3400	Moco-Moco	Jimenez	W, 2	A
					Y, 1	A
		3350	Tara-Marca	Chahua	W, 2	A
					Y, 1	A
	Italaque	3600	Italaque	Uriarte	W, 2	A
					Y, 1	A
		3200	Huayanka	Toledo	W, 2	C
					Y, 1	C
		3200	Huatacana	Sevahcollo	P,1	C
					W,2	A
					Y 2	C
		3500	Tamampaya	Quilli	P, 1	C
					Y, 2	C
		3400	Yok'arhuaya	Paco	Y, 1	C
					W, 2	C
Muñecas	Pusillani	3225	Pusillani	Bosque	W, 1	A

[†] Y=yellow; P=purple; W=white; 1=main clone; 2=secondary clone.
[†] A=home consumption; B=exceptionally marketed; C=commonly marketed.

8.6 Conservation of the cultivated yacon and its wild relatives

No survey of the conservation status of *Smallanthus* species has been made. It would be important to evaluate their presence in the existing national parks and reserves. However, *Smallanthus* species may not be favoured by pristine, conventional protected environments. As plants adapted to invade vegetation gaps, *Smallanthus* may also prefer disturbed habitats created by human intervention. If this proves to be true, an ideal environment would be areas where slash-and-burn agriculture is practised. This also may be valid for the relatives or wild forms of other crop species and it would be important to consider areas like these within the framework of park and reserve systems.

An interesting example of these aspects is present in the Machu Picchu sanctuary in Peru. Sanctuary officials have always tried to expel the peasants established within the limits of the sanctuary. However, besides the growing of yacon landraces, the activities of these people create an environment ideal for at least two wild *Smallanthus* species and many other crop-related species (e.g. *Cyphomandra, Physalis).* It would be very important to carefully evaluate if these peasants and the partially disturbed environment that they create do not actually belong in the sanctuary. In areas like this, a compromise between conservation efforts aiming at different aspects (historical, biological and agronomical) should be possible.

Closely related to the last consideration is the idea of *in situ* conservation, a system that maintains not only the germplasm but also all the information associated with that germplasm. Rea (1995a) has described a successful *in situ* conservation system set up in Bolivia that could be used as a model in other areas of the Andes.

Yacon can be grown *in vitro* using modified Murashige & Skoog media (Kuroda *et al.* 1993; Estrella and Lazarte 1994). De la Cruz and Jiménez (1997) and Velasque and Ortega (1997) have evaluated several alternative modified Murashige & Skoog media to reduce growth and extend *in vitro* conservation for at least 6 months.

9 Breeding

There are no reports of breeding attempts involving yacon. Characterization and evaluation of existing accessions in germplasm banks are being carried out in Ecuador (Castillo *et al.* 1988; Tapia *et al.* 1996), northern Peru (Seminario 1995b; Franco and Rodríguez 1997) and southern Peru (Lizárraga *et al.* 1997). Kuroda and Ishihara (1993) were able to select lines of higher sugar content by tissue culture. Nevertheless, no information is available on selected yacon clones being released for wider cultivation.

A first difficulty while breeding yacon will be its reduced fertility However, this is by no means an insurmountable hurdle. On the other hand the presence of staminate and pistillate flowers makes pollination control considerably easier than in other Compositae, such as sunflower, which requires the use of male sterility to facilitate hybridization.

Yacon is especially amenable to *in vitro* culture, opening an attractive window of opportunities for modern biotechnological manipulation. However, it is essential to define objectives in order to apply the tools available.

Future breeding and selection objectives may diverge depending on the type of farmers, production scale, fresh produce, industrial processing (e.g. purified oligofructans, syrup, chips) and target market (Andean, international). For example, throughout the Andes clones with yellow flesh are preferred at the market level (see data by Rea in Table 4, Tapia *et al.* 1996), while other types are cultivated mainly for family consumption. In contrast, westernized supermarkets may favour a wider range of flesh colours. A more uniform size would be another important characteristic to standardize commercialization and processing.

Evaluation trials have yielded some potentially useful correlations. Productivity (t/ha) is correlated with number of roots/plant (Franco and Rodriguez 1977). The refractive index of the root juice as a rapid estimator of sugar content, a measurement commonly used in other crops, is also valid for yacon (Kuroda and Ishihara 1993).

10 Ecology of the species

There is very little published information about the environmental requirements of yacon, as there has been virtually no conventional research on yacon ecophysiology. Yacon and most yacon relatives are believed to have evolved in the humid eastern slopes of the Andes not far from the equator, a region with mild temperatures and generally with abundant rainfall although with a distinct dry period. These conditions have probably shaped yacon's ecological requirements.

10.1 Photoperiod

Yacon has been described as day-neutral for stem and tuberous root formation (National Research Council 1989). However, this process begins very late in the growing season at higher latitudes (23°S, Jujuy province, Argentina; 46°S, Otago province, New Zealand). This behaviour may indicate that the plant has a weak short-day response.

10.2 Temperature requirements

While native from subtropical to warm-temperate environments, yacon shows a high plasticity, being able to grow and produce in a wide altitudinal range (900-3500 m in Bolivia, Peru and Ecuador; 600-2500 m in northwestern Argentina; 600 m in Brazil; sea level in New Zealand and Japan). Aerial parts are frost-sensitive, with leaves damaged at -1°C. Cultivation is common in some regions with light frost, like the Ecuadorian highlands or many inter-Andean valleys in Peru, Bolivia and northwestern Argentina, because in these regions frosts generally occur at the end of the growing season. In New Zealand, stems were killed almost to the ground by -3 to -4°C, and a temperature of -7°C for several hours damaged all underground organs. Temperatures below 10-12°C combined with high solar radiation led to chilling damage of the leaves (Grau 1993). Optimum growth occurs in the range 18-25°C. Foliage is able to tolerate high temperatures (at least up to 40°C) without damage symptoms, provided that an adequate water supply is maintained. Low night temperatures appear to be necessary for optimum storage root formation. Farmers in Argentina and southern Bolivia indicate that medium-altitude sites (1500-2000 m) are best for storage root production while warmer lowland sites are better for 'seed' (rhizome) production, but root yields are lower.

10.3 Water requirements

Adult yacon plants possess a developed canopy with a high transpiration capacity, requiring a good and regular water supply. Irrigation is a necessary complement in most dry Andean intermontane valleys where yacon is cultivated. Production areas in Bolivia receive 300-600 mm, while 800 mm are considered the optimum. In many regions temporary wilting is very common on sunny summer days, even when the soil has an adequate water level. On the other hand, yacon can survive long dry spells. However, productivity is significantly affected under these conditions. While irrigation may be critical in some cases, overwatering can lead to cracking of the root

skin, which affects the exterior quality and market value and may promote root rot during storage.

10.4 Soil requirements

Yacon adapts to a wide variety of soils, but does better in rich, moderately deep to deep, light, well-structured and well-drained soils. Growth is poor in heavy soils. It grows very well in the humus- and mineral-rich soils of the Andean slopes after slashing and burning of the forest. Very good crops are also obtained in sandy river terraces in the Tarija area, Bolivia, and in lateritic soils corrected with dolomite in the state of São Paulo, Brazil. Yacon can tolerate a wide pH range, from acid to weakly alkaline.

11 Agronomy

11.1 Propagation

Yacon is propagated vegetatively with 8-12 cm long offsets ('seeds') taken from the underground and aboveground rootstock ('crown'), with a few or no roots attached. The rootstock can be divided into pieces easily, and these offsets are normally obtained during the harvesting of the roots. Storage roots with no stem attached are not able to produce shoots.

Aerial stem cuttings can be easily rooted if protected from desiccation. Rooting is best under mist, and it can be significantly accelerated using auxins (Indol-butyric acid).

11.2 Crop husbandry

Field preparation varies considerably from region to region and by production scale. The system used at present in the Cusco region, southeast Peru, may be very similar to the one used at the time of yacon domestication. According to Lizárraga *et al.* (1997), in that region field preparation begins with tree-cutting and land-clearing *(roce),* usually in June-July. The material is left to dry, then placed in rows and burned in during August. The material not burned (branches, stems) is taken out of the field *(manq'opeo).* From the beginning of September until the end of November, depending on rainfall, the yacon offsets are planted manually. Planting distance varies: 70-100 cm between rows and 60-80 cm between plants.

In northern Bolivia traditional cultivation begins with the preparation of ploughed maize or potato fields, where the offsets are planted in furrows (Rea 1992). Rows are cultivated and earthed-up during the growing season. Where irrigation is available, planting can be done throughout the year.

In São Paulo, Brazil, yacon offsets are placed in furrows, 1 m wide and 30-40 cm high, at a depth of 15 cm, 90-140 cm apart (Kakihara *et al.* 1996). Soil pH, normally around 4.0 in these lateritic soils, is modified to 6.0 with the addition of dolomite. Management includes fertilization with N-P-K plus Zn (4-14-8 at 2000 kg/ha) and ammonium sulphate (200 kg/ha), and irrigation by aspersion.

11.3 Pests and diseases

In cloud forest areas, like the Cusco region, Peru, yacon crops are affected by a wide range of insects. However, natural control agents are present and effective (Lizárraga *et al.* 1997). Pest pressure is much lower in the dry intermontane valleys. In any case, control measures are not commonly used in the Andes. Table 5 lists some of the species associated with yacon.

A few bacteria and fungi have been cited affecting the underground organs and stems of yacon. *Fusarium* in Peru (Lizárraga *et al.* 1997) and *Erwinia chrysanthemi* in Japan (Mizuno *et al.* 1993) have been identified as causal factors of wilting, while an unidentified rot affects the xylem of stems in Bolivia. *Sclerotinia* causes soft rot of the tuberous roots in Peru (Lizárraga *et al.* 1997). *Alternaria* has been found producing marginal necrosis of the leaves in Ayacucho, Peru (Barrantes 1988).

Table 5. Yacon pests

Pest	Damage/activity	Region, Country	Reference
Liriomyza sp . (Agromyzidae, Diptera)	leaf-mining	Cusco, Peru	Lizárraga *et al.* 1997
Stink bugs (Pentatomidae, Coridae, Hemiptera)	leaf-sucking	Cusco, Peru	Lizárraga *et al.* 1997
Diabrotica sp. (Chrysomediae, Coleoptera)	flower-chewing	Cusco, Peru	Lizárraga *et al.* 1997
Unknown larvae, (Scarabeidae, Coleoptera)	tuberous root-boring	Cusco, Peru	Lizárraga *et al.* 1997
White fly	leaf-sucking	New Zealand	Endt 1992
Looper caterpillar	leaf-chewing	New Zealand	Endt 1992
Papilio sp. (Lepidoptera)	leaf-chewing	São Paulo, Brazil	Mr S. Kakihara, 1996, pers. comm.
Nematodes	root damage	São Paulo, Brazil	Mr S. Kakihara, 1996, pers. comm.

Few studies are available on viruses affecting yacon. There is a report indicating that yacon is free of several common tuber viruses, including those affecting potato (potato leaf-roll, X, Y, S, M; National Research Council 1989). However, clonal decline (cansancio = fatigue) and the need to 'rejuvenate' the 'seed' have been reported by farmers in the La Paz region, a phenomenon that strongly suggests viral infection. Kuroda and Ishihara (1993) indicated that cucumber mosaic cucumovirus infected yacon under field conditions, yielding less vigorous plantlets *in vitro*.

Agoutis, rodents of the genus *Dasiprocta,* have been mentioned attacking yacon tuberous roots in the La Paz region, Bolivia.

Yacon, being a perennial plant, has been suggested as a crop adequate to reduce soil erosion in steep slope areas of the Andes. Yacon leaves tolerate partial shading, a trait that could be used with advantage in agroforestry systems. These two traits warrant a more detailed study, as they can be critical in many regions of the Andes. Yacon may have been associated with slash-and-burn agriculture since prehistoric times. In modern times, however, population pressure and land scarcity make this strategy unsustainable in many areas. Therefore, it would be critical to develop sound agroforestry systems where yacon could fit as a stabilizing component.

11.4 Harvesting and post-harvest handling

Roots reach maturity in 6-7 months in the medium-altitude sites and up to a year in high sites. Storage roots are very brittle when turgid and the plant must be dug carefully to prevent breaking them. Tuberous roots are usually dug and separated

manually from the crown. Mechanical potato harvesters have been successfully employed in Brazil (Kakihara *et al.* 1996).

For consumption the roots are exposed to sunlight for a few days to increase their sweetness. This procedure leads to the partial hydrolysis of oligofructans, yielding larger amounts of reducing sugars (fructose, glucose and sucrose). Table 6 shows the changes in reducing sugars and non-reducing sugars.

For long-term storage the roots are placed in a dark, dry, cool room. Under these conditions yacon roots can be kept for several months. Virtually no changes have been observed in the relative amounts of sugars in yacon tuberous roots stored at 4°C (Table 7).

Metabolic activity of harvested yacon tuberous roots is low, similar to potatoes and lower than oca *(Oxalis tuberosa)* and mashua *(Tropaeolum tuberosum)* (Table 8).

Table 6. Changes in reducing sugars and non-reducing sugars (as % of dry matter) after sun exposure for several days (from Vilehna *et al.* 1996)

Days	1	2	3	6	8
Reducing sugars	61.5	59.8	56.1	58.0	56.3
Non-reducing sugars	21.8	21.5	25.1	25.0	25.0

Table 7. Changes in reducing sugars and non-reducing sugars (as % of dry matter) in yacon tuberous roots maintained at 4°C for several days (from Vilehna *et al.* 1996)

Days	0	5	10	20	40
Reducing sugars	58.3	58.1	58.2	58.0	58.0
Non-reducing sugars	23.5	23.9	23.7	23.4	23.5

Table 8. Respiratory rate of different roots and tubers at 17°C, 96 hours after harvest (Grau 1993b)

	Respiratory rate (mg CO_2/kg FW per hour)
Yacon	29
Oca	47
Mashua	56
Potato	20

11.5 Yields

A very interesting trait of yacon is its high productivity. Table 9 summarizes some data available on yacon fresh matter yield. Dry matter varies from 15 to 30% of fresh weight. More detailed information concerning dry matter productivity is required to assess accurately its potential for processing and industrial purposes.

Table 9. Maximum yacon productivity obtained in different environments

Site	Yield (FW t/ha)	Source
Ahuabamba, Peru	28	Lizárraga *et al.* 1997
Santa Catalina, Ecuador	74	Castillo *et al.* 1988
Cajamarca, Peru	95†	Seminario 1995a
Capão Bonito, Brazil	100	Kakihara *et al.* 1996

† Assuming a density of 10 000 plants/ha.

12 Limitations

While in some situations they can affect yields in the Andean region, none of the pests and diseases mentioned in Section 11.3 appears to be decisive in limiting yacon production. Yacon's progressive disappearance from many areas seems to be more dependent on its intrinsic characteristics, cultural change and market factors. As a limited source of energy, yacon does not play a vital role in subsistence agriculture, and priority is probably given to crops that are essential in the diet. As a rather unusual sort of 'fruit', yacon is always in danger of being displaced by conventional fruits, especially when they are associated with 'westernizing' cultural changes. Local Andean markets are not organized adequately to promote yacon qualities and to present it in a stimulating form to the customers. Unlike other, colourful Andean tubers (e.g. oca, ulluco), yacon's comparatively dull aspect may be a deterrent to anyone who does not have a strong cultural attachment to it.

If yacon were to increase its importance as a crop, several agronomic aspects may pose limitations.

- Viral infections are the likely cause of 'seed decline', an issue that may require the development of virus-free propagation material schemes.
- Fungal and bacterial rot and wilt problems under field conditions.
- Splitting and cracking of the tuberous roots before harvest is a problem under certain environmental conditions. Irrigation management is a critical aspect to be addressed to avoid this problem.
- Tuberous roots are easily affected by physical damage during harvest and post-harvest handling, and the wounds can easily lead to fungal or bacterial rot during storage.

13 Prospects

13.1 Advantages of yacon

Yacon possesses an attractive set of features advantageous to producers, processors, consumers and the environment.

- High fresh weight productivity
- Adaptability to a wide range of climates and soils
- Potential good fit in agroforestry systems
- Erosion control
- Potential use as a forage for both underground and aerial parts
- Wide range of processing alternatives
- Good post-harvest life, if managed properly
- Exceptional qualities for low-calorie diets
- Medicinal properties.

13.2 Development objectives

Yacon has been suggested as an industrial crop, particularly as a source of sugar syrup (National Research Council 1989). Yacon productivity is much higher than that of topinambur, an older source of inulin and a potential competitor. It is tempting to speculate about yacon being transformed into a modern industrial crop with the application of modern agronomic technology, fertilization, genetic engineering, etc. However it is yet to be seen if yacon could compete with other established starch and sugar crops, which are being subjected to enormous breeding efforts, in an age when many of them are still heavily subsidized. Even if a strategy like this succeeds, it is unlikely that the Andean region would benefit much from it. In general, Andean ecosystems pose severe limitations to large-scale industrial crops.

Less spectacular but more attractive may be the further development of yacon as what it already is, a specialty and health food. Urban populations are increasing in the Andean countries and urban inhabitants are the ones who could require the sort of food properties that yacon can provide. Small- or medium-scale Andean systems that emphasize low input, environmentally friendly and organic production of yacon could compete advantageously with large-scale and probably higher-yielding crops in other regions.

14 Research needs

Compared with most other Andean root and tubers, yacon knowledge is rather limited and many fundamental aspects of its biology and agronomy are virtually unknown. As a first approach, several specific courses of action can be proposed:

- Field collecting, conservation and evaluation of local clones should continue.
- Field collecting of wild *Smallanthus* species/wild yacon.
- Chromosomic and molecular analysis of the different yacon accessions/morphotypes in order to clarify their relationships.
- Taxonomic and phylogenetic studies of the genus *Smallanthus* in South America using conventional morphological, numerical systematic, chromosomic and molecular analysis in order to clarify the relationships between the different wild species and yacon.
- Artificial crossing between different clones of yacon and different species of *Smallanthus.*
- Breeding interspecific hybrids to increase variation.
- Physiological analysis of tuberous root formation and development, propagation material and dormancy.
- Physiological analysis of pollen viability and longevity.
- Physiological analysis of seed viability, germination, dormancy and longevity.
- Evaluation of pests and diseases and the resistance/tolerance present in different clones.
- Development of IPM and organic management systems for yacon. While pest pressure appears to be low at present, this may rapidly change if there is an increase in the cultivated area.
- Study traditional yacon farming systems as models of organic management.
- Experiment with yacon in agroforestry systems and polycultures.
- Evaluation of the aerial parts as forage.
- Development and evaluation of post-harvest technologies, particularly for small farmers.
- Development and evaluation of different processing technologies.
- Development of standardized techniques for quantitative estimation of oligofructans.
- Biochemical and nutritional/medicinal studies
- Evaluation of the medicinal properties of the leaves.

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Appendix I. Research contacts

The values in brackets list the *Pachyrhizus* accessions (not including breeding lines or hybrids) recorded in the germplasm collections at the various institutions: A = *Pachyrhizus ahipa,* E = *P. erosus,* F = *P. ferrugineus,* P. = *P. panamensis,* T. = *P. tuberosus.*

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Related IPGRI publications

Promoting the conservation and use of underutilized and neglected crops.

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8.	Chayote. *Sechium edule* (Jacq.) SW.	1996
9.	Bambara groundnut. *Vigna subterranea* (L.) Verdc.	1997
10.	Breadfruit. *Artocarpus altilis* (Parkinson) Fosberg	1997
11.	Cat's whiskers. *Cleome gynandra* L.	1997
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13.	Sago palm. *Metroxylon sagu* Rottb.	1997
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18.	Grass pea. *Lathyrus sativus* L.	1997
19.	Buckwheat. *Fagopyrum esculentum* Moench	1997
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