Compositional Diversity of the Yacon Storage Root

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Yacon is a little-known, nonstarchy Andean root crop, which is eaten raw and functions as fruit in traditional food systems. It belongs to the Asteraceae (sunflower family) and is vegetatively propagated. Botanically, the crop has been referred to until recently as *Polymnia sonchifolia* Poepp. & Endl., but the binomial *Smallanthus sonchifolius* (Poepp. & Endl.) H. Robinson is gaining acceptance among taxonomists (Grau and Rea, 1997).

Yacon is a very productive crop with root dry matter (DM) yields in soils of moderate fertility exceeding 10 t/ha in 6-8 mo. The dark-skinned roots vary from spherical to oblong and weigh from 100 g to 1 kg. The concentration of a yellow orange pigment responsible for yacon's light flesh color varies by genotype. Defining organoleptic attributes of the yacon root are a succulent, tender crunchiness, which approaches that of a watery radish or apple, and a mildly resinous but pleasantly sweet taste.

Smallholders in the Andes cultivate yacon fairly commonly for subsistence. Rarely, however, do the roots reach rural fairs, and reliable production estimates for the crop are not available. Typically, only a few plants or rows are cultivated in field corners or backyard gardens and, through piecemeal harvest, provide a continuous supply year-round. The lack of urban demand for this root is poorly understood, but constraints may include the root's short shelf life of a few days and a lack of consumer familiarity.

The bulk of yacon DM has previously been shown to consist of free sugars and fructans of low polymerization, i.e., fructo-oligosaccharides (FOS) (Ohyama et al., 1990, Wei et al., 1991). FOS consist of short chains of fructose units linked by (2® 1) ß-glucosidic bonds. They carry a single D-glucosyl unit at the non-reducing end of the chain (1® 2)-a as in sucrose.

The nutritional significance of the sweet-tasting FOS is that the human small intestine has no enzyme to hydrolyze the glucosidic bonds. Therefore, FOS are considered indigestible and serve as dietetic sweeteners. Health benefits are also claimed for fructans. They have been shown to stimulate the growth of bifidobacteria in the human colon, to suppress putrefactive pathogens, and to reduce serum cholesterol concentrations. They are thus increasingly added to pastry, confectionery, and dairy products (Campbell et al., 1997).

There is limited information on the chemical composition of yacon and it mostly comes from one cultivar, presumably Ecuadorian, grown under temperate conditions in Japan. The object of this study was to determine the chemical composition of the yacon root and its variation in a germplasm sample taken from throughout the crop's geographic range in a tropical highland environment. Yacon chemical composition in relation to product development and nutrient removal by harvested roots is examined. This study intends to contribute to the increased use of the biodiversity of this neglected Andean crop in its native range.

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Materials and Methods

Field cultivation

Ten yacon accessions, for which attributes are given in Table 1, were grown in natural soil in an open-sided, insect-proof, quarantine greenhouse in the Tumbaco Valley near Quito, Ecuador, under thermic and light conditions close to the surrounding equatorial environment at 2,500 m altitude. Monthly mean temperatures varied from 14.6°C to 16.0°C, with average daily minimums ranging from 4 to 8°C and maximums from 23 to 29°C. Monthly sunshine was 110-230 h. Before planting, samples taken from the sandy soil had a pH of 7.2-7.5. Nitrogen content of the soil ranged from 22 to 30 µg/ml soil (low), P content 80-200 µg/ml (high), and K content 0.29-0.68 meq/100 ml soil (medium to high). Three to four plots per accession were used in a completely randomized design.

Pre-rooted apical cuttings were planted on 12 Aug 1995, at a spacing of 1 m x 0.7 m. Mineral fertilizers at the rate of 50 kg N/ha and 100 kg K/ha were applied 4 wk after planting, at which time the plants were hilled up. Plots were weeded at 2 and 4 mo after planting. Furrow irrigation was provided as needed.

Chemical composition determination

When all accessions had become senescent (8 mo after planting), 2 plants/plot were harvested, yielding 20-50 roots with root fresh wt of 6-10 kg. Harvested roots were speedily delivered to the laboratory, where they were peeled and chopped into 1-1.5 cm cubes. The cubes were thoroughly mixed and a sample of 1-2 kg was taken for subsequent analysis. One-third of the sample was used to extract juice with a kitchen extractor for determining the refractometric index (°Brix). The remaining root cubes were immediately frozen and subsequently freeze-dried. Dried samples were ground to the consistency of flour and stored at –80°C until analysis. All values obtained for freeze-dried material were corrected to a fresh wt basis.

Moisture content (MC) was determined for fresh and freeze-dried root material by vacuum oven drying for 24 h at 70°C, fat by Soxhlet extraction using petroleum ether as solvent, protein as Kjeldahl N x 6.25, and

Table 1. Geographical attributes and mitotic chromosome number of yacon clones used in this study.

Accession[a]	Year collected	Country	Province	Locality	Altitude (m)	Latitude	Longitude	Mitotic chromosomes
ASL 136	1992	Peru	Cajamarca	Chota	2,900	06°33′S	78°38′W	87
AW 5075	1991	Peru	Cajamarca	Cancan	2,600	07°11′S	78°19′W	58
ARB5027	1991	Peru	Lima	Tintín	3,200	12°20′S	75°47′W	58
ARB5073	1991	Peru	Cajamarca	Sucre	2,600	06°56′S	78°08′W	58
ARB5074	1991	Peru	Cajamarca	Sucre	2,600	06°56′S	78°08′W	58
ECU1243	1984	Ecuador	Azuay	Cumbe	2,560	03°10′S	78°09′W	58
HN1013	1992	Argentina	Jujuy	Bárcena	1,900	23°58′S	65°26′W	58
MHG919	1991	Bolivia	Cochabamba	Pairumani	2,600	17°25′S	66°20′W	58
MHG923	1991	Bolivia	Cochabamba	Paracti	2,100	17°10′S	65°55′W	58
MHG927	1991	Bolivia	Cochabamba	Locotal	1,800	17°10′S	65°45′W	58

[a] Accession ECU1243 is maintained by Instituto Nacional de Investigaciones Agropecuarias, Quito, Ecuador; all other accessions are kept in the CIP genebank.

ash (minerals) by incineration at 550°C for 4 h. Potassium and Ca were determined by flame spectrophotometry, P spectrophotometrically (molybdovanadate method). Crude fiber was determined on defatted samples using the Fibertec system (Tecator A.B., Högenäs, Sweden). We calculated total carbohydrates as total DM less protein, fat, and ash.

Free sucrose, glucose, and fructose were extracted with water at 70°C for 30 min and determined with a high performance anion exchange chromatograph (HPAEC). Fructans were determined indirectly by a novel method adapted from Hoebregs (1997). This method relies on the acid hydrolysis of the sample, followed by HPAEC determination of the released sugars as was done for free sugars.

Hydrolysis depolymerizes fructans and sucrose into its component sugars, glucose and fructose. By determining the glucose and fructose content before hydrolysis (G_{free}, F_{free}) and after hydrolysis (G_{total}, F_{total}), and considering the loss of water in the hydrolysis of sucrose, we can calculate glucose and fructose released from fructans as

$G_{Fructans} = G_{total} - G_{free} - S/1.9$ and

$F_{Fructans} = F_{total} - F_{free} - S/1.9$

where G = glucose, F = fructose, and S = sucrose. The average degree of polymerization (DP) of fructans is then

$$DP = F_{Fructans} / G_{Fructans} + 1$$

and the quantity of fructans originally present in the sample becomes

$$\text{Fructans} = C\,(F_{Fructans} + G_{Fructans})$$

where C is a constant correcting for water gained for each glucosidic bond during polymerization:

$$C = [180 + 162\,(DP - 1)] / 180 \cdot DP.$$

The caloric value per 100 g edible portion was calculated using a formula adapted from Merrill and Watt (1973), namely: kcal = (3.36 x % protein) + (3.60 x % [total carbohydrates – fructans]) + (8.37 x % fat). This formula assumes that no fructans are metabolized in humans. A handheld Atago refractometer was used to determine °Brix at 18°C. Duncan's multiple range test and Pearson correlation coefficients were calculated using SAS procedures GLM and CORR, respectively. Principal component analysis was done with NTSYS-pc, v. 1.80 (SAS, 1989; Rohlf, 1992).

Results

Chemical composition of yacon relative to root fresh matter (FM) is shown in Table 2. Composite factors relative to root DM are shown in Table 3. For all 10 accessions low values and narrow ranges of DM (98-136 g/kg) and carbohydrate content (89-127 g/kg) were found, especially when accession AW5075 was excluded. Carbohydrates accounted for 91-94% of DM. Discounting the outlying accession AW5075, the accessions also had narrow ranges for fructans (50-89 g/kg FM, 52-66% DM) and total free sugars (18-31 g/kg FM, 14-29% DM). By contrast, AW5075 had a much reduced fructan content (31 g/kg FM, 32% DM) and correspondingly high free sugar content (42 g/kg FM, 43% DM). This accession matured precociously and, when harvested, had started developing new sprouts.

Accession ASL136 had the highest values for DM, total carbohydrates, fructans, and °Brix. This accession from Peru is also distinguished by its dodecaploid nature (9A + 3B = 2n = 87; A = 7, B = 8) from the other material (Table 1), which has been shown by Salgado (1996) to be octoploid (6A + 2B = 2n = 58). In a recent field trial of 24 Peruvian accessions, ASL136 ranked among the highest in DM content and yield (C. Arbizu, CIP, Lima, Peru, 1999, pers. comm.) thus underscoring

Table 2. Chemical composition of 10 yacon accessions per 1 kg of root fresh matter.

Variable	Range	Mean	C.V.	Accessions[a]									
			(%)	ASL136	AW5075	ARB5027	ARB5073	ARB5074	ECU1243	HN1013	MHG919	MHG923	MHG927
Dry matter (g)	98-136	115	8	136 a	98 d	114 bc	115 bc	109 cd	111 bc	109 cd	118 bc	123 b	120 bc
Total carbohydrates (g)	89-127	106	8	127 a	89 d	104 bc	105 bc	100 cd	102 bcd	100 cd	111 bc	114 b	112 bc
Fructans (g)	31-89	62	23	89 a	31 d	62 bc	61 bc	50 c	59 bc	58 bc	68 b	74 b	72 b
DP	3.6-4.3	3.9	6	4.2 a	4.3 a	3.8 bcd	3.6 e	3.6 de	4.2 a	3.7 cde	3.9 bc	4.0 b	3.9 bc
Total free sugars (g)	18-42	26	27	19 cd	42 a	27 bc	26 bcd	31 b	24 bcd	24 bcd	22 cd	20 cd	18 d
Free glucose (g)	2.3-5.9	3.4	32	2.8 d	2.3 d	2.8 d	4.5 b	5.9 a	2.4 d	4.0 bc	3.0 d	3.3 cd	2.8 d
Free fructose (g)	3.9-21.1	8.5	58	4.6 c	21.1 a	9.4 bc	7.5 bc	9.3 bc	11.4 b	6.6 bc	5.6 c	3.9 c	4.3 c
Free sucrose (g)	10-19	14	18	12 cd	19 a	15 bc	14 bcd	16 ab	10 d	13 bcd	13 bcd	12 bcd	11 d
°Brix	9.0-12.6	10.7	9	12.6 a	9.0 c	10.6 abc	10.6 abc	9.9 bc	10.7 abc	10.2 bc	10.8 abc	11.8 ab	11.1 abc
F_{tot}/G_{tot} ratio	1.95-2.86	2.38	12	2.64 b	2.84 ab	2.36 c	2.07 d	1.95 d	2.86 a	2.14 cd	2.35 c	2.34 c	2.37 c
Protein (g)	2.7-4.9	3.7	19	3.3 de	3.5 cde	4.7 ab	4.9 a	3.7 cde	4.3 abc	3.8 bcd	2.7 e	2.7 e	3.7 cde
Fiber (g)	3.1-4.1	3.6	8	3.6 abc	3.5 bcd	3.3 cd	3.7 abc	3.8 ab	4.1 a	3.4 bcd	3.1 d	3.6 abc	4.0 a
Fat (mg)	112-464	244	43	191 cde	289 bc	171 de	311 b	464 a	234 bcd	331 b	118 de	194 cde	112 e
Energy (kcal)	148-224	174	12	148 c	224 a	170 bc	177 bc	197 ab	168 bc	165 bc	163 c	155 c	156 c
Ash (mg)	4,275-6,014	5,027	10	5,630 ab	4,881 abc	5,071 abc	4,931 abc	4,357 bc	5,369 abc	5,015 abc	4,275 c	6,014 a	4,944 abc
Calcium (mg)	56-131	87	25	68 def	84 bcde	94 bc	92 bcd	103 b	131 a	76 cdef	61 ef	101 b	56 f
Phosphorus (mg)	182-309	240	17	291 abc	197 d	240 abcd	245 abcd	204 d	302 ab	232 bcd	182 d	309 a	224 cd
Potassium (mg)	1,843-2,946	2,282	15	2,859 ab	1,969 c	2,267 bc	1,999 c	1,843 c	2,361 abc	2,327 abc	2,065 c	2,946 a	2,382 abc

[a] Means followed by a common letter are not significantly different at $P < 0.05$ by DMRT.

Table 3. Carbohydrate composition of 10 yacon accessions relative to root dry matter (%).

Accession	Total Carbohydrates	Fructans	Total free sugars	Free glucose	Free fructose	Free sucrose
ASL136	93	66	14	2.0	3.4	8.5
AW5075	91	32	43	2.3	21.6	19.5
ARB5027	91	54	24	2.5	8.3	13.3
ARB5073	91	53	22	3.9	6.4	12.0
ARB5074	92	46	29	5.4	8.7	14.7
ECU1243	91	52	23	2.1	11.1	9.4
HN1013	92	53	22	3.8	6.1	12.1
MHG919	94	58	19	2.6	4.9	11.3
MHG923	93	60	16	2.7	3.2	10.1
MHG927	93	60	15	2.3	3.6	9.1

its production potential. At a root production of 50 t/ha, which underestimates yield potential of yacon under reasonable soil fertility, ASL136 would have yielded 4.5 t fructans/ha. From the same root production, fructose and sucrose totaling 5.8 t/ha could have been obtained through hydrolysis of fructans and from free sugars (calculations not shown).

Free glucose and fructose were among the most variable root parameters; with C.V. 32% for free glucose and C.V. 58% for free fructose. There was a significant and highly negative correlation between fructans and free fructose (-0.88, Table 4) indicating the interrelation of these metabolites in depolymerization. Interestingly, free fructose was positively correlated to DP (0.42), which suggests that polymer elongation increased with the size of the fructose pool.

Conversely, high glucose concentrations are associated with lower DPs (r = -0.68), perhaps because they increase the number of fructan molecules *competing* for free fructose. Although there were significant differences of DP between accessions, the range was narrow 3.6-4.3 (C.V. = 6%). The ratio of total fructose to glucose (F_{tot}/G_{tot}) indicates that in a syrup obtained after acid hydrolysis of yacon root carbohydrates, fructose would be present at a concentration 2-3 times greater than glucose (Table 2).

As shown in Table 4, °Brix was highly and positively correlated with fructan content (r = 0.84) and DM (r = 0.86), which suggests that refractometric measurements provide convenient and quick assessments of these important variables. Free fructose, sucrose, and total free sugars are noted for their inverse correlation with the refractometric index as well as fructans. That implies accessions high in fructans are low in free sugars. Noncarbohydrate compounds are omitted from Table 4, since they were only weakly correlated among themselves and with carbohydrate variables.

As Table 2 shows, yacon is a poor source of protein (2.7-4.9 g/kg FM). It is also low in lipids (112-464 mg/kg FM), but has moderate levels of fiber (3.1-4.1 g/kg FM). It is a good source of K (1.8-2.9 g/kg FM), a little less than half of its total mineral content. Food energy ranged from 148 to 224 kcal/kg FM and is several times lower than for comparable foods.

Using the variables shown in Table 2, a principal component analysis (PCA) was computed. The first component explained 54% of total variation; the second accounted for 20%. PCA did not reveal any

Table 4. Pearson correlation coefficients[a] of chemical variables of yacon root fresh matter.

Variables	Dry matter	Free glucose	Free fructose	Free sucrose	Total sugars	Fructans	°Brix	DP[b]
Dry matter	1							
Free glucose	-.13	1						
Free frucose	-.77 a	-.16	1					
Free sucrose	-.58 a	.13	.75 a	1				
Total sugars	-.76 a	.08	.94 a	.91 a	1			
Fructans	.95 a	-.14	-.88 a	-.75 a	-.90 a	1		
°Brix	.86 a	-.20	-.69 a	-.57 a	-.71 a	.84 a	1	
DP	-.04	-.68 a	.42 a	.03	.20	-.07	.01	1

[a] Computed across repetitions: n = 36; a = significant at $P < 0.01$.

[b] Degree of polymerization.

geographically defined clusters of accessions (Figure 1). That suggests yacon chemical diversity is not partitioned into geographical subgroups, which would allow the search for special characteristics in germplasm from certain areas. Carbohydrate variables were highly correlated with the first and second principal components (data not shown). Thus, these variables contribute more than others in differentiating yacon clones by chemical characteristics.

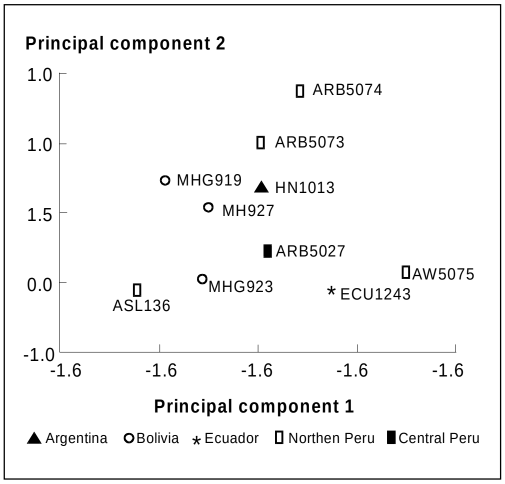

Figure 1. Principal component analysis on compositional data of 10 yacon accessions.

Discussion and Conclusions

The yacon accessions used in this study were collected between 1984 and 1992 during multicrop missions or as chance collections (Table 1). Thus they were not the result of a systematic collection effort aimed at capturing maximum yacon diversity. Northern Peru, with four accessions, and Cochabamba Department, Bolivia, with three accessions, are likely to be over-represented in the sample. The collection sites, however, describe an area that is congruent with the distribution of the species, which stretches from Ecuador to northern Argentina. Also, the accessions come from widely differing ecologies and a considerable altitudinal range. Therefore, samples do encompass a reasonably large part of yacon diversity, permitting conclusions about compositional diversity from the data obtained.

Although claims for high inulin content in yacon continue to be made, most prominently in the often cited *Lost Crops of the Incas* (NRC, 1989), the consistently low DP in 10 yacon accessions (3.6-4.3) shows that yacon fructans are of low molecular weight. This is in agreement with Ohyama et al. (1990). Yacon fructans are therefore different from the inulins in chicory (*Cichorium intybus*) with a DP range of

7-12 and individual fructan chains up to 80 fructose units long (Van Waes et al., 1998). High molecular weight inulin also accounts for most of the carbohydrates in Jerusalem artichoke (*Helianthus tuberosus*) (Praznik and Beck, 1987; Wei et al., 1991). Yacon also differs from Jerusalem artichoke in that it has significant fructose and glucose contents. Fructose accounts for 3-22% of root DM, glucose for 2-5% (Table 3).

In the calculation of food energy (148-224 kcal/kg FM), we have assumed that fructans behave as dietary fiber in the intestinal tract (Quemener et al., 1994) and make no caloric contribution during digestion. Fructans are unlikely to be broken down to a significant extent by stomach acidity, but some degradation occurs in the colon due to bacterial fermentation (Silva, 1996). Therefore, our food energy values somewhat underestimate true caloric values. In any case, food energy of yacon is very low and fully justifies the root's reputation as a low-caloric diet food.

The data do not support the notion of chemical differentiation of yacon along geographic gradients (Figure 1). Overall, there was little compositional diversity in the 10 yacon accessions. Carbohydrate variation due to physiological factors (e.g., plant age) and postharvest conditions (e.g., storage duration) appear to have much more practical relevance than genetic differences. For example, Ohyama et al. (1990) observed fructans to be reduced to 20% of DM after storage for 3 mo "under cold conditions." Also, Wei et al. (1991) report decreasing fructans and increasing fructose after storage. Considerable compositional changes also occur during the traditional *soleado* treatment after harvest. It involves spreading the harvested roots in an unshaded place for a week or so. That results in increased root sweetness and a concomitant rise in °Brix (Hermann, unpublished data), which, apart from respirative water loss, is most likely due to the incremental de-polymerization of fructans.

Highest DM and fructan yields (accession ASL136) were associated with dodecaploidy compared with octoploidy in the other accessions. This provides a pointer for identifying superior germplasm and for breeding yacon.

Based on Table 2, nutrient removal from the field per t root FM can be calculated as 0.4-0.8 kg N, 0.2-0.3 kg P, and 1.8-2.9 kg K. These data allow an approximation of minimal fertilizer requirements for yacon. The ranges for nutrient removal per 100 kg soluble carbohydrate produced (fructans and free sugars) are 0.5-0.9 kg N, 0.2-0.4 kg P, and 2.3-3.2 kg K. These figures identify yacon as not only high in N-use efficiency but also demanding in its K requirements.

Despite its high fructan productivity, yacon is unlikely to become a source of purified dietetic sweeteners or fructose products in the near future. That is because of several factors including 1) lack of suitable extraction technology and industrial scale production, 2) competition from very low priced, high-fructose syrups from corn starch, and 3) protectionism of sugar markets.

It is more likely that processed yacon products requiring little or no refining could be targeted as a natural or low-calorie food to a health-conscious clientele. Entrepreneurial farmers in Brazil and Japan have already seized this opportunity and are producing a number of processed yacon products for niche markets (Grau and Rea, 1997; Kakihara et al., 1997). One such product consists of air-dried tuber slices, which resemble dried apples. Current research at CIP examines processing parameters bearing on final product quality.

Another potentially interesting product is unrefined yacon syrup. It could be marketed as a dietetic sweetener the consistency of honey and possibly priced at the same level. Yacon syrup-making in rural Andean settings could find much inspiration from makeshift technology developed in the early days of maple syrup production. The challenge for yacon product development is to design research interventions that will allow Andean farmers to retain some of the value added through processing.

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