

# First records of *Sticta arenosella* and *S. cellulosa* from South America based on molecular and morphological data

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**Abstract.** Two isidiate species, *Sticta arenosella* and *S. cellulosa*, are reported from South America for the first time and the former species also as new to the Southern Hemisphere. *Sticta arenosella* was found in Chile and *S. cellulosa* in Bolivia. The identification of both species was confirmed by sequencing of the nuITS rDNA marker, a universal barcode of fungi, and the haplotype network analyses. Specimens of *S. cellulosa* possess sparse apothecia, which previously have not been observed in this species.

**Key words:** barcoding, distribution, haplotype network, integrative taxonomy, lichens, Neotropics

## Introduction

Integrative taxonomy is a concept in the identification of lichen-forming fungi that aims to identify species using multiple tools, the most common combination being phenotypic characters supported by phylogenetic data (Dayrat 2005; Goulding & Dayrat 2016). The usefulness of this method has been tested on different lichen groups (e.g., Alors et al. 2016; Frisch et al. 2020), including macrolichens such as *Peltigera* Willd. (Magain et al. 2018, 2023) or *Cora* Fr. (Lücking et al. 2017), which often show high intraspecific and low interspecific variability, making their identification much more difficult (Lücking et al. 2021). For the genus *Cora*, Lücking et al. (2017) suggested to use an integrative taxonomic approach called ‘turbo-taxonomy’, which involves the use of electronic databases such as barcoding or BLAST searches for species identification. Comparison of the sequences obtained with barcodes is particularly useful for simple taxon identification, which often accompanies studies on the distribution of individual species.

Integrative taxonomy is also used to recognize species in the genus *Sticta* (Schreb.) Ach. Moncada (2012) applied this approach to specimens from Colombia, resulting in an increase in the number of *Sticta* species from 115 (Kirk et al. 2008) to 180 (Moncada & Lücking 2012; Moncada et al. 2013a, b; Moncada et al. 2014a, b,

2015, 2021a, b; Suárez & Lücking 2013). Similar studies have been conducted worldwide, for example in Brazil (Dal Forno et al. 2018; Torres et al. 2021), Bolivia (Ossowska 2021; Ossowska et al. 2022a, b, 2024; Crous et al. 2023), East Africa (Kaasalainen et al. 2023), Ecuador (Yáñez-Ayabaca et al. 2023), Hawaii (Moncada et al. 2020, 2021b), North America (Simon et al. 2018a, b; Di Meglio & Goward 2023) and Puerto Rico (Mercado-Díaz et al. 2020). Despite several such taxonomic attempts, our knowledge of the distribution of *Sticta* species is still incomplete.

During our studies of *Sticta* specimens from Bolivia and Chile, we discovered two specimens with isidia whose morphology did not match any known species. It was also not possible to identify them using molecular data (sequences of the nuITS rDNA marker), as no similar sequences were available in GenBank, suggesting that they might represent unknown species. However, after the publication of Di Meglio and Goward (2023) and Kaasalainen et al. (2023), we compared our sequences again in a BLAST search. The sequence of the Bolivian sample showed similarity to the sequences of *S. cellulosa* Kaasalainen and the Chilean material to *S. torii* Ant. Simon & Goward, but our specimens differed morphologically from the descriptions of these species: the Bolivian material, which was genetically similar to *S. cellulosa*, had apothecia (not reported in the original description), whereas the Chilean sample had laminal isidia more characteristic of *S. arenosella* Di Meglio & Goward, a taxon that is phylogenetically close to *S. torii*. These discrepancies prompted further investigation, including haplotype network analyses. As a result, we present the first records of *S. arenosella* from Chile, which is also the first one

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from South America and the Southern Hemisphere, and *S. cellulosa* from Bolivia, which is new to South America. This paper aims to provide information on their distribution and morphology, including a description of the apothecia of *S. cellulosa*, which have been observed for the first time in this species.

## Materials and methods

### Material

Specimens of *Sticta* were collected by M. Kukwa in Bolivia in 2017 and by U. Schiefelbein in Chile in 2023. The specimens are deposited in LPB and UGDA herbaria. Morphological and anatomical studies were carried out using a Nikon SMZ 800N stereomicroscope. In addition, spot test reactions were performed using a water solution of potassium hydroxide (K). The distribution map was prepared using QGIS 3.30.1 software.

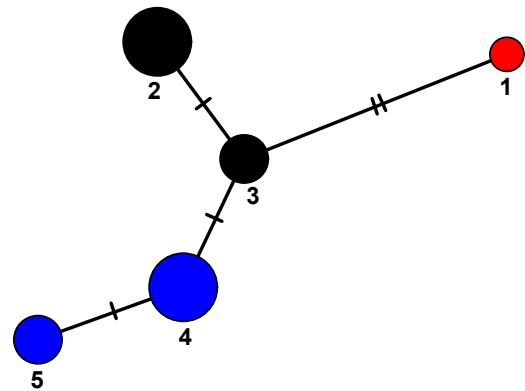
### DNA extraction, PCR amplification, DNA sequencing, and haplotype network analysis

The DNA extraction and PCR amplification followed the protocol outlined in previous works (Ossowska 2021; Ossowska et al. 2022a, b). A Macrogen sequencing system conducted the sequencing (<http://www.macrogen.com>).

Both complementary strands F and R were assembled and edited using BIOEDIT 7.0.9 (Hall 2011). The newly generated nuITS rDNA sequences were compared to *Sticta* sequences and pre-marked using a BLAST search (Altschul et al. 1997). Haplotype networks were created for both samples to compare the new sequences with those deposited in GenBank. To obtain the necessary data, we downloaded all sequences of *S. arenosella*, *S. cellulosa*, and *S. torii* and aligned them using Seaview (Galtier et al. 1996; Gouy et al. 2010). The alignment for *S. arenosella* and *S. torii* contained ten sequences, while *S. cellulosa* had four sequences. We plotted the TCS network (Clement et al. 2002) for both datasets using PopArt networks (<http://popart.otago.ac.nz>) and modified it in Inkscape (<http://inkscape.org>). The new sequences of *S. arenosella* and *S. cellulosa* obtained in this study have been deposited in GenBank (Table 1).

## Results and discussion

The nuITS rDNA sequence obtained from a single Chilean specimen (Schiefelbein 6518) exhibits 99.45% similarity to the sequence of *S. torii* (MH374893) and 99.44% similarity to the sequence of *S. arenosella* (MH374894). Due to the unresolved outcome using BLAST, a haplotype network analysis was performed (Fig. 1). Three haplotypes were identified in *S. arenosella* (nos. 1, 2 and 3) and two in *S. torii* (nos. 4 and 5). The *S. arenosella* haplotypes differ from *S. torii* in up to three positions. Our sample from Chile (haplotype no. 1) differs from other *S. arenosella* sequences by two or three positions and from *S. torii* by three to four positions (Fig. 1). Furthermore, we



**Figure 1.** Haplotype network showing relationships between nuITS rDNA sequences of *Sticta arenosella* (black and red dots) and *S. torii* (blue dots). The new sequence of *S. arenosella* from Chilean sample is marked as a red dot (see also Table 1).

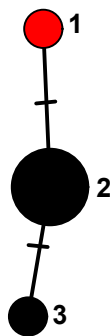
observed a difference in sequences of *S. arenosella* and *S. torii* at the nucleotide position no. 417 in the alignment: *S. arenosella* has an A at this position, whereas *S. torii* has a C. Our sequence also has an A at this position, as do all *S. arenosella* sequences. Di Meglio and Goward (2023) stated that *S. arenosella* and *S. torii* are phylogenetically closely related and genetically very similar, but differ in the structure and distribution of isidia (Di Meglio & Goward 2023), which are marginal and dendrisco-cauloid in the mature form of *S. torii*, and laminal in *S. arenosella* (Simon et al. 2018b; Di Meglio & Goward 2023). Our specimen has laminal, non-dendrisco-cauloid isidia, and as the sequence is most similar to *S. arenosella*, we have classified it as *S. arenosella*. The genetic differences between these two species appear to be small,

**Table 1.** List of the nuITS rDNA sequences used in haplotype network. Newly obtained sequences are in bold. Haplotype numbers refers to numbers presented on Figs 1 and 2.

Species	Haplotype number	GenBank accession number	Country
<i>Sticta arenosella</i>	1	<b>PP273997</b>	Chile
	2	MT183691–MT183693, MH374895	USA
	3	MH374894 (from holotype), MH374896	
<i>Sticta torii</i>	4	MH374891–MH374893, MT183695	Canada
	5	MH017853, MH017854 (from holotype)	
<i>Sticta cellulosa</i>	1	<b>PP273998</b>	Bolivia
	2	OP999548 (from holotype), OP999549, OP999559	Africa
	3	OP599545	

however nuITS rDNA may not be the best marker to show the genetic distance between these two morphologically distinct species. Similar issues have been also reported for *S. antoniana* B. Moncada & Lücking and *S. tomentosa* (Sw.) Ach. (Moncada et al. 2020; Moncada et al. 2021b). In these cases, as in *S. arenosella* and *S. torii*, it is not possible or very difficult to separate species on the basis of nuITS rDNA sequences, whereas morphological differences between *S. antoniana* and *S. tomentosa* are evident (see also Ossowska et al. 2024). Similar problems were found in the case of *Usnea antarctica* Du Rietz and *U. aurantiacoatra* (Jacq.) Bory, which lacked support from analyses of traditionally used loci, and only after the RADseq and comparative genomics was it possible to separate the two species, which were previously proposed as synonyms (Grewe et al. 2018). This method was also employed in the genus *Parmelina* Hale and resulted in the separation of two novel species from *P. tiliacea* (Hoffm.) Hale (Barcenás-Peña et al. 2023).

The nuITS rDNA sequence obtained from a Bolivian specimen of *S. cellulosa* (Kukwa 14689) showed 99.79% similarity to the sequence of the holotype (OP999548). The haplotype network revealed that *S. cellulosa* is represented by three haplotypes that differ by only one or two positions (Fig. 2). The majority of *S. cellulosa* sequences, including the type specimen, cluster within haplotype no. 2, which differs from haplotype no. 1 represented by the Bolivian sample by one position.



**Figure 2.** Haplotype network showing relationships between nuITS rDNA sequences of *Sticta cellulosa*. The new sequence from Bolivian samples is marked as a red dot (see also Table 1).

## Taxonomy

***Sticta arenosella*** Di Meglio & Goward, *Bryologist* 126: 97. 2023. (Fig. 3A–B)

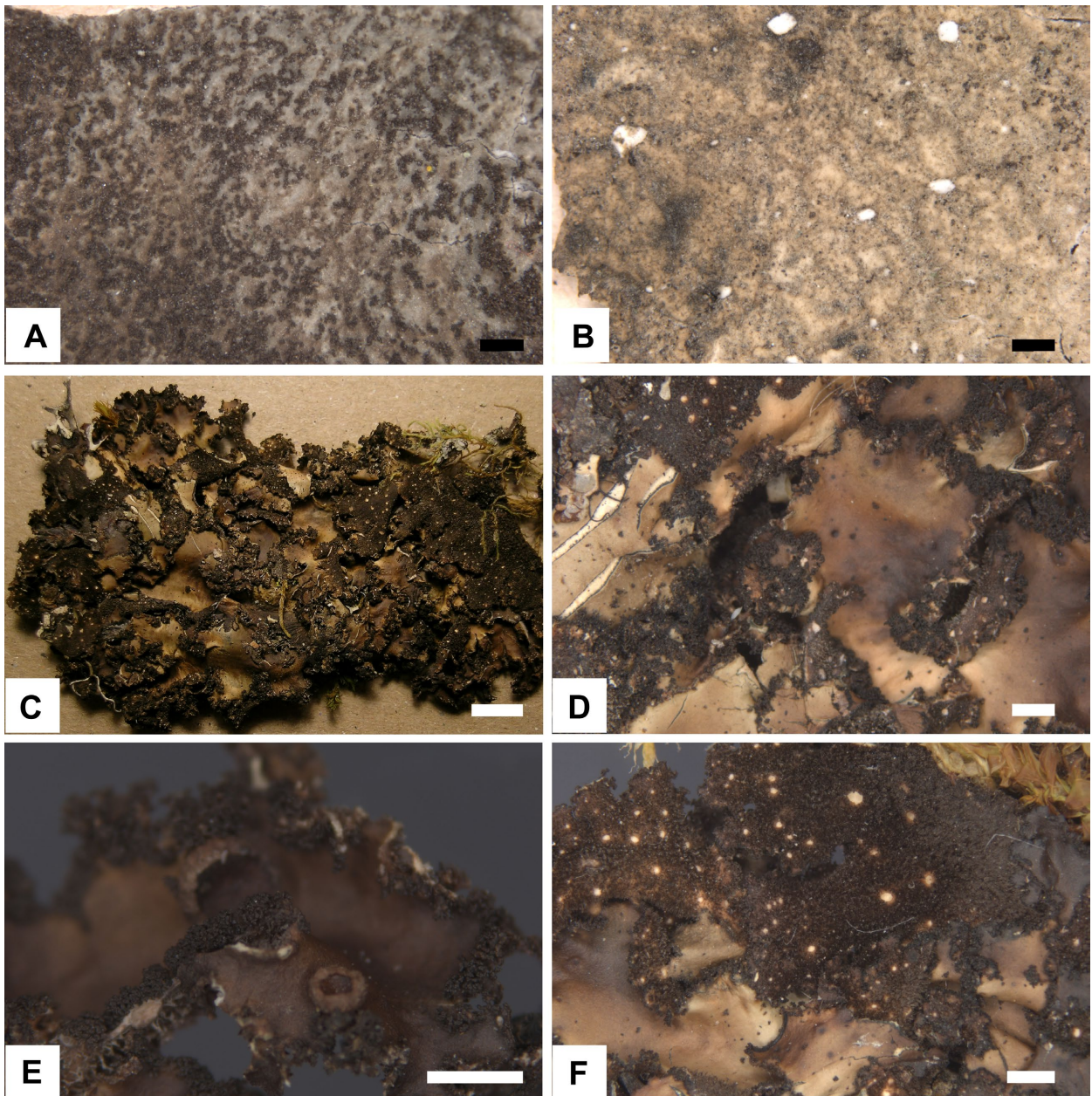
**Notes.** For a detailed description of *S. arenosella*, see Di Meglio and Goward (2023). Diagnostic characters for this species are the suborbicular, non-branched lobes with involute margins, and abundant, aggregated, and laminal isidia, which are simple to strongly branched in the apices and darker than the upper cortex. The upper surface is pale greyish to greyish brown, smooth to weakly scrobiculate. The lower surface is pale, smooth to slightly ridged, with sparsely distributed, creamy to whitish-greyish orange, hirsute to fasciculate primary tomentum (but lobe margins are free of tomentum) and secondary tomentum. Cyphellae

are sparse, round to irregular, cupuliform. Apothecia are not known in this species (Di Meglio & Goward 2023).

*Sticta arenosella* is a morphodeme of *S. fuliginosa* (With.) Ach. (Di Meglio & Goward 2023). Both taxa share similar phenotypic characteristics, but are phylogenetically distinct, belonging to clades II and I sensu Widhelm et al. (2018), respectively. The size of the thalli highlights the differences between the two species. In *S. fuliginosa*, it can exceed 10 cm and its lobes are deeply incised, while the isidia are unbranched, whereas in *S. arenosella* the thalli are up to 5 cm and unbranched, and the isidia simple to branched. Furthermore, the lower surface in *S. fuliginosa* is white or light orange to brown, with dense, white to dark brown tomentum with abundant cyphellae and the membrane of the cyphellae is not papillate (Magain & Sérusiaux 2015). In *S. arenosella*, the lower surface is pale with sparse tomentum and cyphellae that have a papillate membrane (Di Meglio & Goward 2023).

Clade II in the sensu Widhelm et al. (2018) also includes species such as, *S. arbusculotomentosa* B. Moncada & Betanc., *S. ciliata* Taylor, *S. gyalocarpa* (Nyl.) Trevis., or *S. hawaiiensis* B. Moncada & Lücking. However, *S. arenosella* can be distinguished from them by the absence of cilia and/or apothecia, the presence of isidia, and the structure of the tomentum. Other *Sticta* species with laminal isidia which may be confused with *S. arenosella*, and which have also been recorded from South America include *S. aymara* Ossowska, Kukwa, B. Moncada, Flakus, Rodr. Flakus & Lücking, *S. viviana* Alej. Suárez & Lücking, and *S. sylvatica* (Huds.) Ach. (Moncada 2012; Suárez & Lücking 2013; Magain & Sérusiaux 2015; Ossowska et al. 2022b). However, in *S. aymara* isidia are abundantly branched from the base, in *S. viviana* they are corymbose (like cauliflower), while in *S. sylvatica* the isidia are similar to those of *S. arenosella*, but granular to cylindrical. The taxa also differ in the lower surface and the structure of the tomentum. In *S. sylvatica* and *S. aymara*, the lower surface is undulate to veined, and in both species, the primary tomentum is dense to the margin (Moncada 2012; Magain & Sérusiaux 2015; Ossowska et al. 2022b). *Sticta viviana* has a rugose lower surface and the tomentum is dense and thick, except at the margin (Suárez & Lücking 2013). *Sticta sylvatica* is also known from Europe (Magain & Sérusiaux 2015), while *S. viviana* and *S. aymara* have only confirmed records from South America (Suárez & Lücking 2013; Ossowska et al. 2022b).

*Sticta arenosella* has only been reported from the coastal region of British Columbia in North America, from which it is known from its southern boundary of Central Oregon Cascades to central coastal and interior British Columbia (Di Meglio & Goward 2023). Our record is the first from the Southern Hemisphere and South America, where the taxon was found in Chile in the Department of Magallanes y Antártica Chilena (Fig. 4). To date, there has been no research on *Sticta* in Chile using the concept of integrative taxonomy, and out of the twelve *Sticta* species treated by Galloway (1994), only two have been confirmed with molecular data (Högnabba et al. 2009).



**Figure 3.** Morphology of *Sticta arenosella* (Schiefelbein 6518) and *S. cellulosa* (Kukwa 14689). A – upper surface *S. arenosella* with laminal isidia; B – ridged lower surface *S. arenosella* with sparse tomentum; C–D – upper surface of *S. cellulosa* with mostly marginal isidia; E – apothecia and isidia of *S. cellulosa*; F – lower surface of *S. cellulosa* with dark tomentum. Scales: A–B, D–F = 1 mm; C = 5 mm.

These are *S. gaudichaldia* Delise, which is characterized by the presence of apothecia and the absence of vegetative propagules, and *S. hypochra* Vain., which has dark, reddish-brown marginal and lamina-shaped isidia (Galloway 1994). Since Galloway's monograph, more than a dozen new *Sticta* taxa have been distinguished, including isidiate *S. andina* B. Moncada, Lücking & Sérus. and *S. scabrosa* B. Moncada, Merc.-Díaz & Bungartz (Moncada et al. 2021a, b; Ossowska et al. 2022a), which have been distinguished from *S. weigeli* (Ach.) Vain. reported by Galloway (1994).

**Specimens examined.** CHILE. Dept. Magallanes y Antártica Chilena; Prov. de Última Esperanza, Torres del Paine, National Park Torres del Paine, forest N of the Guarderia Lago Grey, elev. 75 m, 51°7'18"S, 73°7'51"W, *Nothofagus* forest, 14 Jan 2023, U. Schiefelbein 6518 (UGDA).

*Sticta cellulosa* Kaasalainen, in Kaasalainen et al., Journal of Fungi 9: 17. 2023. (Fig. 3C–F)

**Notes.** For a detailed description of *S. cellulosa*, see Kaasalainen et al. (2023). The species is identified by an irregular thallus with elongated lobes, smooth to centrally foveolate upper surface usually with a scrobiculate pattern of isidiate ridges (in Bolivian material very locally present), the lack of cilia, abundant, aggregated, dark brown to black isidia, which are cylindrical to coralloid and often form a scrobiculate pattern along the ridges. The upper surface is yellowish-brown to dark brown, while the lower surface is smooth and dark brown with dark brown to black primary tomentum, dense to the margin, with secondary tomentum and squarrose rhizines. Cyphellae are dispersed, rounded to irregular, cupuliform



**Figure 4.** Distribution map of *Sticta arenosella* (rhombus) and *S. cellulosa* (dots); blue – localities from literature, red – new localities (base map provided by Natural Earth, [www.naturalearthdata.com](http://www.naturalearthdata.com)). Localities of *S. cellulosa* from Africa are located in close proximity to each other (see Kaasalainen et al. 2023), and marked with only one dot on the map.

to slightly urceolate. All parts of thallus do not react with K (Kaasalainen et al. 2023).

In the specimens from Bolivia, we observed apothecia, which were not previously reported from the species. Their characteristics are as follows: apothecia biatorine, scarce, submarginal, subpedicellate, dispersed, up to 1.5 cm in diam. and ca. 0.5 mm high; discs red-brown to brown; apothecial margin brown to dark brown, smooth to partly verrucous and slightly crenate near disc; margin cortex up to 100  $\mu\text{m}$  wide, outer part orange-brown; apothecial medulla yellowish, K+ lemon yellow; hypothecium orange-brown, up to 75  $\mu\text{m}$  high; hymenium up to  $\mu\text{m}$  85 high, hyaline, but pale orange-brown in upper part; epithecium orange-brown, up to 5  $\mu\text{m}$  thick; ascospores 1–3-septate, 25–32  $\times$  5–7  $\mu\text{m}$ . The description of the apothecia was made on the basis of one that was the largest, as most were very small.

*Sticta cellulosa* belongs to the clade III sensu Widhalm et al. (2018), as do other taxa described from Bolivia (Moncada & Lücking 2012; Ossowska 2021; Ossowska et al. 2022a, b; Crous et al. 2023). Within this clade are *S. amboroensis* Ossowska, Kukwa, B. Moncada & Lücking and *S. carrascoensis* Ossowska, Kukwa, B. Moncada & Lücking characterized by the absence of vegetative propagules (Ossowska et al. 2022b). Other species, *S. andina*, *S. weigeli*, and *S. isidiokunthii* B. Moncada & Lücking produce isidia similar to *S. cellulosa*. However, *S. cellulosa* differs from them by the presence of the isidiate scrobiculation, which develop close the lobe

margins (Kaasalainen et al. 2023). In addition, *S. andina*, which is closely related to *S. cellulosa* according to the phylogenetic data presented in Kaasalainen et al. (2023), has flattened to dorsiventral isidia and phyllidia (Moncada et al. 2021a, b; Ossowska et al. 2022a), whereas *S. weigeli* has a medulla that reacts intensely yellow with K and the primary tomentum is spongy (Moncada 2012; Ossowska 2021). *Sticta isidiokunthii*, on the other hand, is distinguished by lighter colored upper and lower surfaces (Moncada 2012; Moncada & Lücking 2012). The characteristics of these and other species of *S. weigeli* morphodeme are presented in detail by Ossowska (2021).

Other *Sticta* taxa with marginal isidia include, for example, *S. beauvoisii* Delise, *S. emmanueliana* B. Moncada, Lücking & Lumbsch and *S. hypoglabra* B. Moncada & Lücking (McDonald et al. 2003; Moncada 2012; Moncada et al. 2020, 2021b; Yáñez-Ayabaca et al. 2023). However, the differences between them can be seen in the color of the upper and lower surfaces, the primary tomentum, and the shape of the cyphellae. *Sticta beauvoisii* and *S. emmanueliana* have a greyish-brown upper surface, while in *S. hypoglabra* it is light brownish grey. The lower surface and tomentum in *S. beauvoisii* and *S. hypoglabra* are paler than in *S. cellulosa*, and the cyphellae are urceolate with a wide pore (McDonald et al. 2003; Moncada 2012; Yáñez-Ayabaca et al. 2023). In *S. emmanueliana*, the lower surface is dark in the central part of the thallus and lighter at the margins, with a greyish-brown tomentum (Moncada et al. 2020, 2021b).

*Sticta cellulosa* was previously only known from East Africa in Tanzania (Kaasalainen et al. 2023). This is the first known record of the species from South America, where it was found in Bolivia in the department of La Paz (Fig. 4).

**Specimens examined.** BOLIVIA. Dept. La Paz, Prov. Bautista Saavedra, Área Natural de Manejo Integrado Nacional Apolobamba, between la Curva and Charazani, elev. 3780 m, 15°08'09"S, 69°02'03"W, open area with shrubs, Ceja de Monte Superior (Altimontano), on shrub, 15 Nov 2014, M. Kukwa 14689 (LPB, UGDA).

## Conclusions

In recent years, the genus *Sticta* has been studied in Bolivia using the concept of integrative taxonomy. As a result, the number of taxa in the genus increased by more than 47% (Moncada & Lücking 2012; Ossowska 2021; Ossowska et al. 2022a, b, 2024; Crous et al. 2023), confirming the hypothesis of Ossowska et al. (2022a) that the diversity of *Sticta* in Bolivia is probably as high as in Colombia.

The genus *Sticta* exemplifies the importance of integrative taxonomy in lichen identification. ‘Turbo-taxonomy’ can aid in rapid species identification, but it should always be accompanied by observations of specimen morphology and anatomy. In this study, we described apothecia of *S. cellulosa* from Bolivia, although they were not observed in specimens from East Africa. In contrast, if we had relied solely on molecular evidence to identify the specimen from Chile, we would have misidentified it as *S. torii*. However, a combination of molecular evidence and morphological characters enabled us to correctly identify it as *S. arenosella*.

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