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Chromosome studies in *Hippeastrum* (Amaryllidaceae): variation in genome size

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This paper presents the karyotype and DNA content of 12 diploid species of *Hippeastrum* from South America. The variation in genome size is compared with the karyotype and DNA content of *Amaryllis belladonna* from South Africa. The *Hippeastrum* species present a uniform and bimodal basic karyotype formula, but significant differences are found in the total chromosome volume (TCV) and nuclear DNA content. A positive correlation between the DNA content and TCV is also observed. The karyotype's constancy is a product of changes in DNA content occurring in the whole chromosome complement. The DNA addition to the long and short sets of chromosomes varies independently. In species with higher DNA contents, the short chromosomes add equal DNA amounts to both arms, maintaining their metacentric morphology, whereas the long chromosomes add DNA only to the short arm, increasing the chromosome symmetry. These data show that the evolutionary changes in DNA amount are proportional to chromosome length, maintaining the karyotypic uniformity. *A. belladonna* has a larger DNA content and possesses a karyotype different from that of *Hippeastrum* spp., supporting the distinction between the two genera and upholding the name *Amaryllis* for the South African entity against *Hippeastrum* for the South American genus. © 2007 The Linnean Society of London, *Botanical Journal of the Linnean Society*, 2007, **155**, 171–178.

ADDITIONAL KEYWORDS: bimodal karyotype – nuclear DNA content – orthoselection.

INTRODUCTION

The genus *Hippeastrum* Herb. comprises more than 70 species in tropical and subtropical regions of South America. The karyotypes and chromosome numbers of many species have been studied previously (Naranjo & Andrada, 1975; Arroyo, 1982; Naranjo & Poggio, 1988; Brandham & Bhandol, 1997). The basic chromosome number is $x = 11$ and all species show a constant bimodal basic karyotype of four short [metacentric (m) or submetacentric (sm)] and seven long [four sm and three subterminal (st)] chromosomes. Polyploidy is the only conspicuous change in the karyotypic constitution, with triploids, tetraploids, and pentaploids being known (Naranjo, 1969; Naranjo & Andrada, 1975; Arroyo, 1982; Naranjo & Poggio, 1988; Brandham & Bhandol, 1997).

Bimodal karyotypes occur in many plants and animals and represent a very specialized karyotypic form. In plants, bimodality frequently characterizes groups of genera and/or species (Brandham, 1983; Kenton *et al.*, 1990; Naranjo *et al.*, 1998). The existence of groups of taxa with similar bimodal karyotypes is a result of karyotype orthoselection or karyotype conservation (White, 1973).

Recently, Bennett & Leitch (2005) emphasized the importance of genome size data in plant systematic and phylogenetic studies. Furthermore, it has been well documented in many taxa that variations in nuclear DNA amount are correlated with some karyological traits (Cerbah *et al.*, 2001; Siljak-Yakovlev *et al.*, 2003; Albach & Greilhuber, 2004; Garnatje *et al.*, 2004).

In this paper, interspecific differences in the DNA amounts of 12 diploid South American species of *Hippeastrum* are documented, analysed, and discussed. The data are compared with the karyotype and DNA

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content of the monotypic species *Amaryllis belladonna* L. from South Africa.

MATERIAL AND METHODS

Cytological studies were carried out on material cultivated at the Royal Botanic Gardens, Kew, with the exception of one accession of *H. argentinum* that was donated by A. T. Hunziker (ATH 18258). The sources of the material are listed in Table 1.

CYTOLOGICAL ANALYSIS

For squash preparations, root tips were pretreated for 2.5 h in 0.002 M 8-hydroxyquinoline at 20 °C, fixed in 3 : 1 absolute ethanol : acetic acid, hydrolysed in 1 M HCl at 60 °C for 10 min, and stained in Feulgen. The total chromosome volume (TCV) was estimated using the formula $TCV = (\pi \times r^2 \times TCL) \times 2$ (r , average chromatid radius; TCL, total chromosome length). The average of the total centromeric index (TCI) was estimated using the formula $TCI = (\text{short arm/total length} \times 100)/n$. The centromeric indices for short and long chromosomes (CI_S and CI_L , respectively) were calculated separately. The nomenclature used for chromosome morphology is that of Levan, Fredga & Sandberg (1964). To estimate the karyotype asymmetry, two numerical parameters were used, following Romero Zarco (1986): A_1 [intrachromosomal asymmetry index = $1 - (\text{short arm/long arm})/n$] and A_2 [interchromosomal asymmetry index = standard deviation (S)/mean length (X)]. Both indices are independent of the number and size of the chromosomes. The determination of the karyotype parameters was carried out using a Mini Mop (Kontron) image analyser. Mean values for the karyotypes were calculated from measurements of a minimum of five scattered metaphase plates in each accession.

FEULGEN STAINING AND CYTOPHOTOMETRY

In each accession, 2C DNA content was measured in 20 telophase nuclei. Root tips were fixed in 3 : 1 absolute ethanol : acetic acid for 1–4 days. The staining method described in Tito, Poggio & Naranjo (1991) was used. The amount of Feulgen staining per nucleus, expressed in arbitrary units, was measured at a wavelength of 550 nm using the scanning method on a Vickers M85 microspectrophotometer. The DNA content per basic genome, expressed in picograms, was calculated using *Allium cepa* cv. 'Ailsa Craig' as a standard ($2C = 33.55$ pg; Bennett & Smith, 1976). The differences in DNA content were tested using an analysis of variance, and comparisons between means were performed using Scheffé's method (Scheffé, 1953).

RESULTS AND DISCUSSION

The basic chromosome number $x = 11$ was found in the 12 studied species, all of which were diploid ($2n = 22$; Table 1). All the species analysed had a bimodal chromosome complement, based on four long sm, three long st, and four short m chromosomes in the haploid set (Table 1, Figs 1–5). Sometimes telocentrics (t) were present, or chromosome types intermediate between any of the above. All *Hippeastrum* species studied so far possess a nucleolar organizer region in a terminal position on the short arm of one st-t chromosome, forming a small satellite, as shown by positive staining with the silver technique by Naranjo & Poggio (1988). In four species, some chromosomal rearrangements were detected at low frequency, such as pericentric inversions and reciprocal translocations between long and short chromosomes (Fig. 5C, E, H, I). B chromosomes were found in two species, *H. morelianum* and *H. tucumanum* (Fig. 3). All of these data showed the presence of a conserved bimodal karyotype. In this case, selective mechanisms constraining changes in the karyotype could be active, suggesting that the existing karyotype may have some fundamental importance for genome organization and evolution of the genus.

The total DNA content of the 12 studied species of *Hippeastrum* varied between $2C = 13.35$ and $2C = 17.09$ pg (Table 1). Significant differences in DNA amount of the basic genome were found in each species ($F = 63.67$, $P < 0.01$). A positive correlation between the DNA content and TCV was also found (Table 2). The distribution of DNA content between species was continuous, and no grouping of species with particular DNA contents was found (Tables 1, 2). These results were unexpected on the basis of the similar karyotype found in all species (Table 1, Figs 1–5). The significant increase in DNA amount without any significant karyotype change could be explained by a nonrandom distribution of these changes. Similar results have been found for South and North American species of *Lathyrus* (Klamt & Schifino-Wittman, 2000; Seijo & Fernández, 2003).

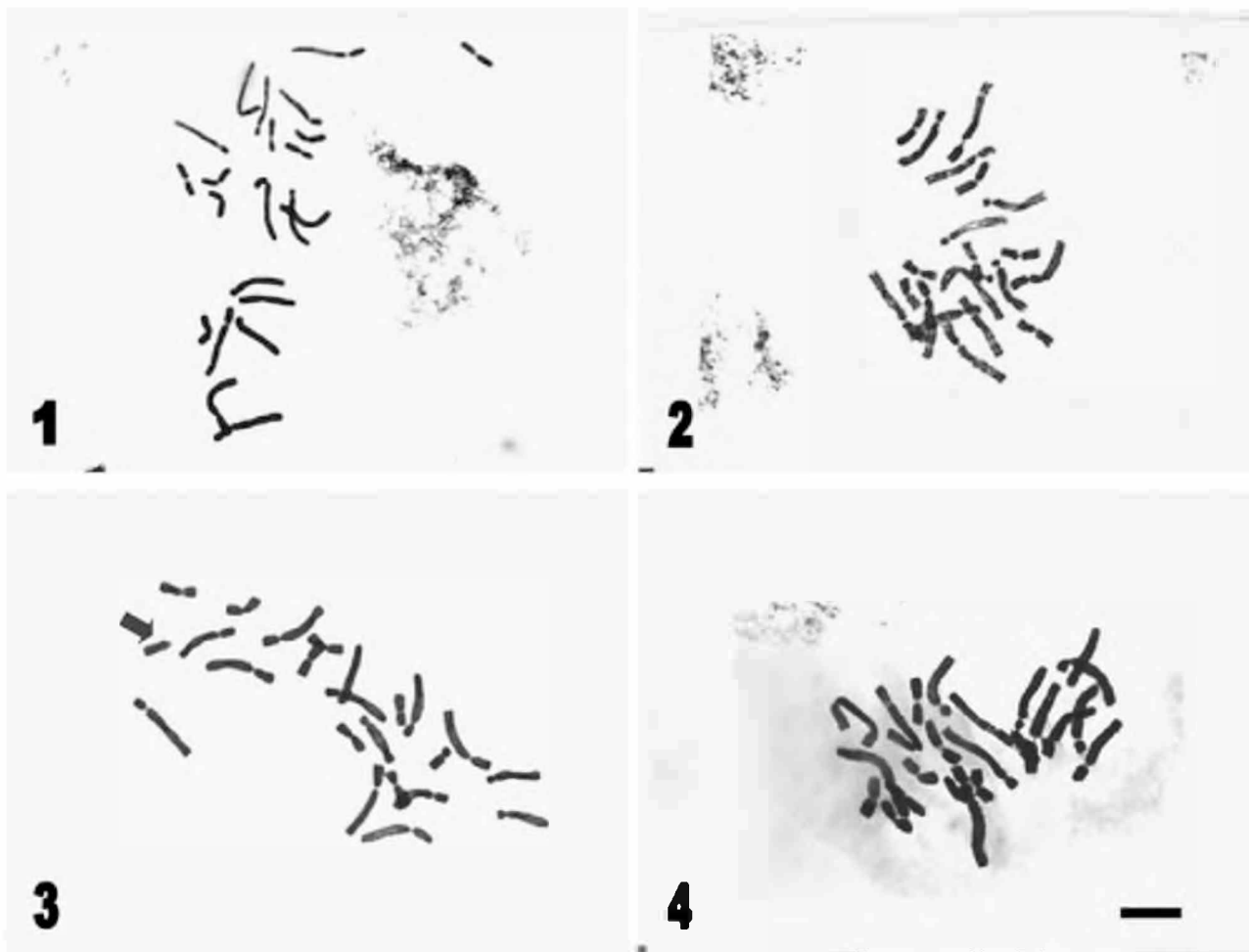
Rees (1984) proposed two strategies to explain the nonrandom distribution of DNA changes: (1) DNA addition proportional to chromosome size; or (2) addition of equal amounts of DNA to each chromosome. Both types of strategy are present in different sections of the genus *Vicia*. In the section *Vicia*, an increase in DNA content is achieved by the addition of equal increments to all the chromosomes of the complement, leading to a more symmetrical karyotype (Raina & Rees, 1983). By contrast, in section *Australis*, Naranjo *et al.* (1998) found that evolutionary changes in DNA amount were proportional to the relative length of each chromosome arm, maintaining

Table 1. Origin, karyotype formula, and DNA content in diploid species of *Hippeastrum* and *Amaryllis* (all $2n = 22$)

Species	Origin	Kew accession	Basic karyotype formula						2C DNA (pg) ± SE	DNA (pg) per basic genome
			m	m-sm	sm	sm-st	st	st-t		
<i>Hippeastrum</i> Herb.										
<i>H. morelianum</i> (Lamaille) Traub	Brazil, Sao Paulo, Serra do Mar	419-72-03853/1 419-72-03853/2	4		2	1	2	2	26.69 ± 0.34	13.35
<i>H. correiense</i> (Bury) Worsley	Brazil, Sao Paulo	419-72-03854	4		2	2	1	2	26.89 ± 0.27	13.45
<i>H. parodii</i> Hunz et Cocucci*	Argentina, Corrientes, Tres Cerros	400-76-03888	4		4		3		29.05 ± 0.25	14.52
<i>H. rutilum</i> (Ker-Gawl.) Herb.	Brazil	501-66-50111	4		4		3		29.93 ± 0.30	14.96
<i>H. tucumanum</i> Holmberg	Argentina	361-75-03430	4		3	1	3		30.20 ± 0.23	15.10
<i>H. psittacinum</i> (Ker-Gawl.) Herb.	Brazil	088-60-08801	4		3	1	3		30.68 ± 0.16	15.34
<i>H. evansiae</i> (Traub & Neils.) Moore	Bolivia	302-79-02858	4		3	1	2	1	31.33 ± 0.23	15.89
<i>H. argentinum</i> (Pax) Hunz.	Argentina, Catamarca, Ambatos	ATH† 18258	4		2	3		2	31.92 ± 0.29	15.96
<i>H. hybrid</i>		344-79-03154	4		3	1			32.15 ± 0.18	16.07
<i>H. aulicum</i> (Ker-Gawl.) Herb.	Brazil, Santa Catarina	434-79-04428	4		3		3		32.40 ± 0.35	16.20
<i>H. solandriflorum</i> Herb.	Argentina, Corrientes, Tres Arroyos	301-79-02627	4		4	1			33.12 ± 0.30	16.56
<i>H. machupijchense</i> (Vargas) Hunt	Perú, Cuzco, Machupichu	376-76-03600	4		4		3		33.35 ± 0.48	16.68
<i>Amaryllis</i> L.										
<i>A. belladonna</i> L.*	South Africa	000-69-34090	4	1	6				38.29 ± 0.19	19.14

*Data taken from Naranjo & Poggio (1988).

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Figures 1–4. Mitotic metaphases in *Hippeastrum* species, all $2n = 22$. Fig. 1. *H. morelianum*. Fig. 2. *H. correiense*. Fig. 3. *H. tucumanum*. The arrow shows a B chromosome. Fig. 4. *H. evansiae*. Scale bar, 10 μm .

karyotype uniformity. An equivalent situation has been found in species of *Aloe*, which have different total genome sizes but retain bimodal karyotypes, with the longer and shorter chromosomes remaining in similar proportion between species (Brandham, 1983).

When TCI and CI_L were measured (Table 2), positive relationships were obtained between TCI and DNA amount ($r = 0.798$) and CI_L and DNA amount ($r = 0.977$) (Table 2). However, when CI_S was analysed separately, it did not show any relationship with DNA amount (Table 2). This could mean that only the long chromosomes suffer changes in DNA amount, whereas the short chromosomes remain unchanged. If this were the case, the percentage volume of the short chromosomes (CV_S) would decrease when TCV increased. This is not the case, as the volume of the short chromosomes in relation to TCV is the same (or very similar) in all species studied (Table 2). To maintain CI_S of the short chromosomes, whilst their volume

and DNA content increase, the addition of DNA in proportion to each chromosome arm must occur. However, the more symmetrical CI of the longer chromosomes in species with a higher DNA content indicates that the addition of DNA occurs mainly in the short arms of all the long chromosomes.

In *Hippeastrum*, the addition of DNA to the long and short sets of chromosomes within each genome thus varies independently. The short chromosomes add equal DNA amounts to both arms, maintaining their metacentric morphology, whereas the long chromosomes add DNA only to the short arm, increasing their symmetry in the species with higher DNA amounts (Table 2).

In many cases, karyotype rearrangement may be implicit in the conservation of bimodality, reshuffling the new genome size into a more efficient organization. In the species of *Hippeastrum* studied previously, major structural chromosome changes have been reported rarely (Brandham & Bhandol, 1997)



Figure 5. Karyograms of *Hippeastrum* spp. A, *H. morelianun*. B, *H. correiense*. C, *H. parodii*. Arrow shows a pericentric inversion in a long chromosome. D, *H. rutilum*. E, *H. tucumanum*. Arrows indicate a reciprocal translocation between a short and a long chromosome. F, *H. psittacinum*. G, *H. evansiae*. H, *H. argentinum*. Arrows indicate a reciprocal translocation between a short and a long chromosome. I, *H. hybrid*. Arrow shows a pericentric inversion in a short chromosome. J, *H. solandriiflorum*. Scale bar, 10 μ m.

Table 2. Karyotype characteristics of diploid species of *Hippeastrum* and *Amaryllis*

Species, $2n = 22$	TCI	CI _S	CI _L	TCV (μm^3)	CV _S (%)	2C DNA (pg) \pm SE	Asymmetry indices	
							A ₁	A ₂
<i>Hippeastrum</i>								
<i>H. morelianum</i>	28.63	43.75	19.99	95.30	23.21	26.69 \pm 0.34	0.55	0.32
<i>H. correiense</i>	31.07	45.58	22.78	104.20	24.44	29.05 \pm 0.25	0.51	0.29
<i>H. parodii</i> *	28.14	42.46	23.67	112.10	23.91	29.93 \pm 0.30	0.52	0.29
<i>H. tucumanum</i>	31.35	43.20	24.89	112.20	24.90	30.68 \pm 0.16	0.50	0.31
<i>H. psittacinum</i>	32.81	45.85	25.37	115.00	24.85	31.33 \pm 0.23	0.48	0.32
<i>H. evansiae</i>	32.21	46.87	23.83	116.10	23.24	31.92 \pm 0.29	0.47	0.32
<i>H. solandriiflorum</i>	31.01	42.58	24.39	120.71	23.59	33.35 \pm 0.48	0.51	0.31
<i>H. machupijchense</i>	30.24	42.42	26.17	121.79	23.65	34.18 \pm 0.24	0.50	0.30
<i>Amaryllis</i>								
<i>A. belladonna</i> *	35.03	46.54	30.54	133.20	28.15	38.29 \pm 0.19	0.43	0.21

A₁, intrachromosomal asymmetry index; A₂, interchromosomal asymmetry index; CI_L, average of centromeric indices of long chromosomes; CI_S, average of centromeric indices of short chromosomes; CV_S, volume of short chromosomes as percentage of volume of all chromosomes; TCI, total centromeric index; TCV, total chromosome volume.

*Data taken from Naranjo & Poggio (1988).

and then only as heterozygotes, as also reported here (Fig. 5). This suggests that they do not play any significant role in the chromosome evolution of the genus.

Brandham & Bhandol (1997) studied the karyotype of several species of *Hippeastrum* and *A. belladonna*, all from Bolivia, and found that both genera present a karyotype the same as that described here for *Hippeastrum* species. However, Naranjo & Poggio (1988) found important karyotypic differences between accessions of *A. belladonna* from South Africa and South America.

South African *A. belladonna* ($2n = 22$) has a DNA content larger than that of *Hippeastrum* spp. ($2C = 38.29$ pg) and possesses a different karyotype ($4m + 1m\text{-sm} + 6sm$) (Naranjo & Poggio, 1988). Moreover, the nuclear organizer region (NOR) is in the short arm of an $m\text{-sm}$ chromosome, forming a linear satellite, as demonstrated by Ag-NOR banding (Naranjo & Poggio, 1988). In Figure 6, the asymmetry of the karyotype, indicated by the arm ratio (A₁) and length (A₂), is plotted against the total DNA content. Amongst the *Hippeastrum* taxa, the species with a higher DNA content show karyotypes that are more symmetrical than those of species with a lower DNA amount. It can be seen that *A. belladonna*, with the highest DNA amount, occupies an isolated position when compared with the *Hippeastrum* species. This is a result of its more symmetrical karyotype (Naranjo & Poggio, 1988). These important karyotypic differences and several morphological and anatomical characteristics (Arroyo & Cutler, 1984) support the distinctive-

ness of the two genera, and uphold the name *Amaryllis* for the South African entity against *Hippeastrum* for the South American genus, as discussed by Naranjo & Poggio (1988).

In summary, *Hippeastrum* shows a karyotypic constancy, as all species have the same bimodal karyotype. However, there are significant interspecific differences in nuclear DNA amount. These are the result of an increase in DNA in the short arms of the long chromosomes and in both arms of the short chromosomes, the latter in proportion to the length of the arms, maintaining the uniformity of chromosome morphology. The results obtained in this work suggest that there is an internal homeostasis that selects for a particular type of genome organization in which the bimodality is achieved through a particular distribution of DNA.

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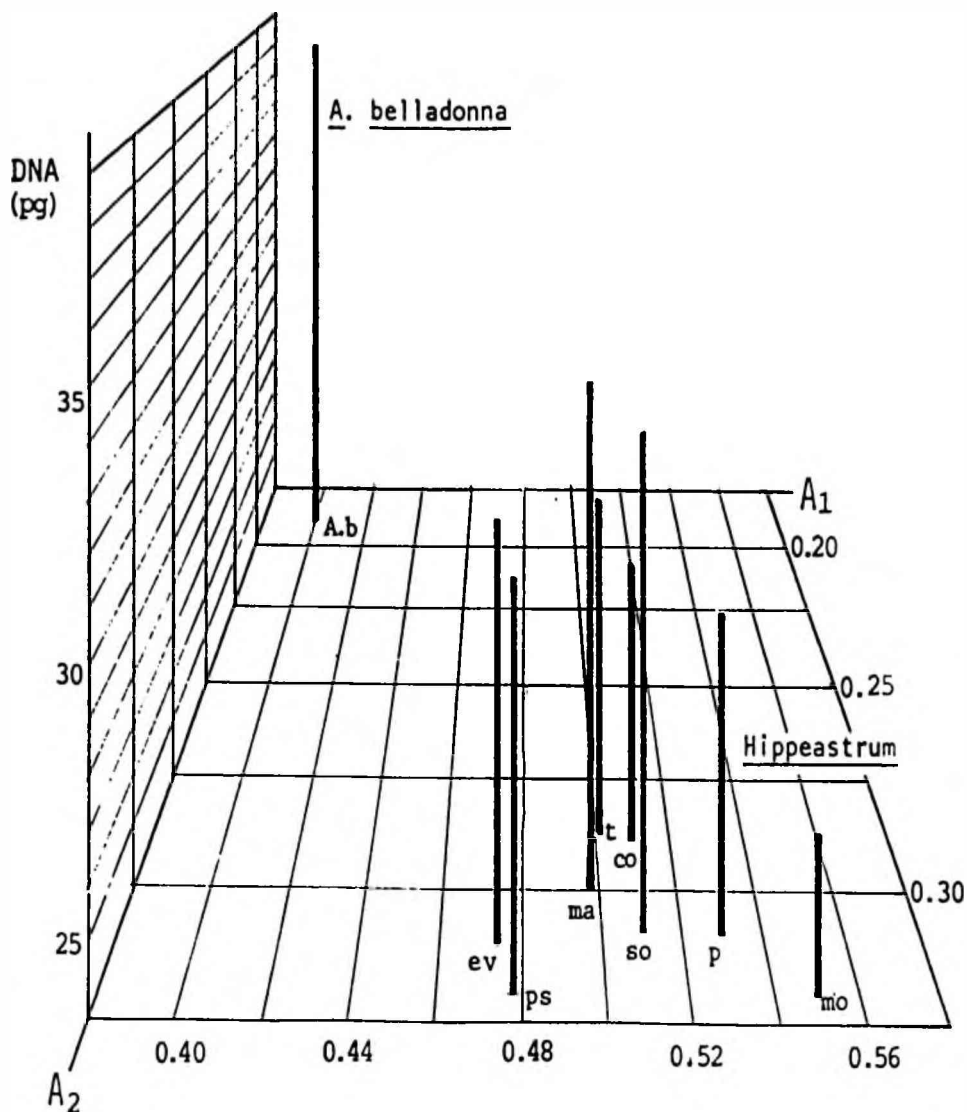


Figure 6. Scatter diagram showing asymmetry indices against DNA amounts of *Amaryllis belladonna* and *Hippeastrum* species. A.b, *A. belladonna*; co, *H. correiense*; ev, *H. evansiae*; ma, *H. machupijchense*; mo, *H. morelianum*; p, *H. parodii*; ps, *H. psittacinum*; so, *H. solandriflorum*; t, *H. tucumanum*.

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