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REVISITING SPECIES LIMITS OF *SOLIDAGO DAHURICA* AND *S. PACIFICA* (ASTERACEAE: ASTEREAE)

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ABSTRACT

A multivariate morphometric study based on revised geographical distributions of *Solidago dahurica* and *S. pacifica* compared with *S. decurrens* was conducted to determine how much statistical support would be found for the modified species limits. The revised limits were statistically supported.

Solidago ser. *Solidago* includes 9-12 species following the taxonomic treatments in Semple and Beck (2021) and Semple and Beck (2023), the difference depending upon the taxonomic rank (variety or species) of 3 described taxa in central and southern Japan. The ranges of distributions of the taxa in *Solidago* ser. *Solidago* are shown in Fig. 29 of Semple et al. (2020), including the locations of samples used in the multivariate analyses for that study.

Sakaguchi et al. (2018) followed a more traditional nomenclature (Iwatsuki et al. 1995) in their molecular analysis of ser. *Solidago* and included taxa from Kamchatka, Russia, Korea, China, and Japan — all were treated as subspecies or varieties of *S. virgaurea*. More recently, the unpublished DNA based phylogenetic research by Shota Sakaguchi indicates that *Solidago pacifica* has a much larger range than shown in Semple et al. (2020), which includes all plants from the Kamchatka Peninsula, Khabarovsk Krai, Primorsky Krai, and Sakhalin Island in eastern Russia, while *S. dahurica* does not occur on the Kamchatka Peninsula.

In Semple et al. (2020), specimens from the Himalayas were treated as belonging in either *Solidago dahurica* (ovary/fruit bodies that were sparsely to moderately distally strigose) or *S. virgaurea* (ovary/fruit bodies that were moderately to more densely strigose both proximally and distally). Semple et al. (2020) acknowledged that some individuals from the Himalayas were assigned with difficulty to *S. virgaurea* and *S. dahurica*. Unpublished molecular results by Sakaguichi indicate that only *S. dahurica* is likely present in the Himalayas. Thus, *S. dahurica* has fruits in the southwestern portion of its range that converge with the fruit pubescence characteristic of some individuals of *S. virgaurea* from Europe and adjacent northwestern Africa.

The purpose of this study was to determine statistical support for recognizing the revised species limits of *Solidago dahurica* and *S. pacifica*, using the data on specimens of these two species, and the widely distributed eastern Asian species *S. decurrens* included in Semple et al. (2020).

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MATERIAL AND METHODS

Herbarium specimens were borrowed and examined from the following herbaria: A, BM, GH, K, MO, PE, WAT in MT (Thiers continuously updated). Data on 23 specimens of *Solidago dahurica*, 37 specimens of *S. decurrens* var. *decurrens*, and 14 specimens of *S. pacifica* were

included in a STEPWISE discriminant analysis. In total, 18 vegetative and 16 inflorescence and floral traits were scored for the analyses (Table 2 in Semple et al. 2020).

All analyses were performed using SYSTAT v.10 (SPSS 2000). Details on the methodology were presented in Semple et al. (2016) and are not repeated here.

RESULTS

The Pearson correlation matrix yielded r > |0.7| for most pairs of leaf traits and some floral traits reducing the number to be used to the length and width of the upper stem leaves, involucre height, number of ray florets, ray floret strap length and width, number of disc florets and disc floret corolla and pappus length. Basal rosette leaves were often not present and were not included in the analyses. Lower stem leaves were present on many specimens but were not included in the analyses because their traits correlated highly among themselves and with mid and upper stem leaf traits.

In a STEPWISE discriminant analysis of 75 specimens of *Solidago dahurica* (23 specimens), *S. decurrens* (37 specimens), and *S. pacifica* (14 specimens), the following 6 traits were selected as the most significant discriminating traits in order of decreasing F-to-remove values: ray floret strap width (10.40), ray floret strap length (6.69), upper stem leaf width (5.85), involucre height (4.37), disc floret pappus length at anthesis (3.10), and upper stem leaf length (2.19). Wilks's lambda, Pillai's trace, and Lawley-Hotelling trace tests of the null hypothesis that all groups were the samples of one group had probabilities of p = 0.000 that the null hypothesis was true. The F-matrix for the discriminant analysis is presented in Table 1. F-values based on Mahalanobis distances of the between group centroids indicated the largest separation was between *S. dahurica* and *S. decurrens* var. *decurrens* (28.758); the smallest separation was between *S. dahurica* and *S. pacifica* (5.089).

Table 1. The between groups F matrix, df 9 63

Group	*dahurica*	*decurrens*
decurrens	28.758	
pacifica	5.089	8.113

Approx. F = 11.9234; df = 6 2 71

In the Classificatory Discriminant Analysis of 23 specimens of *Soliago dahurica*, 37 specimens of *S. decurrens* var. *decurrens*, and 14 specimens of *S. pacifica*, the percents of correct a posterori assignment to the same a priori group were 89% for *S. decurrens* var. *decurrens*, 86% for *S. pacifica*, and 83% for *S. dahurica*. Thirty-three specimens of the 37 specimens (89%) *S. decurrens* var. *decurrens* a priori group were assigned a posteriori into the *S. decurrens* var. *decurrens* group: 2 specimens with 100% probability, 19 specimens with 92-99% probability, 7 specimens with 81-86% probability, 4 specimens with 74-6% probability, and 1 specimen with 50% probability (*Sino-Amer. Exped. 2016* A; western Hubei Prov.). Four specimens of the *S. decurrens* var. *decurrens* a priori group were assigned a posteriori to *S. pacifica* with 76% probability (*Wilson 1695* K; Hubei Prov. China), 54% probability (*W.T. Tsang 20773* MO; GuangDong Prov., China), 51% probability (*K. Seto 31829* A; Shiga Pref., Japan) and 51% probability (*C.B. Clarke 18650 B* BM; Megahalaya Prad., India). Twelve specimens (86%) of the *S. pacifica* a prior group were assigned a posteriori to *S. pacifica*: 1 specimen with 97% probability, 2 specimens with 83% probability, 3 specimens with 73-79% probability, 3 specimens with 60-62% probability, and 3 specimens with 58% probability (*Maack s.n.* GH; 1 Sep 1855, ad fl. Amur, Mandschuria [Heilongjiang Prov.], China), 57% probability (*A.K. Skvortsov s.n.* MO; vicinity of Vladivostok, Russia), and 56% probability (*Stewart s.n.* GH; Kamchatka, Russia). Two specimens of the *S. pacifica* a priori group were assigned a

posteriori to *S. dahurica* with 95% probability (*Brummitt & Brummitt 232* K; southern Kamchatka Peninsula; midsize plants; this was shown in Figs. 5 and 6G of Semple et al. (2020) as *S. dahurica*) and 75% probability (*Kharkevich & Buch 837* K; northern Kamchatka Peninsula; short plants). Seventeen specimens (83%) of the *S. dahurica* a priori group were assigned a posteriori to *S. dahurica*: 2 specimens with 100% probability, 6 specimens with 92-98% probability, 2 specimens with 88% and 81% probabilities, 3 specimens with 70-73% probability, 3 specimens with 61-68% probability, and 1 specimen with 53% probability (*Gomolitzky s.n.* MO; Tian Schan, Uzbekistan). Five specimens of the *S. dahurica* a priori group were assigned a posteriori to other species: 3 specimens to *S. pacifica* with 78% probability (*M. Tabata et al. 20280* A; Nepal; fruit bodies are moderately strigose to near base), 57% probability (*Navonova 4493* MO; Krasnojarsky region, Siberia, Russia; fruit body glabrate), and 53% probability (*Kopronovich 66* MO; Manchuria [Heilongjiang], China); and 2 specimens to *S. decurrens* var. *decurrens* with 73% probability (*Russell 1729* BM; Korakoram, Jammu and Kashmir, India; fruit sparsely strigose distally) and 52% probability (K*onnikov-Galitsky 1218* MO; Zabaykasky Krai, Russia).

Table 2. Linear and jackknife classification matrices from the Classificatory Discriminant Analysis of 3 a priori groups; a posteriori placement to groups in rows.

Group	*dahurica*	*decurrens*	*pacifica*	% correct
dahurica	19	2	2	83
decurrens	0	33	4	89
pacifica	2	0	12	86
Totals	21	35	18	86

Jackknife classification

Group	*dahurica*	*decurrens*	*pacifica*	% correct
dahurica	18	2	3	78
decurrens	0	32	5	86
pacifica	2	2	10	71
Totals	20	36	18	81

Two dimensional plots of CAN1 versus CAN2 canonical scores for 75 specimens of *Solidago dahurica, S. decurrens* var. *decurrens*, and *S. pacifica* are presented in Fig. 1. The eigen values on the first two axis were 2.679 and 0.180.

Observations were made on numbers of peduncle bracts and phyllary shape and width on all specimens that had been included in Semple et al. (2020). Peduncles generally had 1-2 bracts in most species of ser. *Solidago* and the phyllaries tended to be broader (1.2-1.3 to rarely 1.6 mm wide) at least proximally (ovate) in *S. pacifica* than all other species and the lower phyllaries sometimes graded into distal peduncle bracts which were broader the most species. Phyllaries in heads of *S. decurrens* var. *decurrens* were noticeably narrower than those of *S. pacifica*. Phyllaries of *S. dahurica* were narrower than in *S. pacifica* and generally more similar to those of *S. virgaurea*. In some individuals the phyllaries of *S. dahurica* were a bit broader and approached those of *S. pacifica* but were not as broad as those of *S. pacifica*.

DISCUSSION

There was a significant improvement in placement of specimens of the expanded *Solidago pacific* into *S. pacifica* a posteriori in this study, 86%, compared to the 56% reported in Semple et al. (2020) in the analysis that included seven species of ser. *Solidago* (*S. dahurica*, *S. decurrens*, *S.*

kurilensis, *S. litoralis*, *S. minutissima*, *S. pacifica*, and *S. virgaurea*) and the range of *S. pacifica* did not include more northern Russian Pacific coastal and Kamchatka Peninsula specimens with none placed a posteriori with higher than 77%. In Fig. 5 of Semple et al. (2020) the illustration for *Solidago dahurica* was a collection from Kamchatka, *Brummitt & Brummitt 232 (*K), which was treated here as a specimen of *S. pacifica* and was placed a posteriori into that species with 95% confidence. Thus, an alternative specimen, *Webster & Nasir 6410 (*GH) with 93% a posteriori probability, is illustrated here in Fig. 2 to represent *S. dahurica*. All specimens of *S. dahurica* included in Fig. 3 were also all placed a posteriori into *S. dahurica* in the analysis reported here.

Solidago pacifica is illustrated here in Fig 4 with *Komarov 1499 (*K) from Heilonjong Prov., China, which was placed a posteriori here into S. *pacifica* with 97% probability. All specimens of *S. pacifica* included in Fig. 5 were also all placed a posteriori into *S. pacifica* in the analysis reported here. Attention is drawn to the broad inner and outer phyllaries in Fig. 5G (outer 1.1-1.5 mm and inner 0.8-1.3 mm), which appears to be a useful key character in separating nearly all specimens of *S. pacifica* from those of *S. dahurica* (3G; outer 0.8-1.3 mm, inner 0.6-1.1 mm) and *S. decurrens* (7F; outer 0.6 mm, inner 0.6-0.9 mm).

All specimens from the Himalayas were placed in *Solidago dahurica* in the analysis presented here. This included specimens with more hairy fruit bodies that had been treated as belonging in *S. virgaurea* in Semple et al. (2020). Five specimens of *S. dahurica* were placed here a posteriori into *S. pacifica* or *S. decurrens*. One was from the Himalaya Mountains, *Russell 1729* (BM) from Korakoram, India (disputed territory), which was placed here into *S. decurrens* with 73% probability and it had fruit bodies with a few very distally placed hairs. The second specimen was *Tabata et al 20280* (A) from Nepal, which was placed a posteriori into *S. decurrens* with 53% probability and had fruit bodies that were moderately hairy both distally and proximally, which is not a trait of *S. decurrens*.

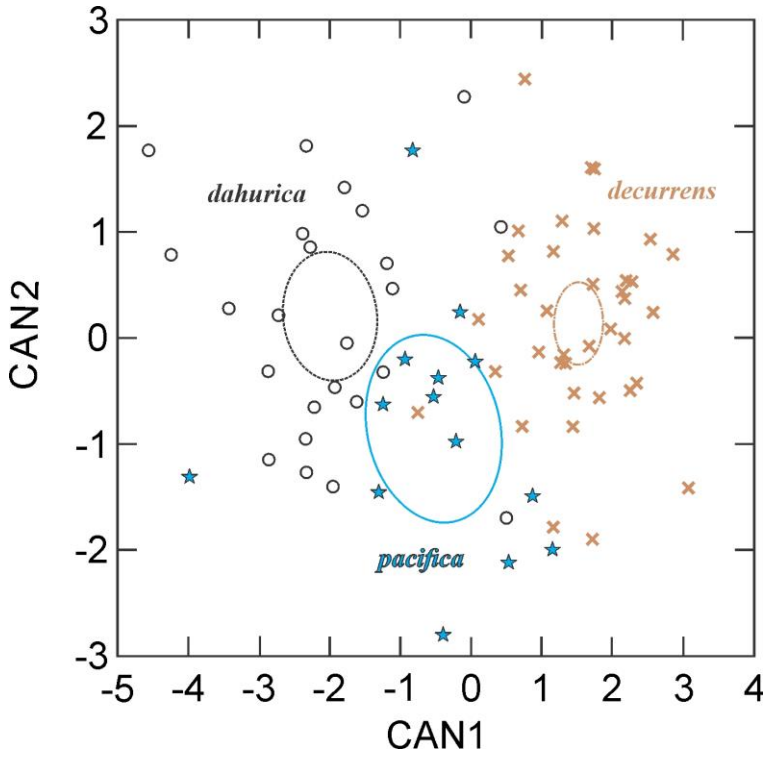

Figure 1. Plot of canonical scores (CAN1 vs CAN2) for 74 a priori specimens of three species of *Solidago* ser. *Solidago* based on a STEPWISE discriminant analysis using six traits: *S. dahurica* (open black circles), *S. decurrens* (light brown ×s), and *S. pacifica* (light blue stars); 95% confidence limits indicated by ellipses.

Figure 2. *Solidago dahurica*, *Solidago dahurica*, *Webster & Nasir 6410* GH from Chhachor Pass, Kashmir, Himalayas.

Figure 3. Details of the morphology of the *Solidago dahurica*. **A.** Mid stem, Kazakhstan, *Fesissman s.n.* K. **B-C**. Basal leaf and leaf margin, Kyrgyzistan, *Sodombekov KPL-00126* MO. **D.** Mid stem leaf of small plant, Pakistan, *Abel 110* BM. **E.** Upper stem leaf, Nepal, *Polunin et al. 2610* BM. **F.** Narrow inflorescence, *Tabata et a.l 20280* A. **G.** Heads, *Fesissman s.n.* K.. **H-I.** Distally hairy disc floret cyselae. **H.** *Stainton et al. 7839* BM. **J.** More hairy disc floret cypsela body, *Abel 110* BM. Scale bars = 1 mm in A, C, and G-J; = 1 cm in B, D-F.

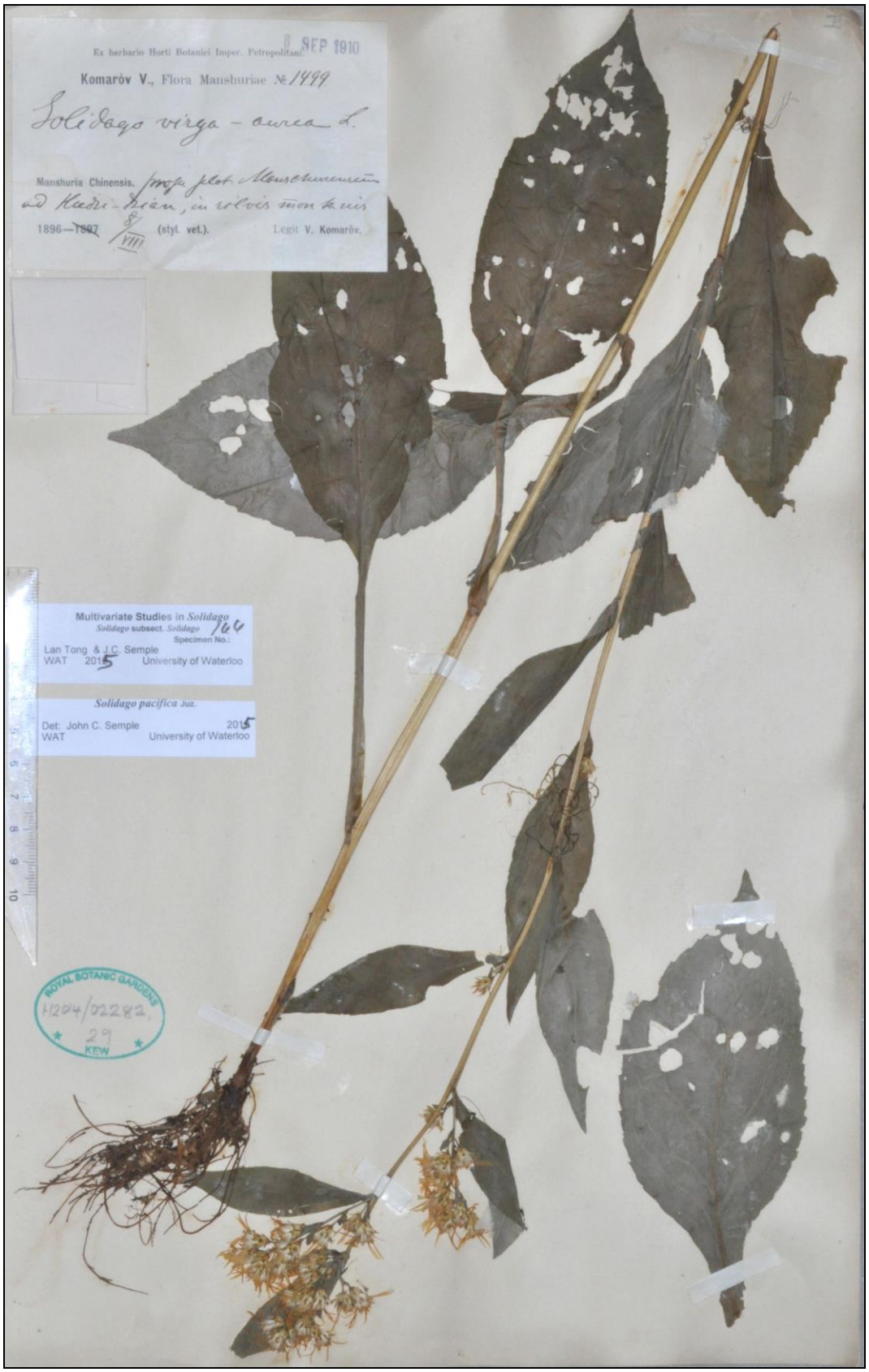

Figure 4. *Solidago pacifica*, *Komarov 1499* K from Heilonjong Prov., China.

Figure. 5. Details of the morphology *Solidago pacifica*. **A.** Mid stem, Heilongjiang Prov., China, *Komarov 1499* K. **B.** Lower mid stem leaf, *Komarov 1499* K. **C.** Lower mid stem leaf margin, Primorski, Russia, *Boyko s.n.* K. **D.** Mid stem leaf, *Hua Team 152* PE. **E.** Upper stem leaf in inflorescence, Kamchatka Peninsula, Russia, *Eyerdam s.n.* MO. **F**. Heads, *Komarov 1499* K. **G.** Phyllaries, Jilin Prov., China, *Wan & Chow 81116* BM. **H.** Ray and disc floret cypselae, *Smith 1957* A. Scale bars = 1 mm in A, F-H; = 1 cm in B-E.

Figure 6. *Solidago decurrens*, *Sino-American Expedition 1681* A, tall shoot from Guizhou Prov., China.

Figure 7. *Solidago decurrens, Lin 817* MO, small shoots from Taiwan.

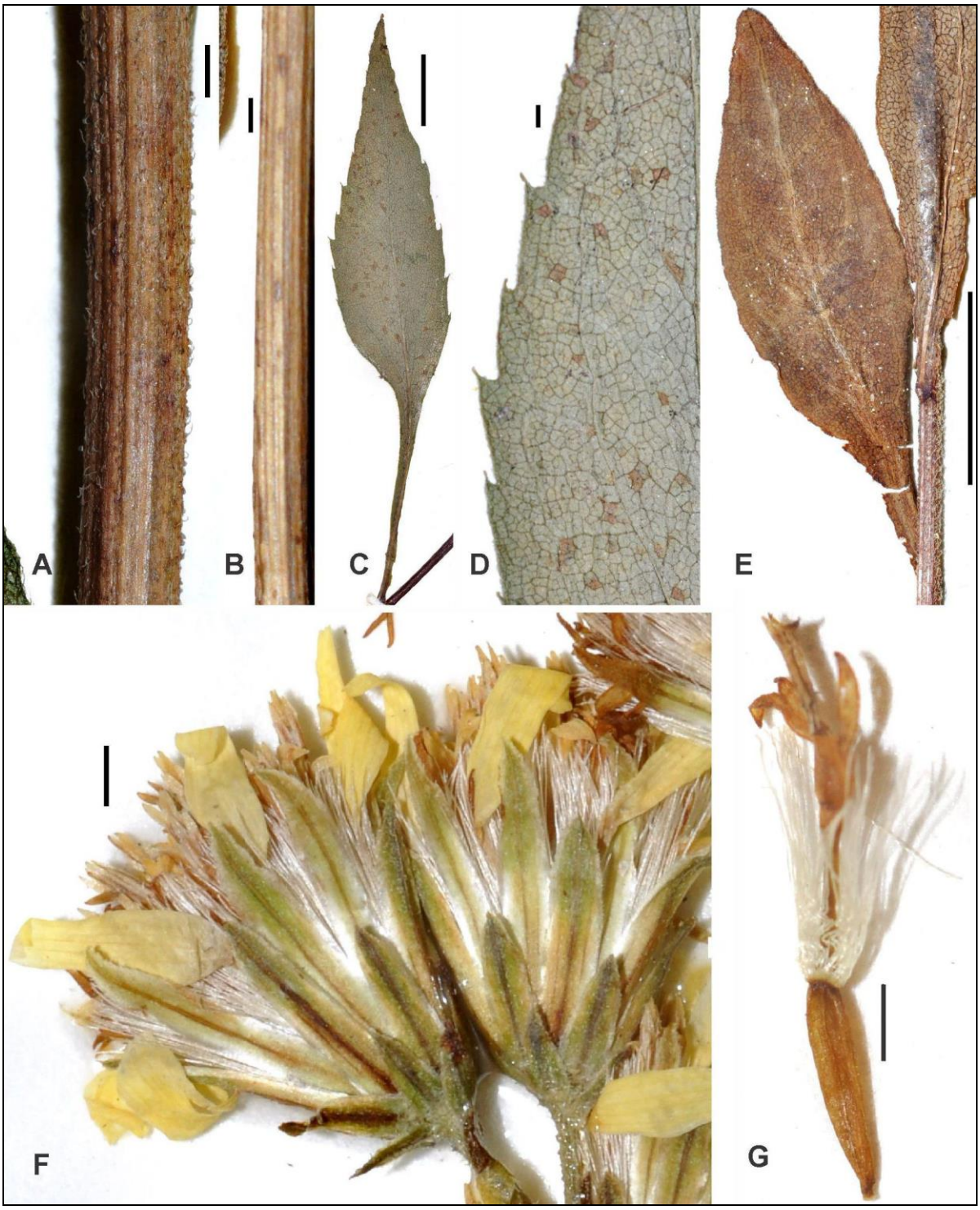

Figure 7. Details of the morphology of the *Solidago decurrens*. **A.** Mid stem, Taiwan, *Lin et al 77* A. **B.** Lower mid stem, Luzon, Philippines, *Sulit 2182* A. **C-D.** Lower stem leaf and leaf margin, Jiangxi Prov., China, *Lai & Shan 4428* MO. **E.** Mid stem leaf, Megahalaya, India, *Hooker 36* K. **F.** Heads, Guizhou Prov., *An MingTai 5319* MO. **G.** Disc floret cypsela with corolla still attached, *Lin et al. 77* A. Scale bars = 1 mm in A-B, D, and F-G; = 1 cm in C and E.

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