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THE YAM BEAN PROJECT: A PAN-TROPICAL EVALUATION OF THE TUBER-BEARING LEGUME (GENUS *PACHYRHIZUS* DC)

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Abstract

The Yam Bean Project, now in its 10th year, examines the potential of the genus *Pachyrhizus* as an attractive alternative to traditional root and tuber crops. It has demonstrated the crop's potential for high yields (up to 160 t/ha) and significant contributions to sustainability, and as a multi-purpose crop. Five species of yam bean—three of which are cultivated—grow in nine different countries of Latin America, Africa, the Far East, and South Pacific. All five species have been studied taxonomically, biosystematically, and agronomically to evaluate their potential as tuber crops for the tropics and subtropics. Field collections have been carried out throughout the genus's area of distribution. All species have been evaluated under field conditions, and East Asian landraces were included in field trials to evaluate the performance of the considerable variation found within *P. erosus*. Field trials involving intra- and interspecific hybrids were carried out in Guanajuato (Mexico), Turrialba (Costa Rica), and Tongatapu (Tonga, South Pacific). The rotenone content of mature seeds was determined; and its potential use as a cheap crop protective agent explored. Further evaluations were carried out on the efficiency of biological nitrogen fixation, drought tolerance, and tolerance of variations in edapho-climatic conditions.

Introduction

In the quest for new, sustainable, and high-yielding crops that would improve the diet and food self-sufficiency of developing countries, tuber-bearing legumes have recently attracted attention. These species possess several attractive characteristics: they are highly nutritious and adaptable, tolerate poor soils, and resist pests and diseases. In addition, because they bear tubers, they can survive and still produce a crop if a sudden dry spell occurs. The yam bean genus (*Pachyrhizus* Rich. ex DC) has several features that establish it as a sustainable crop for

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the tropics or subtropics. Most definitions of sustainable agricultural systems are related to the environmental and economic impacts arising from use of land for agricultural purposes. The high yield performance of yam beans under rainfed conditions and its minimum input requirements can help conserve resources and reduce the use of synthetic chemicals.

Reports on disease and pest problems in yam beans are few, partly because the aerial plant parts contain the insecticidal compound rotenone, which can also be toxic to humans (NRC 1979).

The crop's ability to fix atmospheric N, a major limiting nutrient to mass production, results in a reduced N fertilizer requirement. Moreover, the application of N fertilizer negatively affects yield and efficiency of biological nitrogen fixation (BNF).

The variation in different traits, both within and among species, provides a broad genetic base for selecting parental material for improving the crop. In addition, as most interspecific hybrids are viable and fertile, the substantial variation recorded in this material has considerably increased the scope for further development of new cultivars.

Since 1985, scientists working in the Yam Bean Project, funded under the European Union's "Science and Technology for Developing Countries" (STD) programmes, have been exploring the potential of the genus, including breeding methods and the scope for introducing it into new areas.

Origin and History of Cultivation

Pachyrhizus belongs to the tribe Phaseoleae, subtribe Diocleinae. Of the five recognized species, three [*P. erosus* (L.) Urban, *P. tuberosus* (Lam.) Spreng, and *P. ahipa* (Wedd) Parodi] are cultivated for their tuberous roots, while the other two [*P. panamensis* Clausen and *P. ferrugineus* (Piper) Sørensen] are wild.

Pachyrhizus erosus

The first to be described by Linnaeus in 1753 was the Mexican species *P. erosus*, known under its Mexican name *jícama*. The morphological diversity recorded in this species appears to be centred in Central America rather than in Mexico. The herbarium specimens of Mexican origin are more uniform, except for a few wild collections from the state of Veracruz. On-going molecular analyses will, most likely, help determine and clarify its origin and domestication.

Archaeological evidence suggests that this bean was grown by early pre-Columbian civilizations such as the Aztecs and the Mayas, but *P. erosus* was known outside the Neotropics only since the discovery of Mexico and Central America.

Today, this high-yielding species is the most widely distributed of the yam beans. It was introduced to the Philippines by the Spaniards via the Acapulco-Manila route in the 16th century; from there, its cultivation spread to Indonesia and the rest of the Far East, and into parts of the Pacific. From middle to late 18th century, further introduction took place from the Philippines and Indonesia via Ceylon and India to the Mascarenes and then along the west coast of the African continent.

An interesting historical anecdote relates to its introduction into French Guiana. Believing it to be of Far Eastern origin, several French scientists recorded the crop in the Far East and Oceania at the beginning of the 19th century, for example, Gaudichaud-Beaupré in the Philippines and Oceania, and Perrottet in the Philippines and Indonesia. The French botanist and explorer Perrottet took samples of the species from an island in Indonesia in 1821 and, travelling progressively westward, introduced it to Mauritius and Réunion (the Mascarene Islands), French West Africa (Senegambia) and finally to Cayenne (French Guiana). In so doing, he came close to re-introducing the plant to its original distribution area. The fascinating possibility therefore exists that some of the cultivars known from the French Caribbean today may have completed a round-the-world trip, while others may 'only' have crossed over from Central America.

Areas outside Mexico and Central America, where *P. erosus* has been introduced and is cultivated or where the plant is known to have escaped from earlier cultivation, can be established from herbarium material and other sources, for example, in Brazil (WE Kerr, 1992, personal communication).

Pachyrhizus ahipa

The Andean yam bean (*P. ahipa*), known locally as *ajipa*, also has a long documented history of cultivation. Several Andean cultures are known to have valued this refreshing juicy crop, and dried tubers have been found in Peruvian 'mummy bundles'. The plant was also frequently depicted on pottery from Paracas Necropolis and the southern coast of Peru, and on textiles from nearby Andean civilizations such as Nasca.

Pachyrhizus ahipa is cultivated in the provinces of Jujuy (herbarium specimens seen) and Salta, Argentina. However, at least some of the cultivars recorded in this region originate from seeds introduced from Bolivia, that is, Bolivia farm labourers working in Argentina recall importing seed when visiting relatives (M Sørensen, 1993, personal observations). No records exist of wild plants in the area.

Although the traditional distribution area of this species is in the Andean valleys of northern Argentina, Bolivia, Peru, and Ecuador, it is now rarely found outside Bolivia. Recent (May-June 1994) field collections in Bolivia have resulted in comprehensive recordings of the present cultivation practices and an increased understanding of the genetic variation of the locally grown landraces. The species has several distinct characteristics that are agronomically interesting:

- A semi-erect, bushy, determinate growth found in the landraces from southern Bolivia and the provinces of Jujuy and Salta in northern Argentina;

- A short growth period at lower altitudes and in warmer conditions;

- Most importantly, material from southern Bolivia and northern Argentina is photothermally neutral, that is, unaffected by variations in daylight and temperature.

Pachyrhizus ahipa is the only species never recorded in the wild. Substantial evidence exists that it was known and cultivated by the Incas in pre-Columbian times. Two hypotheses on the origin of this species have been advanced: (1) Ceja de Montaña, Peru, where supposedly the first domestication took place from regional wild forms; and (2) Peruvian river valleys at altitudes of 1500-2500 m (i.e., valleys of the Rivers Marañón, Mantaro, Pampas, Apurimac, and Urubamba).

Pachyrhizus tuberosus

This Amazonian species has a more obscure history of cultivation, doubtless for lack of archaeological remains from earlier civilizations in its area of distribution. *Pachyrhizus tuberosus* was cultivated by the Guaraní Indians in Bolivia; at the beginning of the century, it was cultivated in fields along the Paraná River in Paraguay. In Ecuador, cultivation of this species can be dated back to the pre-Columbian period. In 1978, *P. tuberosus* was collected near Limoncocha (Ecuador), where it was cultivated by the Aucas (herbarium specimen 5465).

Pachyrhizus tuberosus has been recorded as being used from the wild or as being cultivated by the following ethnic groups in South America: Chimane and Tacana (Bolivia); Mato Grosso (Brazil); Panare (Venezuela); mestizos (Colombia); Cayapa, lowland Quichua, mestizos, Shuar, and Waorani (Ecuador); and Aguaruna, Amausha, Campa, Cocamas, Huachipayre, and Machiquenga (Peru). The fact that the crop is also found on several Caribbean islands points to its introduction by Arawak or Carib Amerindians and thus to a history of cultivation that predates Columbus.

Furthermore, field collections in the western province of Manabí (Ecuador) have yielded a previously unknown landrace, known locally as *jiquima*, with distinctly different morphological characteristics. In contrast, most materials originating from the Amazonian region have a highly uniform appearance, except for a few landraces whose lobed leaflets differ from the predominant pattern of entire leaflets. Another exception was recently discovered in the province of Loreto, Peru: a plant, locally known as *chuin,* that has only one tuber, which grows vertically. This contrasts with the commonly cultivated *P. tuberosus*, which produces several tubers extending vertically. Seeds of *P. tuberosus* from Trinidad were distributed to the botanic gardens of Calcutta, Ceylon, Brisbane, Melbourne, Sydney, and Adelaide. No herbarium specimen has been found of this species outside the neotropics; thus, these seeds may have been *P. erosus*.

Two wild locations of *P. tuberosus* have recently been discovered, possibly rediscovered, by J. Estrella E. and colleagues in the western province of Los Ríos in Ecuador and in the non-delimited zone between the provinces of Pichincha and Esmeraldas.

According to Salvador Flores Paitán (personal communication), *P. tuberosus* cultivars found in Amazonia were originally introduced from the eastern valleys of the Peruvian Andes, lying at altitudes of 1000-1500, notably of the Province of San Martín. Again, molecular evaluations will, hopefully, clarify the origin of the Amazonian landraces.

The Cultivated Species: Description and Distribution

Pachyrhizus erosus

Morphology. An herbaceous vine, it shows wide variation in leaflet shape, from dentate to palmate. The species is defined by the lack of hairs on the petals, number of flowers (4-11) per lateral inflorescence axis, and length of inflorescence (8-45 cm). Morphological characters of the legumes (pods), both qualitative and quantitative, are also used to separate the species: the size (6-13 cm x 8-17 mm), reduction of strigose hairs at maturity, and colour (pale brown to olive-greenish brown). The colour (olive-green, brown, or reddish brown) and shape (flat and square to rounded) of seeds are also specific to the species. The cultivars used in Nayarit, Mexico, have dark brown tubers and milky sap, whereas the Guanajuato cultivars have whitish brown tubers and a watery, transparent sap.

Distribution. It is found in the wild state in the Mexican states of Jalisco, Guanajuato, San Luís Potosí, Michoacán, Morelos, Puebla, Guerrero, Oaxaca, Veracruz, and Chiapas; central and western Guatemala; El Salvador; western Honduras; western Nicaragua; and north-western Costa Rica.

Cultivated in the Mexican states of Nayarit, Guanajuato, Yucatán, and Quintana Roo, where it is often found as an escape. In states where it grows wild, different cultivars are also often found as escapes, as the plant is widely cultivated in most southern Mexican states. This situation also applies to El Salvador and north-western Honduras, where cultivation is widely practised (M Grum, personal observation).

In Guatemala, cultivation is limited to the southern states of Santa Rosa, Jutipa, and Chiquimula. *Pachyrhizus erosus* is also found occasionally in fields of shifting cultivation in the state of Petén (M Sørensen, personal observation), and is often found as a relic from earlier cultivation. Numerous locations of wild material also exist. In general, this situation is probably true for central and western Honduras and Nicaragua, where little or no cultivation is currently practised.

Several collections of *P. erosus* were recorded from Belize, but the plant was probably introduced for cultivation from northern Yucatán Peninsula.

Habitat. Areas with annual dry season and average annual rainfall ranging from 250-500 to >1500 mm. Along edges of deciduous forests and in scrub vegetation. Soil types range from deep clay to sandy loam. Recorded at altitudes from 0 to 1750 m, but mostly found between 500 and 900 m.

Flowering season. Flowers seen in all months except January, but 90% during July-October, and at later dates in the southern parts of the distribution area, that is, at the end of the rainy season. Mature legumes recorded from August-February. In 1985, mature legumes were collected in mid-March in Costa Rica.

Pachyrhizus ahipa

Morphology. An erect to semi-erect herbaceous plant (30-40 cm tall), with very short inflorescences (5-9 cm). The number of lateral axes on the main inflorescence axis is greatly reduced (0-6), with only 2-6 flowers per lateral axis. The wing and keel petals are usually glabrous, but slightly ciliolated specimens have been seen. The legume is 13-17 cm long and 11-16 mm wide; the seeds are rounded, reniform, black or mottled black and white.

Distribution. Widely cultivated in Bolivia and Peru in fertile valleys at altitudes between 1500 and 2800 m. Herbarium specimens have been seen from the provinces of Sorata and Tarija in Bolivia.

Habitat. As stated, this species is known from cultivation only, in cool tropical or subtropical valleys, with an annual mean rainfall ranging from 500 to 1500 mm.

Flowering season. Usually sown in December, it flowers in February-March and legumes are mature by April.

Pachyrhizus tuberosus

Morphology. Notably the largest species in the genus, its vines attain lengths of more than 10 m. The leaflets are entire (occasionally slightly dentate) and uniform. The inflorescence is 7-29 cm long, with 7-33 flowers per lateral axis. The wing and keel petals are usually ciliolate, although glabrous specimens have been recorded. The legumes are the longest in the genus, at 13-19 cm, and 14-23 mm wide and, in some cultivars, they are strigose. The seeds are rounded, reniform, orange-red, black or mottled black and white.

Distribution. Widely cultivated in the Amazonian region of South America, it appears to be native to the western part of this region. It has been collected from Colombia, Venezuela, British Guiana, Brazil, Bolivia, Peru, and Ecuador, and is reportedly cultivated in the eastern provinces of Paraguay (L Ramella, personal communication). It has been introduced to the Caribbean islands of Puerto Rico, Jamaica, Hispañola, and Trinidad.

Habitat. Found in tropical to subtropical evergreen rain forests, it is restricted to areas with an annual mean rainfall of 1500-4100 mm. It grows at altitudes from 0 to 1550 m, and occasionally forms dense tangles.

Flowering season. Given its highly heterogeneous origin and uncertain status (i.e., whether wild or cultivated), the exact time and length of the flowering season cannot be determined. Specimens in full bloom have been registered in all months except February and July, but most materials flower between October and June. Mature fruits are seen between March and December.

Comments. *Pachyrhizus tuberosus* was introduced and cultivated in Brazil. A recent hypothesis suggests that *P. tuberosus* may only be a cultivar of *P. erosus*, selected for its larger roots. All plants of this species grown in either glasshouses or the field have produced tubers of the multi-tuberous type.

To clarify the species' status, we consulted both herbarium material and literature. We used herbarium specimen 4936 from Tarapoto, Peru, to provide the basis for the prototype. The specimen was collected by R Spruce, and two duplicates exist in Kew. One sheet has the entire leaflet type and inflorescence illustrated; the other sheet has a legume similar to the one of the prototype, and a deeply lobed leaf that was not illustrated. This clearly demonstrates that both leaf types occur within *P. tuberosus*, maybe even on the same plant.

But because the material supposedly exists in cultivated form only, and *P. erosus* is known to have been cultivated in the area at the time of the Spruce collection, these two species may in fact be non-specific. However, this hypothesis can be only confirmed by currently on-going genetic and ontogenetic studies of 16 specimens and recently collected germ plasm from Ecuador and Peru. Molecular taxonomic studies being carried out at the University of St. Andrews, Scotland, indicate that the two species can be separated and that each forms a uniform entity (RJ Abbott, personal communication). *Pachyrhizus erosus* and *P. tuberosus* have been shown to be interfertile in the comprehensive interspecific hybridization programme forming the basis for breeding new varieties.

Cultivation Practices and Uses

In contrast to most other tuber crops, all yam bean species are, as a rule, propagated by seed. However, smaller tubers from the multi-tuberous *P. tuberosus* are occasionally used by farmers for propagation, although this information is not confirmed by recent field observations.

Although individual plants of the three cultivated species may produce more than one tuber (this appears to be greatly influenced by spacing in the field), the norm is one tuber per plant. Marketable tubers should weigh 0.5-1.0 kg. In Mexico, the average number of plants/ha is 60,000-80,000. The only other tropical root crop that can match this field performance is cassava (*Manihot esculenta* Crantz), also known as *manioc* or tapioca. In other respects, however, yam beans have the edge: they produce a crop in less time (4-7 mo, depending on the species), and, although they have a much lower dry matter content, their protein content is, on a DM basis, 4-5 times higher. In concrete terms, this translates into more than half a ton of protein/ha (assuming a fresh root yield of 80-100 t/ha). Finally, yam bean tubers retain their quality once they have been harvested. The tubers can be stored for more than 3 mo without significant loss in quality, although they may shrivel as they lose water (NRC 1979).

Yam bean production is increasing in Hawaii, where the crop's ability to fix nitrogen biologically makes it attractive for poor soils.

When compared with traditional tuber and root crops, yam beans are exceptional in that most are consumed fresh, although cassava is occasionally eaten raw in some African countries (e.g., Malawi), even though this practice is considered to constitute a health hazard, given the anti-nutritional compounds present in the roots. Yam bean tubers are also cooked in various ways: in Central America, *jícama* soup is a traditional plate and, in the Far East, thinly sliced tubers are used to prepare various chop suey-like dishes or as a deep-fried vegetable. The above-mentioned *chuin* (*P. tuberosus*) cultivar from Peru has a tuber quality comparable with that of cassava (i.e., high DM content), and is consumed only in cooked form. *Chuin* is commonly cultivated in association with cassava, but the local villagers prefer the flavour of the former.

Yam beans are regarded as a healthy food by American dieticians; the Mexican yam bean, for example, consists of 80%-90% water, 10%-15% carbohydrates, 1.0%-2.5% protein, and 0.1% lipids. The starch is highly digestible and suitable for infant diets. The amino acid content compares favourably with all other tuber crops and fat content is low. The 'chop suey bean'—the commercial name for the yam bean in American supermarkets—is currently the fastest growing specialty vegetable on the U.S. market (e.g., *Newsweek*, July 30, 1990). Yam bean tubers are slightly sweet, with a mild pea-like flavour, and a crunchy texture similar to apples. They can be eaten raw, cooked, deep-fried, or pickled with chilli in vinegar.

Parts of the yam bean other than the tuber are also used as food. In Thailand, the young or immature pods are eaten as a substitute for beans, but care during processing is needed to avoid toxic effects (NRC 1979). Nutritionally, these pods can be compared with soybean legumes. The dried plant material that remains after harvest is used as animal fodder in Mexico.

If the rotenone can be removed from the mature seeds, then the oil is safe for consumption and can be marketed as an alternative to soybean oil. The rotenone itself may be used as an insecticidal agent.

Pachyrhizus erosus

Cultural practices. In Mexico, yam beans are traditionally intercropped with maize (*Zea mays* L.) and common beans (*Phaseolus vulgaris* L.). The three are sown simultaneously with timing varying according to altitude. The common bean is harvested 85-90 days after planting (DAP); maize 110-120 DAP; and yam beans 145-150 DAP. This traditional cultivation system yields about 0.5 t beans/ha, 1 t maize/ha, and 50-60 t yam beans/ha. Yam beans are also cultivated as a monocrop for export.

Different methods of pruning are employed to increase tuber size. With the Mexican yam bean, reproductive pruning, which removes all flowering shoots, is usually carried out 3 or 4 times during the growing season. Flowering in *P. erosus* is induced during short days (M. Sørensen and others, personal communication).

In the states of Nayarit and Guanajuato—the two main areas of large-scale production in Mexico—*P. erosus* is planted during October to November and January to March, respectively. The reason for these separate growing seasons is caused by differences in altitude even though Nayarit (0-100 m) and Guanajuato (>1500 m) are located on almost the same latitude (20^{o} N). Harvesting begins during March-April in Nayarit and in October-November in Guanajuato.

Recently, the effect of foliar application of different plant hormones (e.g., gibberellic acid and chlorocholine chloride) on tuber yield has been studied (Y Elber, personal communication).

Uses. A remarkable feature of boiled or fried tuber slices is the ability to retain a crunchy quality. A fine flour is also obtained from sliced, dried, and ground tubers. If allowed to grow to maximum size, the tubers are used to feed cattle and pigs. With careful processing and cooking, young pods can be used as a vegetable, but because of their rotenone content, they are poisonous when ripe. The rotenone can be extracted from the ripe pods and used as an insecticide. The dried vegetative parts of the plant are used as hay once the tubers are harvested.

Pachyrhizus ahipa

Cultural practices. Cultivation of the Andean yam bean (*P. ahipa*) involves reproductive pruning, but because the inflorescences grow close to the ground (the plants being smaller than the Mexican *P. erosus*), this operation is laborious. Usually grown as a monocrop, it is occasionally intercropped with maize (2-3 m apart). Planting density in monocropped fields varies considerably, but about 250,000 plants/ha is common, yielding about 20 t/ha.

Uses. It is consumed fresh as a vegetable or fruit. In Bolivian markets, the tuber is mostly sold by fruit vendors, and is referred to as *la fruta* or *el fruto* (fruit), not *el raíz* (root) nor *el tubérculo* (tuber). No records or field observations concerning use of the plant's insecticidal properties have been reported.

Pachyrhizus tuberosus

Cultural practices. *Pachyrhizus tuberosus* is known to have been cultivated by the indigenous people of the Amazon region since antiquity. Occasionally the crop is found in *chacras* (fields surrounding remote villages located in highland rain forests) of Peru, particularly the Department of San Martín (C Thirup, personal communication; herbarium specimens). The crop is also grown in shifting cultivation in the Amazon proper.

Seed is sown, preferably in fertile, light, sandy soils with good drainage, at 45-50 kg/ha. Several bud and flower prunings are believed necessary to obtain high tuber quality, and half the aerial parts are removed when flowering starts. Frequently, however, pruning is not carried out—especially in the province of Manabí, Ecuador.

Yields. Although yields vary according to cultural practices, planting density, species, and whether irrigation is used, the average yield in Mexico is 70-90 t/ha. These high yields are achieved in areas (e.g., the state of Nayarit) that have been continuously cropped with yam beans for 40-50 y.

Uses. About 100 years ago, tubers of *P. tuberosus* were reportedly used to make flour in Jamaica, but otherwise the tubers are used in much the same way as those of *P. erosus*. The juicy *ashipa* type with multiple tubers is used locally to prepare a refreshing soft drink (L Jensen and C Thirup, personal communication). Tubers of the *chuin* landrace are always cooked. Young pods are sometimes cooked as a vegetable.

The Project

The STD-funded project, now in its third phase, is an integrated effort involving nine different institutions from Mexico, Central America, South America, Africa, Europe, and the Pacific. Other institutions and private individuals have links with the project through the Yam Bean Network, established as a result of the First International Symposium on Tuber Legumes held in Guadeloupe, 21-24 April 1992.

Germ plasm

When the project was initiated (1985), few seed samples and very little information about the yam bean were available from the world's various gene banks. Through various contacts, about 20 samples of the Mexican yam bean and two samples of the Andean species were produced, but almost no details were available as to the exact origin of this material, the cultivation practices involved, or other relevant data. To make a comprehensive examination of the crop's potential, a thorough recording of the natural and cultivated distribution of the genus had therefore to be undertaken, based on information available from herbarium specimens. Subsequently, several field collections were carried out. Today, about 200 sample groups, covering both wild and cultivated material, are available for hybridization and evaluation (Table 1).

Hybridization and breeding programme

The potential of yam bean as a commercial crop is high:

> Although only five species of yam bean are known to exist, they show such variation in genetic background, form, and structure that substantial improvements can be achieved through breeding.
>
> The potential of the genus as a sustainable crop with a variety of end uses has been clearly demonstrated.
>
> Yam beans produce high yields under a wide range of climatic and soil conditions.
>
> They are readily accepted by consumers of very different socio-economic backgrounds (e.g., Africans and Pacific Islanders), even when unfamiliar with the crop.
>
> Finally, extrapolating from the crop's growing status in the USA, the untapped EU market may also offer valuable export opportunities for yam bean growers.

The project's breeding programme involves carrying out hybridization experiments with a view to developing new, high-yielding cultivars. All known varieties—except those resulting from radiation experiments in India—are the result of selection without previous breeding.

Hybrids, combining the growth characteristics and photothermal neutrality of the Andean yam bean, the vigour of the Amazonian species, and the high-yielding capacity of the Mexican species, would allow the cultivation of this crop under a wide range of climatic conditions. So far, four of the five species have been successfully hybridized. Selections, based on yield and adaptability, began in 1989, and evaluations of the third to sixth generation hybrids are currently under way. At present, about 600 hybrids are being tested at experiment stations in Mexico, Costa Rica, and Tonga.

Field trials

Although the main emphasis is on developing new hybrids, field trials have also taken place in Mexico, Costa Rica, Ecuador, Senegal, Benin, Thailand, and Tonga to examine the potential of existing lines. The trials have been carried out at different altitudes and cover a wide range of soil and climatic conditions, including both high rainfall and semi-arid regions. By way of example, two different types of the Mexican yam bean have yielded from 80-160 t/ha in trials carried out in Benin, Costa Rica, Mexico, and Tonga. One Haitian cultivar of the Amazonian *P. tuberosus* produced a yield of 70 t/ha in Benin. All field experiments have been carried out, using dry-land farming techniques, except for trials in Guanajuato, Mexico, where the record yield of 160 t/ha was obtained, and in Senegal, where yields of 40 and 100 t/ha (*P. erosus*) were recorded at Bambey and Tiago, respectively.

Trials carried out in Portugal by the French partner in the project have demonstrated the astonishing potential of the Andean yam bean under Mediterranean conditions: yields of 54 t/ha, with as much as 24% DM and 9.6%-11.1% of crude protein (DM). Recently collected material from Ecuadorian cultivars of the Amazonian yam bean (*P. tuberosus*) are showing a similarly encouraging yield potential.

When the crop was first introduced into Tonga, local consumers were reluctant to accept the new type of tuber. Although the traditional Tongan diet is largely based on root and tuber crops, the crisp, juicy quality of the yam bean appeared to be too 'exotic'. That it could be eaten fresh was also a novelty. However, with increased demand among the local Asian and European communities, and the attraction of easy cultivation, the Tongans are now growing, marketing, and consuming yam beans in increasing numbers.

The situation in Benin is similar, if not more encouraging. Thanks to local media coverage, a peculiar situation has arisen with several of the field trials subjected to 'unauthorized testing and sampling' at night by local farmers. The biggest problem at the moment is availability of seed for local cultivation.

Biological nitrogen fixation

Like other members of the legume family, it has an efficient symbiosis with nitrogen-fixing *Rhizobium* and *Bradyrhizobium* bacteria, thus eliminating the need for N fertilizer. In contrast to many grain legumes, a substantial amount of the fixed N is returned to the soil if the vegetative aerial parts are left in the field. The crop therefore forms an integral part of a sustainable land use system, from both an ecological and socio-economic viewpoint. Indigenous strains of *Rhizobium* and *Bradyrhizobium* were collected in the field in Central and South America in 1993, and isolates subsequently obtained and evaluated under glasshouse conditions. *Pachyrhizus* genotypes and bacteria strains with high BNF potential will then be selected, with emphasis on improving the host-plant range, and thus providing a simple technology within the reach of developing country farmers.

Rotenone

Another common generic characteristic is the presence of an insecticidal compound called rotenone ($C^{23}H^{22}0^{6}$). Although this compound is not found at toxic levels in the tuber or other parts of the plant, levels are high enough in mature seeds to make them inedible (about 0.5% pure rotenone, and 0.5% rotenoids and saponins). The seeds also have high levels of good quality vegetable oil (about 30% in *P. erosus*), which, if the insecticidal compounds are removed, has a composition that is almost identical to that of soybean oil. The presence of rotenoids in seeds and leaves may have a protective effect for the plant against insect predators.

Field experiments evaluating the use of *P. erosus* seed extract as a low-cost plant protective agent have recently been reported by two project partners:

> In Benin, an aqueous suspension of ground *P. erosus* seed protected two cowpea cultivars (*Vigna unguiculata* (L.) Walp. ssp. *unguiculata*) against *Taeniothrips sjostedrii*, significantly reducing pod damage.
>
> In Tonga, a similar suspension (at three levels of dosage) from *P. erosus* seeds was tested on insect pests of head cabbage (*Brassica oleracae* L. convar. *capitata* (L.) Alef var. *capitata* L. cv. KK-cross), and compared with the commercial insecticide DiPel (*Bacillus thuringiensis* var. *kurstaki*). The larval population (unidentified insect pest) was significantly reduced by all three rates of the suspension. Although the commercial insecticide was more effective, the use of yam bean seed as a low-cost insecticide with no residual effects remains an attractive possibility for low-input, sustainable farming systems.

Drought tolerance

Physiological studies of response to drought in *Pachyrhizus* under field conditions in Senegal, and under glasshouse conditions in France (J Vieira da Silva, personal communication), demonstrated that *P. erosus* is resistant to drought and *P. ahipa* is tolerant. More recent pot trials studied the developmental competition of the reproductive organs (flower, legume, and seed) with the storage organ (tuber) under drought conditions. The *P. ahipa* experiments had four 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 indicated that reproductive pruning had no influence on the physiological response to drought.

The French experiments studied drought resistance in three available cultivars of *P. ahipa* (the newly collected germ plasm has yet to be multiplied). The relationship between the amount of membrane lipids and protoplastic drought resistance (a character already found in other legumes) is being studied. So far, the research has confirmed that membrane resistance depends on a low lipid content—as in other species—useful information for screening genotypes for drought resistance.

In vitro **experiments**

The use of *in vitro* multiplication techniques constitutes an attractive possibility when genotypes of limited availability must be rapidly multiplied for conservation purposes, or when hybrids or new material from field collections, possessing agronomically attractive traits, are identified in field trials. If such genotypes were available in sufficient quantities, they could be submitted to field evaluations almost immediately after being identified or selected.

Several institutions in Costa Rica, Denmark, Ecuador, and Trinidad have begun studying in this field. The experiments so far have involved regeneration and multiplication from adventitious and auxiliary shoots (explants) and callus formation with subsequent organogenesis, that is, the protocol for somatic embryogenic systems is being developed.

Molecular taxonomy

In view of the situation of *Pachyrhizus* germ plasm in South America, widely regarded as critical by national and international agencies, a programme for assessing genetic resources is of the highest priority. The relationships among the different species are currently being studied by the Plant Sciences Laboratory of the School of Biological and Medical Sciences at the University of St. Andrews, Scotland. The use of molecular analyses is key to 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.

To assess and resolve the level and distribution of genetic diversity within and between species of *Pachyrhizus*, the researchers cross breed and examine the stability of resulting genetic characters, using isoenzyme variation over 20 enzyme systems and polymerase chain reaction (PCR) to resolve randomly amplified polymorphic DNA sequence (RAPD) analysis. The analyses are conducted on a representative sample of the existing germ plasm collection of *Pachyrhizus*. The sample includes all species and a wide range of cultivars, landraces, and wild material.

The survey of molecular genetic diversity in the *Pachyrhizus* germ plasm collections will make possible the following:

Estimation of level and distribution of genetic diversity within and among species;

Location of *natural* centres of genetic diversity for collection and conservation;

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*;

Fingerprinting specimens exhibiting genetic traits associated with useful products, for example, the insecticide rotenone.

Conclusions

Yam beans have long been considered as minor, even lost, crops (NRC 1979), despite their obvious potential. Initial research carried out by the yam bean project has served to demonstrate the existence of considerable genetic variation within the genus and genotypes with high-yielding capacity, adaptability, and sustainability. To establish yam beans as an attractive, multiple-purpose, crop for the tropics and subtropics, further research, combined with intensified promotion, is needed.

Reference

NRC (National Research Council). 1979. Tropical legumes: resources for the future. National Academy Press, Washington, DC.

Table 1. Germ plasm materials of yam bean (*Pachyrhizus* spp.) around the world.

Species	Country	Accessions (no.)		Status of collection[a]		
		Cultivated	Wild	Mult.	F. exp.	Hybr.
P. erosus	Belize	2	-	x		
	Brazil	10	-		x	x
	China	4	-		x	
	Colombia	2	-		x	
	Cuba	1	-	x		
	Domin. Rep.	1	4		x	
	El Salvador	3	-	x		
	Guatemala	9	9		x	x
	Honduras	5	-	x		
	Hong Kong	1	-	x		
	Indonesia	3	-	x		
	Macau	3	-		x	
	Malaysia	3	-	x		
	Martinique	1	-	x		
	Mauritius	-	1		x	
	Mexico	45	2		x	x
	Nigeria	2	-		x	
	Thailand	27	-	x		
	USA (Florida)	1	-	x		
	USA (Hawaii)	2	-		x	
	Total	**125**	**16**			
P. ferrugineus	Belize	-	5	x		
	Costa Rica	-	3	x	x	x
	Cuba	-	1	x		
	Guatemala	-	6	x	x	
	Martinique	-	1		x	
	Panama	-	4	x		
	Total	**-**	**20**			
P. panamensis	Panama	-	1		x	x
	Total	**-**	**1**			
P. tuberosus	Bolivia	3	-	x	x	
	Brazil	5	-		x	x
	Ecuador	22	4	x	x	x
	Haiti	1	-		x	x
	Peru	15	-	x	x	x

	Total	**46**	**4**			
P. ahipa	Argentina	1	-	x		
	Bolivia	19	-	x	x	x
	Unknown	2	-		x	x
	Total	**22**	**-**			

a. Mult. = multiplication; f. exp. = field experiment; hybr. = hybridization.