Anthocyanin, Carotenoid Content, and Antioxidant Values in Native South American Potato Cultivars

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Abstract. Tubers of 38 native potato cultivars of different taxonomic groups from South America were analyzed to determine the total anthocyanins, total carotenoids, and antioxidant values. Total anthocyanin ranged from zero to 23 mg cyanidin equivalents/100 g fresh weight (FW). Total carotenoid ranged from 38 to 2020 μ g zeaxanthin equivalents/100 g FW. Oxygen radical absorbance capacity (ORAC) was measured for the anthocyanin (hydrophilic) and carotenoid (lipophilic) extracts. The hydrophilic ORAC ranged from 333 to 1408 μ M Trolox equivalents/100 g FW. The lipophilic ORAC ranged from 4.7 to 30 nM α -tocopherol equivalents/100 g FW. The cultivars consisted of 23 diploids, seven triploids, and eight tetraploids. Total carotenoids was negatively correlated with total anthocyanins. Total anthocyanins was correlated with hydrophilic ORAC. Among clones with less than 2 mg cyanidin equivalents/100 g FW, total carotenoid and lipophilic ORAC were correlated, but this was not true for analysis of all 38 clones. Although total anthocyanins or hydrophilic ORAC values reported here were not outside of the ranges found in North American and other breeding materials, total carotenoids and lipophilic ORACs are higher than previously reported, suggesting that native cultivars of South America with high levels of total carotenoids and high lipophilic ORAC are a unique germplasm source for introgression of these traits into specific potato cultivars outside the center of origin.

Potato (*Solanum tuberosum* L.) was domesticated in the Andes Mountains of South America (Spooner et al., 2006). At the time of European contact, potato was and continues to be a staple of the numerous societies living in the Andes. Potato was first introduced to Europe at the end of the 16th century and then experienced worldwide distribution over several centuries (Hawkes, 1992). Over time, skin and flesh color outside the center of origin have been reduced to a few types that represent a subset of the extant variation in native Andean cultivars. These colors are primarily red and blue anthocyanins that are present in skin or flesh to varying degrees and yellow to orange carotenoids in the flesh that display a broad variation in content. Although native cultivars have been used extensively for introduction of disease and pest resistance traits into long-day adapted cultivars, they have not been accessed with the purpose of introgressing enhanced phytonutrient content until recently (Brown,

2005). Cultivated potato in South America is represented by diploid, triploid, tetraploid, and pentaploid cultivars. Tetraploid cultivars (Group *Andigena*) comprise the greatest number of accessions and have the widest geographic distribution (Glendinning, 1983; Hawkes, 1990).

Cultivated potatoes contain varying amounts of anthocyanins and carotenoids in their tuber skin and flesh (Gross, 1991; Mazza and Miniati, 1993). Potato anthocyanins include acylated glucosides of several aglycons: pelargonidin, petunidin, malvidin, and peonidin (Brown et al., 2003; Fossen and Andersen, 2000; Fossen et al., 2003; Rodriguez-Saona et al., 1998). The carotenoids are xanthophylls, which are not provitamin A carotenoids, and, interestingly, only traces of beta-carotene, which can be converted to vitamin A, are found. Therefore, potatoes are a good source of xanthophylls, components of the human retina, but are deficient in provitamin A compounds. Outside the center of origin of cultivated potato in the Andes of South America, it is rare to find cultivars with anthocyanin pigments conferring red or purple flesh. However, much of the world's production is dominated by yellow-fleshed potatoes, which have higher total carotenoids

than the white-fleshed cultivars of North America and Great Britain. Genetic control of presence or absence of anthocyanins is monogenic, although the distribution of anthocyanin in pigmented flesh may be under complex genetic control (Brown et al., 2003; De Jong, 1991). White versus yellow flesh is thought to be under single gene control with gene maps agreeing on the placement of this yellow flesh factor (*Y/y*) on chromosome 3 (Bonierbale et al., 1988; Gebhardt et al., 1989). White- and yellow-fleshed potatoes have similar composition of carotenoids, with the yellow color of the latter group attributable to higher concentrations (Brown et al., 1993; Gross, 1991). The different types of xanthophylls show variable concentrations in various potato genotypes with lutein predominating and varying amounts of zeaxanthin, violaxanthin, and others reported (Brown et al., 1993; Iwanzik et al., 1983; Lu et al., 2001; Nesterenko and Sink, 2003). The greatest levels of total carotenoids are from the potato cultivars of the Andes referred to as 'Papa Amarilla' (Yellow Potato) and breeding materials derived from this source. They are composed of diploid cultivated potatoes *S. tuberosum* L. in the Groups *Phureja*, *Stenotomum*, and *Goniocalyx* (Spooner and Hetterscheid, 2006).

Brown et al. (1993) reported wide variation in segregating genotypes derived from *Papa Amarilla* germplasm, with some samples exceeding 2000 μ g zeaxanthin equivalents/100 g fresh weight (FW). Several other studies have reported similar high levels (Brown et al., 2005; Lu et al., 2001). In a report by Brown et al. (1993), the existence of a so-called orange allele, *Or*, was postulated at the *Y/y* locus to explain higher levels of carotenoids. Breeding efforts directed at producing commercially viable cultivars with higher levels of anthocyanin and carotenoid for health benefits of their antioxidant properties have recently been undertaken by regional programs (Brown, 2005). The purpose of this study was to analyze native South American cultivars and compare them with modern breeding lines and cultivars in relation to total anthocyanins, total carotenoids, and associated antioxidant values. This information may guide future breeding work to the extent that introgressing traits from South American germplasm may assist in enhancing these traits.

Materials and Methods

Genetic materials. The genotypes chosen for this study consisted of 38 cultivars selected for coloration of skin and flesh combined with high dry matter. Table 1 presents their nomenclature, chromosome number, taxonomic identity, and country of origin. Tubers were produced from plants derived from in vitro stock transplanted to pots and grown in the greenhouse at the Huancayo facility of the International Potato Center, Peru (at 3330 m above sea level). Tubers from 20 different pots per genotype were bulked and two sets of two tubers of each

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Table 1. List of South American cultivar names (if known), International Potato Center (CIP) accession numbers, country of origin, chromosome number (2n =), and group designation within *Solanum tuberosum*.

Cultivar name	CIP number	Origin	Chromosome number	Group
Amarilla Tumbay	701862	Per	24	gon
Calhua Rosada	701165	Per	24	stn
Capacho Azul	703698	Per	24	stn
Caramelo	701676	Per	24	stn
Cashpadana Amarilla	703352	Per	24	gon
Ceccorani	703287	Per	24	stn
Challina	703488	Per	48	adg
Chaucha Amarilla	703308	Per	24	phu
Chiimbina Colorada	701013	Per	36	cha
Chujo Papa	704193	Per	48	adg
Cuchipa Ismaynin	700313	Per	24	stn
Garhuash Pashon	702961	Per	24	gon
Huataqui	701014	Per	36	juz
Ishco Puro	701266	Per	24	stn
Muro Shocco	701273	Per	48	adg
Negra	703789	Per	48	adg
No name	702610	Bol	24	stn
No name	703274	Per	24	phu
No name	703279	Per	24	gon
No name	703280	Per	24	gon
No name	703315	Per	24	gon
Pacocha	703300	Per	36	cha
Papa Chonca	703606	Chl	48	cha
Puca Corika	700739	Per	36	cha
Puca Huayro	701524	Per	36	cha
Puca Pishgush	703168	Per	24	gon
Puca Quitish	703264	Per	48	adg
Puca Trombos	702915	Per	48	adg
Puka Suytu	704355	Per	48	adg
Rosca	703291	Col	24	phu
Tarmeña	701675	Per	36	cha
Tumiri	701568	Per	36	cha
Yana Pituwaya	703286	Bol	24	stn
Yana Ppoccoya	703288	Per	24	stn
Yana Sucre	703197	Per	24	stn
Yana Turuna	703314	Per	24	stn
Yema de Huevo	704218	Col	24	phu
Zapallo	703244	Bol	24	gon

Col = Colombia; Per = Peru; Bol = Bolivia; Chl = Chile; adg = *Andigena*; phu = *Phureja*; gon = *Goniocalyx*; stn = *Stenotomum*; cha = *Chaucha*; juz = *Solanum × juzepzukii*.

genotype were selected randomly to form two replications. Tubers were diced with skin into small cubes (1-cm square), frozen immediately in liquid nitrogen, and maintained at -80°C in tightly sealed Nalgene bottles. Extraction proceeded from the frozen tuber pieces.

Anthocyanin (hydrophilic) extraction and quantification. Anthocyanin extraction followed the protocols outlined in Durst and Wrolstad (2001) as modified by Brown et al. (2003, 2005). Potato tissue was blended and weighed out as 10 g of frozen powder to start the extraction. Monomeric anthocyanin content was determined using the pH differential method (Giusti and Wrolstad, 2001). Pigment content was calculated as cyanidin-3-glucoside equivalents using an extinction coefficient of $26,900\text{ L}\cdot\text{cm}^{-1}\cdot\text{mol}^{-1}$ and molecular weight (MW) of $449.2\text{ g}\cdot\text{mol}^{-1}$.

Carotenoid (lipophilic) extraction and quantification. Total carotenoids were extracted and quantified using the methods reported in Brown et al. (2005), which contained minor modifications of procedures presented in van Breemen (2001). Frozen tissue was pulverized in a blender and measured out as 250 mg of frozen powder. Carotenoids were extracted in a chloroform:

methanol phase separation, retaining the chloroform phase accumulated in two separations, drying, and redissolving in methanol. Concentration was determined by optical density spectrophotometry at 450 nm using the extinction coefficient for zeaxanthin in methanol. Total carotenoids were expressed as micrograms of zeaxanthin equivalents/100 g FW.

Hydrophilic oxygen radical absorbance capacity. Oxygen radical absorbance capacity (ORAC) is a measure of the capacity of an antioxidant to delay the oxidation of a target molecule. ORAC is measured as the decay of fluorescence of a certain fluorogen in the presence of a radical-generating compound and antioxidants. The assay is performed in a fluorometer that measures the decay over time at 2-minute intervals. Antioxidant value is derived from an area under the curve calibrated to a standard antioxidant. The technique used for anthocyanins was derived from Cao et al. (1993, 1995) and modified as reported by Brown et al. (2003, 2005). Hydrophilic ORAC was expressed as microMoles of Trolox equivalents/100 g FW.

Lipophilic oxygen radical absorbance capacity. The lipophilic nature of carotenoids required adapting the ORAC assay to accom-

modate its performance in a polar solvent with an adjuvant to solubilize the carotenoids. The method used was a modification of the procedure of Huang et al. (2002) reported in Brown et al. (2005). Antioxidant values were reported as nanoMoles of α -tocopherol equivalents/100 g FW.

Statistical analysis. Analysis of variance following a randomized complete block design and Duncan's multiple range test was applied to the means (Steel and Torrie, 1980). Correlations were calculated using Microsoft Excel (Microsoft, Redmond, WA). All genotypes were subjected as a single group to analysis of variance by SAS (version 9.1.3, PROC REG; Cary, NC) applying a general linear model. The effect of ploidy was tested by orthogonal comparisons. All analyses were based on two replications.

Results and Discussion

Total anthocyanins ranged from 0 to 23 mg cyanidin equivalents/100 g FW in this group (Table 2). Total carotenoids ranged from 38 to 2020 $\mu\text{g}/100\text{ g FW}$. The genotype 703280 had low total anthocyanins in the flesh but the highest total carotenoids level of all genotypes. The four highest carotenoid levels were found in one diploid and three triploids (703280, 'Tarmeña', 'Puca Corika', and 'Pacocha'). The hydrophilic ORACs ranged between 333 and 1408 μM Trolox equivalents/100 g FW. There was a significant positive correlation of total anthocyanins with hydrophilic ORAC ($r = 0.51$, $P < 0.05$, $R^2 = 0.26$). Lipophilic ORACs ranged between 4.7 and 30 nM α -tocopherol equivalents/100 g FW. There was no correlation between carotenoid content and lipophilic ORAC in the 38 clones as a whole, but when considering cultivars with less than 2 mg of total cyanidin equivalents/100 g FW, total carotenoids and lipophilic ORACs were correlated ($r = 0.48$, $P < 0.05$, $R^2 = 0.23$). The relatively low R^2 values indicated that factors other than carotenoids and anthocyanins also contribute substantially to antioxidant values. Total carotenoids and total anthocyanins were negatively correlated ($r = -0.41$, $P < 0.05$, $R^2 = 0.17$).

The cultivar 'Huataqui' is a member of *Solanum × juzepzukii* (JUZ.), a highly frost-tolerant bitter potato adapted to cultivation at high elevations where risk of midseason frosts is high (Huanco, 1991). It is notable for having no anthocyanin and the second lowest total carotenoids of all cultivars tested.

When the effect of ploidy was examined in Table 3, it is apparent that total anthocyanins is higher with higher ploidy. However, hydrophilic ORAC did not differ among ploidies. Diploids and triploids had greater total carotenoids than tetraploids, and diploids had greater lipophilic ORAC values than tetraploids. Because these clones were selected on the basis of extremes in pigmentation, these differences should not be extrapolated to the thousands of native cultivars

Table 2. Total anthocyanins, hydrophilic oxygen radical absorption capacity (ORAC), total carotenoids, and lipophilic ORAC of South American potato cultivars.

CIP number	Name	Total anthocyanin, mg cyanidin equivalents/100 g FW	Hydrophilic ORAC, μ M Trolox equivalents/100 g FW	Total Carotenoid, μ g zeaxanthin equivalents/100 g FW	Lipophilic ORAC, nM α -tocopherol equivalents/100 g FW	ploidy, 2n =
704355	Puka Suytu	2.0 h-k	472 j-o	153 n-q	7.9 d-h	4x
702915	Puca Trombos	3.4 g-j	617 i-o	666 g-k	7.5 f-h	4x
700739	Puca Corika	3.9 f-i	600 i-o	837 e-h	12.2 b-h	3x
701524	Puca Huayro	4.2 e-i	714 i-n	274 l-q	10.4 c-h	3x
700313	Cuchipa Ismaynin	4.3 e-i	1181 a-c	282 l-q	14.1 b-g	2x
703606	Papa Chonca	4.6 e-h	416 m-o	38 q	6.1 gh	4x
703280	No name	4.7 e-h	764 e-l	2020 a	16.2 b-e	2x
703274	No name	4.9 e-h	672 f-o	33 k-q	15.4 b-f	2x
703264	Puca Quitish	5.2 e-g	769 e-k	120 o-q	9.0 c-h	4x
701675	Tarmeña	5.7 e-g	781 e-j	944-g	9.9 c-h	3x
701676	Caramelo	6.1 e-g	845 d-i	357 j-q	11.9 b-h	2x
703314	Yana Turuna	6.4 d-g	658 g-o	159 n-q	10.9 c-h	2x
703286	Yana Pituwaya	6.6 d-f	735 e-m	560 h-l	9.0 c-h	2x
703300	Pacocha	7.1 de	960 c-h	702 g-j	11.5 c-h	3x
703197	Yana Sucre	9.0 cd	1000 c-f	200 m-q	11.7 c-h	2x
701568	Tumiri	11.6 bc	1113 a-d	421 i-p	6.3 gh	3x
701273	Muro Shocco	12.7 b	1345 ab	124 o-q	10.6 c-h	4x
703315	No name	13.4 b	674 f-o	110 o-q	4.7 h	2x
703488	Challina	20.9 a	1408 a	197 m-q	10.8 c-h	4x
703789	Negra	23.0 a	563 i-o	82 pq	9.6 c-h	4x
701014	Huataqui	0.0 k	621 h-o	89 pq	16.5 b-d	5x
703288	Yana Ppoccoya	0.3 k	386 no	106 o-q	10.2 c-h	2x
704193	Chujo Papa	1.6 i-k	725 e-n	240 l-q	9.0 -h	4x
703287	Ceccorani	0.6 jk	1043 b-e	387 i-q	12.3 b-h	2x
701013	Chiimbina Colorada	0.3 k	499 j-o	449 i-o	11.4 c-h	3x
701165	Calhua Rosada	1.9 h-k	640 h-o	503 h-n	15.6 b-f	2x
702610	No name	0.1 k	495 j-o	543 h-m	11.7 c-h	2x
702961	Garhuash Pashon	0.2 k	651 h-o	630 g-k	17.6 bc	2x
703698	Capacho Azul	0.5 jk	632 h-o	702 g-j	10.5 c-h	2x
703308	Chaucha Amarilla	0.0 k	608 i-o	734 f-i	20.4 b	2x
703244	Zapallo	0.0 k	432 k-o	909 e-g	30.0 a	2x
703168	Puca Pishgush	0.8 jk	435 k-o	1058 d-f	10.8 c-h	2x
701266	Ishco Puro	0.6 jk	424 l-o	1070 de	12.2 b-h	2x
703352	Cashpadana	0.2 k	704 f-n	1076 de	14.8 b-g	2x
703279	No name	0.4 jk	538 i-o	1093 de	16.8 bc	2x
701862	Amarilla Tumbay	0.0 k	333 o	1305 cd	7.6 e-h	2x
703291	Rosca	0.1 k	692 f-n	1444 bc	16.4 b-d	2x
704218	Yema de Huevo	0.0 k	994 c-g	1683 b	7.2 f-h	2x

Means not sharing a letter are significantly different at $P < 0.05$ level using Duncan's multiple range test.

Table 3. Comparison of means of three ploidy levels, diploid, triploid, and tetraploid, for total anthocyanins, hydrophilic oxygen radical absorption capacity (ORAC), total carotenoids, and lipophilic ORAC.

Ploidy	Total anthocyanin mg cyanidin equivalents/100 g FW	Hydrophilic-ORAC μ M Trolox equivalents/100g FW	Total carotenoid μ g zeaxanthin equivalents/100 g FW	Lipophilic-ORAC nM α -tocopherol equivalents/100 g FW
Diploid (N = 23)	2.6 a	675 a	751 a	13.4 a
Triploid (N = 7)	5.5 b	778 a	604 a	10.3 ab
Tetraploid (N = 8)	9.2 c	789 a	202 b	8.8 b

Means tested by orthogonal comparisons. Those not sharing a letter are significantly different at $P < 0.05$.

in the World Collection at the International Potato Center. 'Papa Amarilla', a broad category of potato cultivars in the Andes, embraces both diploid germplasm and *Solanum chaucha*, which is triploid (2n = 36).

On comparison with recently published literature of germplasm in the United States, equivalent and higher total anthocyanin levels can be found. Brown et al. (2003, 2005) reported total anthocyanin values ranging between 15 and 38 mg/100 g FW. Similarly, high levels of total anthocyanin exceeding those values reported here were described by Lewis et al. (1998) in New Zealand. There appear to be in North America and New Zealand breeding materials or named cultivars with levels of anthocyanin surpassing the genotypes in this study. This is not the case when total carotenoids are considered.

Levels of total carotenoids in tuber flesh of cultivars and unusual breeding materials are generally in the range of 50 to 400 μ g zeaxanthin equivalents/100 g FW. Levels exceeding this are derived very clearly from diploid germplasm obtained from Andean locations in South America (Andre et al., 2007; Brown et al., 1993, 2005; Campos et al., 2006; Lu et al., 2001). The high levels of total carotenoids described in these publications are from South American cultivars or breeding materials adapted to long-day latitudes with South American ancestors in the Group Phureja, but they remain experimental in nature. The high total carotenoids trait (i.e., greater than 1000 μ g zeaxanthin equivalents/100 g FW) of South American 'Papa Amarilla' cultivars is still not introgressed into long-day adapted commercial

cultivars grown outside of South America. They constitute a unique and valuable resource for breeding. The highest level of hydrophilic ORAC in the cultivar 'Challina' is close to the highest level reported in Brown et al. (2005): 1408 versus 1420 μ moles Trolox equivalents/100 g FW in 'Challina' and NDOP5847-1 (in citation), respectively. The lipophilic ORAC values presented in Table 2 exceed the highest value of 15 nmoles α -tocopherol equivalents/100 g FW reported by Brown et al. (2005). Cultivars 'Zapallo' and 'Chaucha Amarilla' were measured at 30 and 20 nmoles α -tocopherol equivalents/100 g FW, respectively. Therefore, these examples of Andean germplasm appear to be notable for higher lipophilic ORACs than can be found in North American and New Zealand cultivars. The combination

of high total carotenoids and high lipophilic ORAC is, therefore, a unique phytonutrient trait combination available in particular South American diploid or triploid cultivars.

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