

Metabolite profiling reveals organ-specific flavone accumulation in *Scutellaria* and identifies a scutellarin isomer isoscutellarein 8-O- β -glucuronopyranoside

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Abstract

Scutellaria is a genus of plants containing multiple species with well-documented medicinal effects. *S. baicalensis* and *S. barbata* are among the best-studied *Scutellaria* species, and previous works have established flavones to be the primary source of their bioactivity. Recent genomic and biochemical studies with *S. baicalensis* and *S. barbata* have advanced our understanding of flavone biosynthesis in *Scutellaria*. However, as over several hundreds of *Scutellaria* species occur throughout the world, flavone biosynthesis in most species remains poorly understood. In this study, we analyzed organ-specific flavone profiles of seven *Scutellaria* species, including *S. baicalensis*, *S. barbata*, and two species native to the Americas (*S. wrightii* to Texas and *S. racemosa* to Central and South America). We found that the roots of almost all these species produce only 4'-deoxyflavones, while 4'-hydroxyflavones are accumulated exclusively in their aerial parts. On the other hand, *S. racemosa* and *S. wrightii* also accumulated high levels of 4'-deoxyflavones in their aerial parts, different with the flavone profiles of *S. baicalensis* and *S. barbata*. Furthermore, our metabolomics and NMR study identified the accumulation of isoscutellarein 8-O- β -glucuronopyranoside, a rare 4'-hydroxyflavone, in the stems and leaves of several *Scutellaria* species including *S. baicalensis* and *S. barbata*, but not in *S. racemosa* and *S. wrightii*. Distinctive organ-specific metabolite profiles among *Scutellaria* species indicate the selectivity and diverse physiological roles of flavones.

1 | INTRODUCTION

Medicinal plants have been used in the traditional medicines of indigenous populations for thousands of years. Due to this widespread usage, modern research techniques are being applied to identify the compounds responsible for these medicinal properties and to characterize their modes of action (Shang et al., 2010). A negative

consequence of increased attention to and demand for medicinal plants is the endangerment of native plant populations resulting from overharvesting (Cole et al., 2007). Therefore, development of biotechnology-based mass production systems for these medicinal compounds is desirable. Development of effective biotechnology for chemical production requires an understanding of the biosynthesis of the compounds of interest. In this work, we analyze the levels of

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flavones in various organs of multiple species from the *Scutellaria* genus to better understand flavone biosynthesis in *Scutellaria*.

Part of the mint family Lamiaceae, *Scutellaria* is a genus of plants containing several hundred species with well-documented medicinal effects. Extracts from the aerial parts of *S. barbata* are commonly applied in Eastern medicines to treat swelling, inflammation, and cancer (Tao & Balunas, 2016). These activities, especially its anticancer effects, have drawn significant attention to *S. barbata*, and early phase clinical trials of aqueous extracts have demonstrated its selective cytotoxicity towards breast cancer cells (Chen et al., 2012). In addition, *S. barbata* extracts have exhibited remarkable activity towards multi-drug resistant strains of bacteria (Tsai et al., 2018). *S. baicalensis* is another species extensively applied in Eastern medicines, with extracts of its roots being prescribed to treat diarrhea, dysentery, hypertension, inflammation, and a variety of other diseases (Zhao, Tang, et al., 2019). Numerous clinical studies have demonstrated the neuroprotective, antibacterial, antitumor, antioxidant, and other beneficial health effects of these extracts (Saralamma et al., 2017; Tao et al., 2018; Zhu et al., 2016).

One class of bioactive compounds in *Scutellaria* is flavones (Karimov & Botirov, 2017; Zhao, Tang, et al., 2019). *Scutellaria* species produce two classes of flavones: 4'-hydroxyflavones and 4'-deoxyflavones (Figures 1 and S1). 4'-Hydroxyflavones, including apigenin and its derivatives, are relatively common across the plant kingdom, whereas 4'-deoxyflavones, which include chrysin and its derivatives, are relatively rare outside of *Scutellaria* (Kato et al., 1992; Rao et al., 2002; Rao et al., 2009). Recent works in *S. baicalensis* and *S. barbata* have identified multiple enzymes responsible for flavone biosynthesis in *Scutellaria* and have described the differential activity of specific enzymes towards either 4'-hydroxyflavones or 4'-deoxyflavones (Zhao et al., 2016, 2018; Zhao, Yang, et al., 2019). The enzyme selectivity leads to an organ-specific pattern of flavone accumulation. In this pattern, 4'-hydroxyflavones accumulate at higher concentrations in the aerial parts of the plant than in the roots, and the roots contain higher concentrations of 4'-deoxyflavones as compared to the aerial parts (Tao & Balunas, 2016; Xu et al., 2020).

Flavone profiles of *S. baicalensis* and *S. barbata* have been described, and their reference genomes have been established to further support the biosynthetic studies of flavones. However, due to the large number of uncharacterized species in the genus, it is unknown if the overall flavone pathway and the organ-specific accumulation patterns of *S. baicalensis* and *S. barbata* are well conserved across the genus. In this work, we aimed to expand the current knowledge of flavone diversity in *Scutellaria* by analyzing metabolite profiles of seven species. These species included two well-studied species, *S. baicalensis* and *S. barbata*, and two species native to warm climates, *S. racemosa* and *S. wrightii*. Furthermore, we selected three other *Scutellaria* species widely distributed in Europe, Asia, and North America, including *S. altissima*, *S. tournefortii*, and *S. parvula* (Hasaninejad et al., 2009; Shang et al., 2010; Sutter et al., 2011), respectively. During this analysis, we unexpectedly identified a 4'-hydroxyflavone which has not been included in the recent biosynthetic studies of *S. baicalensis*. We elucidated the structure of

this 4'-hydroxyflavone and quantified its level in the seven species. Our results revealed diversity in site and type of flavone accumulated across the species we selected.

2 | MATERIALS AND METHODS

2.1 | Plant growth conditions

Plants of seven *Scutellaria* species were grown from seed at the University of Florida (Gainesville, Florida, USA) in indoor, climate-controlled conditions at 21–23°C. Fluorescent lighting of intensity 140 $\mu\text{E m}^{-2} \text{s}^{-1}$ was applied in a 16 h light/8 h dark cycle. Plants were watered every 5–8 days, and root, stem, and leaf tissue samples were collected in biological triplicate 6–8 weeks after germination. Seeds of all species except for those of *S. racemosa* and *S. wrightii* were obtained from retailers (*S. altissima*, *S. baicalensis*, and *S. tournefortii* from Plant World Seeds and *S. barbata* and *S. parvula* from Prairie Moon Nursery). To collect seeds of *S. racemosa*, mature plants were taken from a field in Hattiesburg, Mississippi, USA, and grown in indoor, climate-controlled conditions at the University of Florida until seeds were ready to harvest. Seeds of *S. wrightii* were collected directly from mature plants grown in outdoor greenhouse conditions at Far South Wholesale Nursery (Austin, Texas, USA). Herbarium vouchers of all species were submitted to the University of Florida Herbarium, and voucher numbers are provided in Table S3.

2.2 | Flavone extraction and quantification

With High Performance Liquid Chromatography (HPLC), 15 flavones were quantified from root, stem, and leaf tissue samples of plants. The flavones quantified included seven 4'-hydroxyflavones, which were apigenin, apigenin-7-glucuronide (apigenin 7-G), scutellarein, scutellarin, hispidulin, hispiduloside, and isoscutellarein-8-glucuronide (isoscutellarein 8-G). The remaining eight flavones were 4'-deoxyflavones, which were chrysin, chrysin-7-glucuronide (chrysin 7-G), baicalein, baicalin, oroxylin A, oroxyloside, wogonin, and wogonoside. The fresh weight of each tissue sample was determined with an analytical balance immediately after harvesting. Samples were frozen in liquid nitrogen and stored in -80°C until further analysis. An extraction solution of 50% HPLC grade methanol was added to ground samples so that the following ratio was achieved: 30 mg tissue/ml solvent. Samples were then sonicated for 1 h at room temperature. Following sonication, the extraction solution was withdrawn and further diluted with additional 50% methanol to achieve a final ratio of 30 mg tissue/ml solvent. To remove any remaining particulate, extractions were centrifuged at 15,000 rpm for 5 min and syringe filtered with a filter having a pore size of .45 μm .

Flavones were quantified in this final extraction with a Thermo Scientific (Massachusetts, USA) UltiMate 3000 HPLC system. Flavones were separated with an Acclaim RSLC 120 C18 column (2.2 μm , 3.0 \times 100 mm) and eluted by a mixture of .1% formic acid

(A) and 100% acetonitrile (B). Following an 8-min equilibration with 5% B prior to injection, the following gradient was applied: 2 min, 25% B; 2 to 6 min, 25% B; 9 min, 50% B; 9 to 11 min, 50% B; 15 min, 95% B; and 15 to 23 min, 95% B. A flowrate of .5 ml/min was used and the column oven temperature set to 40°C. Peak areas were measured at wavelength 276 nm. Calibration mixes of .1, .5, 1, 5, 10, 25, 50, and 100 ppm were prepared with all 14 flavone standards except

isoscutelellarin 8-G and used to convert peak areas to concentrations in ppm. Chemical standards used to prepare calibration mixes were purchased from ChemFaces (Wuhan, China) or MilliporeSigma (Massachusetts, USA) and dissolved in dimethylsulfoxide to generate stocks of 1,000, 2000, or 4,000 ppm. These stocks were then diluted with 50% methanol and mixed to generate calibrations mixes of the varying concentrations. With the peak areas of these calibration mixes

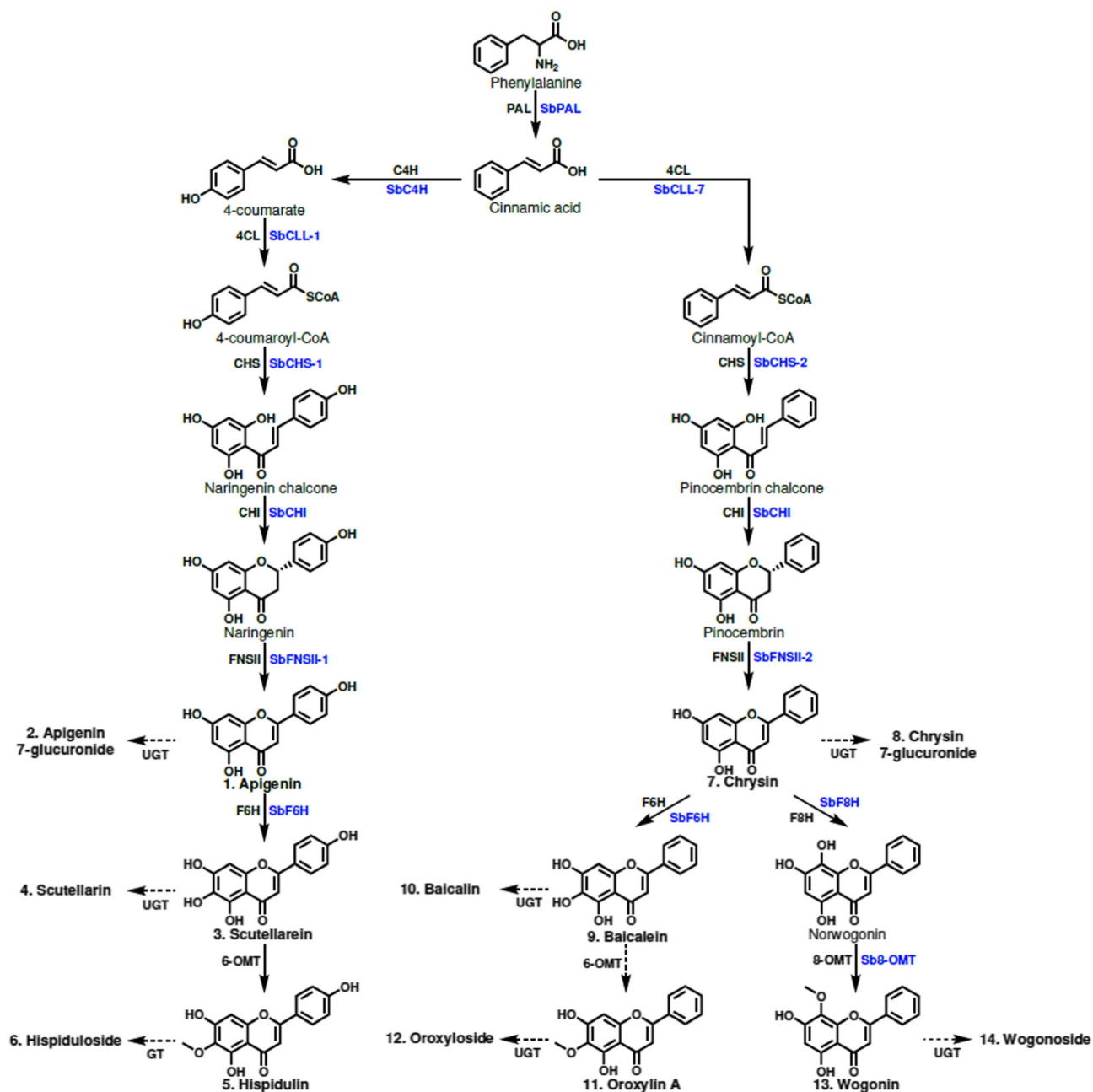


FIGURE 1 Proposed 4'-hydroxyflavone and 4'-deoxyflavone pathway. Structures of glycosylated flavones are not shown to save space but are included in Figure S1. Enzyme names in blue are specific isoforms that have been identified in *S. baicalensis*, and enzyme names in black are general names. Flavones that were quantified have names in bold and are numbered to match the labeling of Figure 2. Enzymes are phenylalanine ammonia lyase (SbPAL), cinnamate 4-hydroxylase (SbC4H), cinnamate-CoA ligase (SbCLL-7), 4-coumarate CoA ligase (SbCLL-1), chalcone synthase (SbCHS-1), pinocembrin-chalcone synthase (SbCHS-2), chalcone isomerase (SbCHI), flavone synthase I (SbFNSI), flavone synthase II (SbFNSII), flavone 6-hydroxylase (SbF6H), flavone 8-hydroxylase (SbF8H), and 8-O-methyl transferase (Sb8-OMT)

and the molecular weight of each metabolite, flavone concentrations in $\mu\text{mol/g}$ fresh weight were calculated. For relative concentration of isoscutellarein 8-G, only peak areas are reported.

Peaks in tissue sample chromatograms were identified based on their retention time and UV spectra (Figure S2) as compared with standards in the calibration mixes. Statistical testing was conducted by comparing the level of a flavone in the organ of a species to the level of the same flavone in the same organ of *S. baicalensis*. An unpaired Student's *t* test with a significance cutoff of .05 was applied to identify values as statistically significant.

2.3 | LC-HRMS

LC-HRMS and HRMS/MS experiments were conducted on Thermo Scientific™ Q Exactive Focus mass spectrometer with Dionex™ Ultimate™ RSLC 3000 uHPLC system, equipped with H-ESI II probe on Ion Max API Source. Water with .1% formic acid (A) and acetonitrile with .1% formic acid (B) were used as the mobile phases to separate analytes on an Agilent Poroshell 120 EC-C18 column (2.7 μm , 3.0 \times 50 mm). A typical LC program with a .5 ml/min flow rate included 10% B for 2 min, 10–95% B in 8.5 min, 95% B for 2.5 min, 95 to 10% B in .5 min, and re-equilibration in 2% B for 2 min. The eluents from the first 2 min and last 3 min were diverted to a waste bottle by a diverting valve. MS1 signals were acquired under the Full MS positive ion mode covering a mass range of *m/z* 150–2,000, with a resolution at 35,000 and an AGC target at 1e6. Fragmentation was obtained using MS2 discovery and Parallel Reaction Monitoring (PRM) mode using an inclusion list of calculated parental ions. Precursor ions were selected in the orbitrap typically with an isolation width of 3.0 *m/z* and fragmented in the HCD cell with step-wise collision energies (CE) of 20, 25, and 30. For some ions, the isolation width was 2.0 *m/z* and step-wise CE of 15, 20, and 25 were used.

2.4 | NMR analysis

For the NMR analysis, 1.6 mg of compound was dissolved in 40 μl DMSO- d_6 . 1D and 2D spectra were recorded in a 1.7 mm TCI CryoProbe on a Bruker Avance Neo-600 Console system (Magnex 14.1 T/54 mm AS Magnet) at Advanced Magnetic Resonance Imaging and Spectroscopy facility, McKnight Brain Institute, the University of Florida. Spectroscopy data were collected and processed using Topspin 4.1.3 software.

2.5 | Chemical shifts

^1H NMR (600 MHz, DMSO- d_6): δ_{H} 12.82 (OH, br, s, 5), 1.34 (OH, br, s, 4'), 8.07 (2H, d, *J* = 8.66 Hz, 2', 6'), 6.93 (2H, d, *J* = 8.66 Hz, 3', 5'), 6.83 (1H, s, 3), 6.29 (1H, s, 6), 5.44 (OH, br, s, 7), 4.82 (1H, *J* = 7.91 Hz, 1''), 3.82 (1H, d, *J* = 9.65 Hz, 5''), 3.51 (1H, t, *J* = 9.26 Hz, 4''), 3.49 (1H, t, *J* = 8.55 Hz, 2''), 3.35 (1H, t,

J = 9.03 Hz, 3''). ^{13}C NMR (151 MHz, DMSO- d_6): δ_{C} 181.72 (C-4), 169.96 (C-6''), 163.86 (C-2), 161.12 (C-4'), 157.23 (C-7), 156.90 (C-5), 149.19 (C-9), 128.85 (C-2', C-6'), 125.11 (C-8), 120.96 (C-1'), 115.96 (C-3', C-5'), 106.25 (C-1''), 103.35 (C-10), 102.33 (C-3), 98.86 (C-6), 76.00 (C-5''), 75.20 (C-3''), 73.69 (C-2''), 71.41 (C-4'').

3 | RESULTS

3.1 | Organ-specific flavone diversity across seven *Scutellaria* species

We selected seven species of *Scutellaria* for organ-specific flavone profiling with High Performance Liquid Chromatography (HPLC). These species included *S. altissima*, *S. baicalensis*, *S. barbata*, *S. parvula*, *S. racemosa*, *S. tournefortii*, and *S. wrightii*. *S. baicalensis* and *S. barbata* have been used in East Asian medicines for thousand years. *S. racemosa* is native to South and Central America (Krings & Neal, 2001), and *S. wrightii* occurs in southwestern regions of North America, such as Texas (Nelson & Goetze, 2010). *S. altissima*, *S. tournefortii*, and *S. parvula* are widely distributed in Europe, Asia, and North America (Hasaninejad et al., 2009; Shang et al., 2010; Sutter et al., 2011), but their flavone profiles have not been studied extensively. We grew plants of each species from seed in climate-controlled conditions and harvested tissue samples from the roots, stems, and leaves of mature plants in biological triplicate. We then quantified concentrations of six 4'-hydroxyflavones (1; apigenin, 2; apigenin 7-glucuronide (apigenin 7-G), 3; scutellarein, 4; scutellarin, 5; hispidulin, 6; hispiduloside) and eight 4'-deoxyflavones (7; chrysin, 8; chrysin 7-glucuronide (chrysin 7-G), 9; baicalein, 10; baicalin, 11; oroxylin A, 12; oroxyloside, 13; wogonin, 14; wogonoside) in these samples (Figure 2; Table 1). *S. baicalensis* is one of the most studied and medicinally applied species, and we selected it as a reference for statistical testing in this work.

Our root-specific flavone profiling indicated that the 4'-deoxyflavone pathway appears to be very well-conserved across all seven species. We detected at least six of eight tested 4'-deoxyflavones in the root of each species (Figure 2c; Table 1). Interestingly, although chrysin is proposed to serve as a precursor for all other 4'-deoxyflavones, we found it only in the root of *S. parvula*, and its glycosylated form, chrysin 7-G, in the roots of three species, *S. baicalensis*, *S. parvula*, and *S. tournefortii*. On the other hand, we observed the accumulation of baicalein, baicalin, oroxylin A, and oroxyloside in the roots of all seven species (Figure 2c; Table 1). *S. wrightii* was the only species to accumulate a significantly greater amount (*p* < .05, Student's *t* test) of baicalin and oroxyloside in its roots than *S. baicalensis*. We also detected significantly elevated (*p* < .05) levels of baicalein and oroxylin A in the roots of *S. wrightii* as compared to *S. baicalensis* (Figures 2c and 3; Table 1). Chrysin can also be converted to wogonin and wogonoside through the reaction of SbF8H and Sb8-OM (Figure 1). We detected both wogonin and wogonoside in the roots of all species except for *S. parvula*, where we did not detect wogonoside. *S. tournefortii* was the only species to

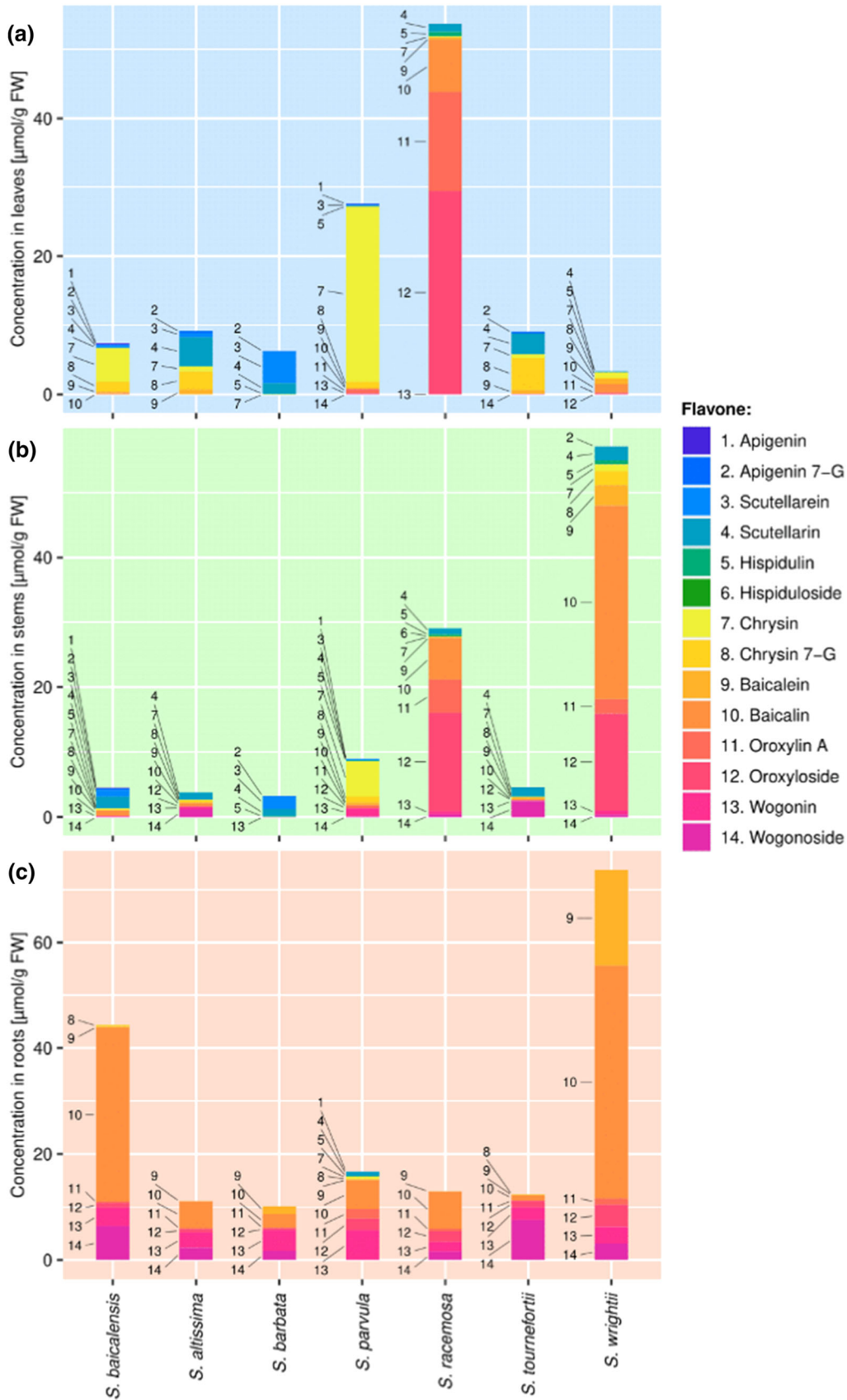


FIGURE 2 Metabolite data collected from the (a) leaves, (b) stems, and (c) roots of seven *Scutellaria* species via High Performance Liquid Chromatography (HPLC). Samples were taken in biological triplicate, and the average concentration of each metabolite calculated. Metabolites are numbered to match their order of occurrence in the flavone pathway, shown in Figure 1

TABLE 1 Organ-specific flavone concentrations collected from seven *Scutellaria* species via HPLC

Species	Organ	Apigenin	Apigenin 7-G	Scutellarein	Scutellarin	Isoscutellarein 8-G ^a	Hispidulin	Hispiduloside
<i>S. baicalensis</i>	Leaves	.19 ± .03	.13 ± .01	.27 ± .14	.10 ± .10	.10 ± .05	n.d.	n.d.
<i>S. baicalensis</i>	Stems	.12 ± .12	.22 ± .01	1.04 ± .43	1.76 ± .28	2.17 ± .60	.03 ± .02	n.d.
<i>S. baicalensis</i>	Roots	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>S. altissima</i>	Leaves	n.d. [*]	.28 ± .15	.65 ± .28	4.17 ± 1.22 [*]	n.d.	n.d.	n.d.
<i>S. altissima</i>	Stems	n.d.	n.d. [*]	n.d. [*]	1.11 ± .13 [*]	.26 ± .01 [*]	n.d.	n.d.
<i>S. altissima</i>	Roots	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>S. barbata</i>	Leaves	n.d. [*]	.01 ± .01 [*]	4.59 ± .33 [*]	1.51 ± .70 [*]	2.34 ± .49 [*]	.10 ± .02 [*]	n.d.
<i>S. barbata</i>	Stems	n.d.	.11 ± .02 [*]	1.90 ± .23	1.13 ± .25	3.89 ± .60 [*]	.09 ± .01 [*]	n.d.
<i>S. barbata</i>	Roots	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>S. parvula</i>	Leaves	.11 ± .01 [*]	n.d. [*]	.22 ± .04	n.d.	n.d.	.13 ± .01 [*]	n.d.
<i>S. parvula</i>	Stems	.02 ± .02	n.d. [*]	.11 ± .01 [*]	.16 ± .08 [*]	n.d.	.07 ± .00 [*]	n.d.
<i>S. parvula</i>	Roots	.06 ± .03 [*]	n.d.	n.d.	.82 ± .19 [*]	n.d.	.10 ± .03 [*]	n.d.
<i>S. racemosa</i>	Leaves	n.d. [*]	n.d. [*]	n.d. [*]	1.20 ± .35 [*]	n.d.	.63 ± .18 [*]	n.d.
<i>S. racemosa</i>	Stems	n.d.	n.d. [*]	n.d. [*]	.94 ± .33	n.d.	.25 ± .06 [*]	.06 ± .06
<i>S. racemosa</i>	Roots	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>S. tournefortii</i>	Leaves	n.d. [*]	.28 ± .07 [*]	n.d. [*]	2.98 ± .65 [*]	.18 ± .03	n.d.	n.d.
<i>S. tournefortii</i>	Stems	n.d.	n.d. [*]	n.d. [*]	1.47 ± .46	.90 ± .24 [*]	n.d.	n.d.
<i>S. tournefortii</i>	Roots	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>S. wrightii</i>	Leaves	n.d. [*]	n.d. [*]	n.d. [*]	.13 ± .09	n.d.	.02 ± .00 [*]	n.d.
<i>S. wrightii</i>	Stems	n.d.	.03 ± .01 [*]	n.d. [*]	2.10 ± .25	n.d.	.63 ± .08 [*]	n.d.
<i>S. wrightii</i>	Roots	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Species	Organ	Chrysin	Chrysin 7-G	Baicalin	Baicalin	Oroxylin A	Oroxyloside	Wogonoside
<i>S. baicalensis</i>	Leaves	4.84 ± .53	1.45 ± .24	.19 ± .08	.20 ± .11	n.d.	n.d.	n.d.
<i>S. baicalensis</i>	Stems	.18 ± .04	.09 ± .01	.06 ± .03	.87 ± .87	n.d.	n.d.	.11 ± .11
<i>S. baicalensis</i>	Roots	n.d.	.30 ± .01	.20 ± .03	32.81 ± 2.22	.23 ± .13	.87 ± .87	3.49 ± .18
<i>S. altissima</i>	Leaves	.75 ± .07 [*]	2.62 ± .18 [*]	.70 ± .18 [*]	n.d.	n.d.	n.d.	n.d.
<i>S. altissima</i>	Stems	.04 ± .02 [*]	.35 ± .05 [*]	.15 ± .05	.47 ± .38	n.d.	.06 ± .06	.34 ± .26
<i>S. altissima</i>	Roots	n.d.	n.d. [*]	.07 ± .00 [*]	5.07 ± .66 [*]	.14 ± .02	.64 ± .07	2.90 ± .21 [*]
<i>S. barbata</i>	Leaves	.03 ± .00 [*]	n.d. [*]	n.d. [*]	n.d.	n.d.	n.d.	n.d.
<i>S. barbata</i>	Stems	n.d. [*]	n.d. [*]	n.d.	n.d.	n.d.	n.d.	.03 ± .02
<i>S. barbata</i>	Roots	n.d.	n.d. [*]	1.49 ± .04 [*]	2.59 ± .49 [*]	.08 ± .01	.34 ± .18	3.88 ± .34
<i>S. parvula</i>	Leaves	25.34 ± .72 [*]	.79 ± .09 [*]	.22 ± .03	.07 ± .03	.59 ± .11 [*]	n.d.	.07 ± .07
<i>S. parvula</i>	Stems	5.37 ± .41 [*]	.91 ± .31 [*]	.34 ± .14 [*]	.17 ± .08	.37 ± .03 [*]	.03 ± .03	1.24 ± .09 [*]

(Continues)

TABLE 1 (Continued)

Species	Organ	Apigenin	Apigenin 7-G	Scutellarein	Scutellarin	Isoscutellarein 8-G ^a	Hispidulin	Hispiduloside
<i>S. parvula</i>	Roots	.40 ± .08*	.18 ± .04*	.12 ± .03	5.35 ± .94*	1.86 ± .31*	2.18 ± .33	5.62 ± 1.10
	Leaves	.12 ± .01*	n.d.*	.34 ± .29	7.59 ± 1.95*	14.39 ± 2.58*	29.39 ± 8.00*	.02 ± .02
<i>S. racemosa</i>	Stems	.03 ± .03*	n.d.*	.24 ± .22	6.36 ± 2.13*	5.09 ± 1.09*	15.17 ± 4.14*	.44 ± .03*
	Roots	n.d.	n.d.*	.08 ± .02*	6.98 ± 1.20*	.44 ± .11	2.02 ± .38	1.82 ± .06*
<i>S. tournefortii</i>	Leaves	.49 ± .02*	4.69 ± .97*	.53 ± .13*	n.d.	n.d.	n.d.	.06 ± .06
	Stems	.01 ± .01*	.15 ± .04	.28 ± .07*	.08 ± .04	n.d.	.06 ± .03	.13 ± .05
<i>S. tournefortii</i>	Roots	n.d.	.08 ± .04*	.13 ± .06	.93 ± .08*	.08 ± .01	1.24 ± .14	2.33 ± .20*
	Leaves	.82 ± .17*	.13 ± .09*	.78 ± .18*	1.21 ± .63	.10 ± .02*	.16 ± .05*	n.d.
<i>S. wrightii</i>	Stems	.99 ± .37*	2.23 ± .11*	3.10 ± 1.31*	29.90 ± .92*	2.24 ± .43*	14.87 ± .26*	.62 ± .07*
	Roots	n.d.	n.d.*	18.10 ± 1.37*	43.99 ± 9.53	1.17 ± .38*	4.22 ± 1.17*	3.13 ± .53

Note: Units for all flavones are $\mu\text{mol/g}$ fresh weight, except for isoscutellarein 8-G, which has units of peak area. Data are presented as mean \pm standard error, as calculated from samples taken in biological triplicate.

Abbreviations: HPLC, High Performance Liquid Chromatography; n.d., not detected.

* p value < .05 relative to *S. baicalensis* for the same organ and flavone. ^aData have units of peak area.

accumulate a significantly greater ($p < .05$) amount of wogonoside in its roots than *S. baicalensis*, and no species accumulated a significantly greater amount of wogonin (Figure 2c; Table 1). Finally, the absence of 4'-hydroxyflavones in the roots of all but one species (*S. parvula*) indicates their specificity to the aerial organs of the plant in most species we selected (Figure 2c).

Aerial tissue-specific flavone profiles of the selected species were much more varied than root-specific profiles (Figure 2a,b). First, of the six 4'-hydroxyflavones we selected, we detected two to four in the leaves of all species analyzed and one to five in their stems. We were unable to detect hispidulin, or its glucoside, hispiduloside, in the leaves or stems of two species, *S. altissima* and *S. tournefortii*. Hispiduloside was particularly rare, and out of all tissue samples taken, we only detected it in the stems of *S. racemosa* (Figure 2a,b; Table 1). Although these more advanced steps in the biosynthetic pathway may not be well conserved, the accumulation of scutellarin in the aerial tissues of all seven species indicates at least partial retention of 4'-hydroxyflavone biosynthesis in these species (Figure 2a,b). Apigenin is a biosynthetic precursor of all other selected 4'-hydroxyflavones (Figure 1). Interestingly, it was scarcely accumulated, as we detected apigenin in the aerial tissues of only two species, *S. baicalensis* and *S. parvula*. This pattern is analogous to the scarce accumulation of chrysin in our root tissue samples.

In addition to 4'-hydroxyflavones, we observed that several species accumulate one to eight of the selected 4'-deoxyflavones in their aerial parts. Remarkably, the leaves of all seven species accumulated chrysin, and except for *S. barbata*, the stems of all species also accumulated chrysin. This widespread accumulation of chrysin in the aerial parts is strikingly different from its scarcity in the roots (Figure 2). Of note, *S. parvula*, *S. racemosa*, and *S. wrightii* accumulated significantly higher ($p < .05$) concentrations of oroxylin A in their stems and leaves as compared to *S. baicalensis* (Figure 3; Table 1). *S. racemosa* and *S. wrightii* also accumulated significantly higher ($p < .05$) concentrations of oroxyloside in their stems and leaves than *S. baicalensis* (Figure 3; Table 1). Overall, our detection of chrysin in the leaves of all species analyzed and baicalein in stems and leaves of most species suggests that specificity of 4'-deoxyflavones to roots is less than that of 4'-hydroxyflavones to aerial tissues.

3.2 | The structural elucidation of a new scutellarin isomer

During our metabolite analysis, we detected multiple new metabolites which we were unable to unambiguously assign their identities. Of these unknown metabolites, one drew our interest because of its pattern of accumulation across the tissue samples we collected (Figure 4). In our HPLC chromatograms, we detected the peak corresponding to this metabolite in the aerial parts of *S. baicalensis* and *S. barbata*, but not in *S. racemosa*. The peak was absent in root chromatograms collected from all seven species. The aerial specificity of this unknown metabolite led us to hypothesize that it was a 4'-hydroxyflavone. To elucidate its structure, we analyzed the

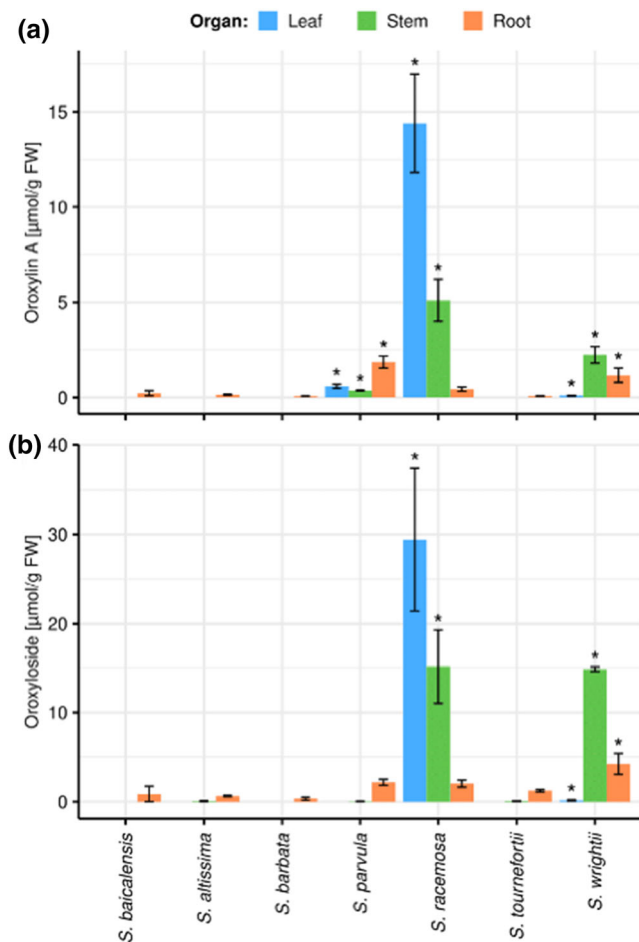


FIGURE 3 Organ-specific (a) oroxylin A and (b) oroxyloside concentrations in seven *Scutellaria* species, as determined via High Performance Liquid Chromatography (HPLC). Concentrations were averaged from tissue samples taken from three biological replicates, and error bars represent standard error. Asterisk (*) indicates p value $< .05$ relative to *S. baicalensis* for the same organ and flavone

unknown metabolite from our *S. barbata* leaf extracts by the liquid chromatography-high resolution mass spectrometry (LC-HRMS). Interestingly, its molecular weight was identical to scutellarin ($[M + H]^+$ m/z 463.0866, calculated for $C_{21}H_{19}O_{12}^+$, 463.0871), but they were eluted with different retention times ($t_m = 6.28$ min for scutellarin vs. 6.94 min for the unknown compound) (Figure 5a). Furthermore, they gave rise to the same major MS/MS fragment, suggesting them to be two isomers (Figure S3).

To further elucidate the structure of this compound, we performed 1D and 2D NMR analysis (Figures S4–S6). Comparison of its 1H and ^{13}C chemical shifts to those of scutellarin allowed the assignment of D -glucuronide (C1'' to 6''), 1,4-disubstituted benzene ring (C1' to 6'), and the carbons on the flavone ring (Jiang et al., 2016) (Figure 5b; Table S1). Based on the 1H chemical shift and coupling constant of the anomer proton H-1'' ($J = 7.86$ Hz), the glucuronyl moiety was determined to be on the β configuration (Ko et al., 2018). Compared with scutellarin, the aromatic proton at δ_H 6.99 (1H, s) was initially assigned to H-8 of the flavone. However, according to 1D-

selective nuclear overhauser effect spectroscopies (NOESY, resonance frequency at 6.28 or 12.81 ppm) and an 1D-selective rotating frame overhauser enhancement spectroscopy (ROESY, resonance frequency at 12.81 ppm), OH-5 correlates with H-3 ($\delta = 6.83$), and a proton at $\delta = 6.29$ (Figure 5b), leading to the assignment of this proton at position 6 ($\delta = 6.29$ ppm). This assignment was further supported by the weak NOE effects of H-6 with OH-5 and H-1'' on the glucuronyl moiety, which further indicated the proximity of the glucuronyl moiety at position 7 or 8. H-1'' also showed weak NOE effects with H2' and H6' on the 1,4-disubstituted benzene ring, suggesting the potential configuration of the compound, where the glucuronyl moiety could be close to the aromatic system. According to an HMBC correlation from H1'' to C8 of the flavone, we then definitely assigned the glucuronyl moiety at position 8 (Figure 5b). Collectively, our 1D and 2D NMR analysis revealed the isolated compound as isoscutellarein 8-O- β -glucuronopyranoside (isoscutellarein 8-G). Comparison with the reported 1H and ^{13}C chemical shifts of this compound (Billeter et al., 1991) confirmed this structural determination (Table S2).

After confirming the identity of this unknown metabolite as isoscutellarein 8-G, we then quantified its relative abundance in all organ-specific tissue samples we collected (Figure 6; Table 1). Isoscutellarein 8-G was accumulated only in the aerial parts of all species, matching the pattern which we had previously observed for 4'-hydroxyflavones including scutellarin. We detected isoscutellarein 8-G in the stems of *S. altissima*, and in the stems and leaves of *S. baicalensis*, *S. barbata*, and *S. tournefortii*. *S. barbata* accumulated the greatest overall concentration of isoscutellarein 8-G in its stems and leaves at levels significantly greater ($p < .05$) than that of *S. baicalensis*. In contrast, *S. parvula*, *S. racemosa*, and *S. wrightii* accumulated no isoscutellarein 8-G in their aerial parts. It is noteworthy that these three species accumulated oroxylin A and its glycoside in their aerial parts (Figure 3).

4 | DISCUSSION

From our analysis of organ-specific flavone diversity, we determined profiles for *S. baicalensis* and *S. barbata*, which matched closely with previous publications (Xu et al., 2020; Zhao et al., 2016). In these flavone profiles, high concentrations of 4'-deoxyflavones accumulated in the roots, and much lower concentrations of 4'-deoxyflavones and 4'-hydroxyflavones accumulated in the stems and leaves (Figure 2; Table 1). As described by Zhao et al. (2016), the root-favored accumulation of 4'-deoxyflavones by *S. baicalensis* is due to root-specific overexpression of several enzyme isoforms with activity exclusively, or near exclusively in 4'-deoxyflavone biosynthesis (Zhao et al., 2016). In contrast to the pattern we observed in *S. baicalensis* and *S. barbata*, we identified that *S. racemosa* and *S. wrightii* accumulated higher concentrations of 4'-deoxyflavones in their aerial parts as compared to their roots (Figure 2; Table 1). Also, all seven species accumulated chrysin and/or chrysin 7-glucuronide in their leaves (Figure 2a; Table 1). This suggests that the expression of 4'-deoxyflavone enzyme

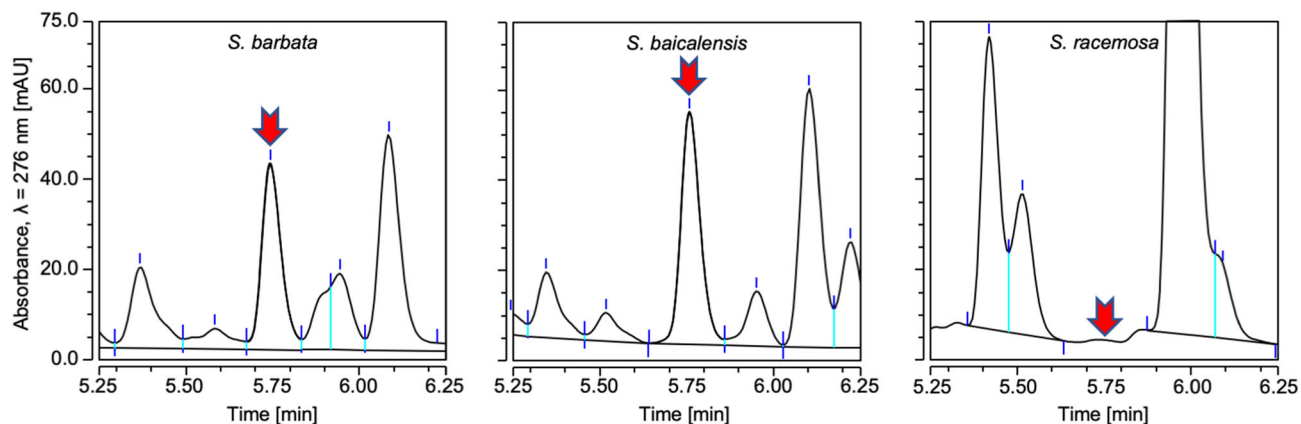
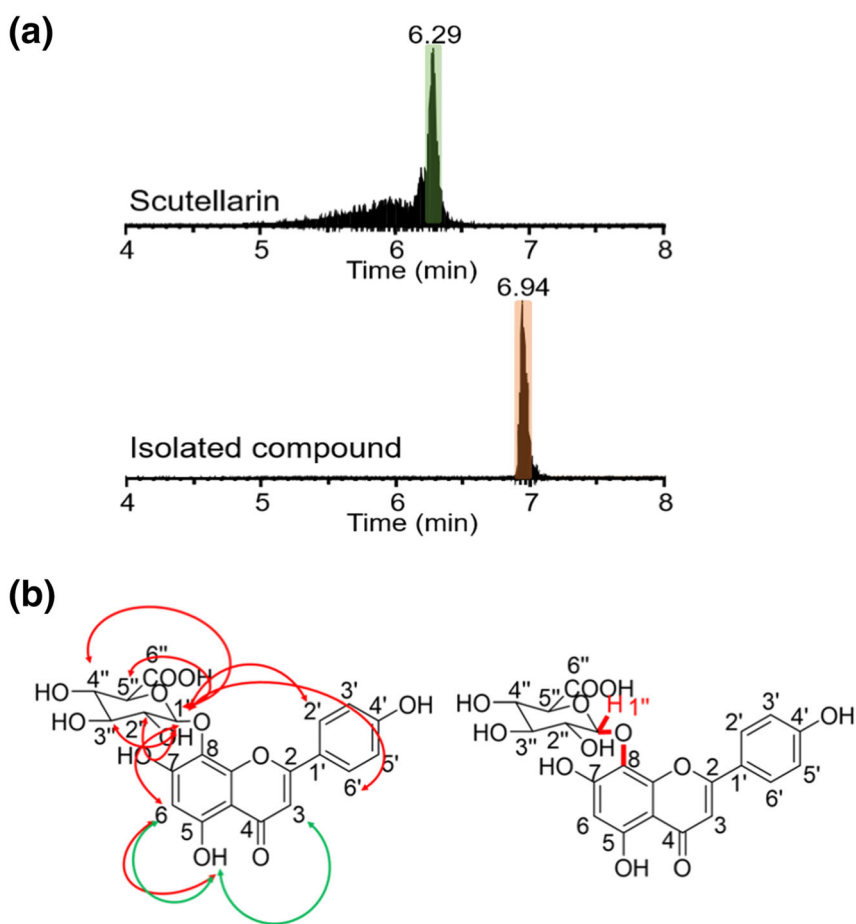


FIGURE 4 Comparison of chromatograms collected via HPLC from *S. barbata*, *S. baicalensis*, and *S. racemosa* stems. Time interval displayed was selected to center the unknown peak in the chromatograms

FIGURE 5 Characterization of a new scutellarin isomer. (a) Standard scutellarin and isolated compound were eluted with different retention times in LC-HRMS analysis. (b) Key NMR correlations of isolated compound. 1D-NOESY and 1D-ROESY correlations are represented by red and green two-way arrows, respectively (left). A three-bond HMBC correlation from H-1'' to C-8 (right)



isoforms is not perfectly root-specific and some enzymes having activities towards 4'-deoxyflavone precursors such as SbCLL-7 and SbCHS-2 may be active in both roots and aerial parts at least under our growth conditions. It is also possible that some fraction of 4'-deoxyflavones are synthesized in the roots and then transported to the aerial parts. The fact that 4'-hydroxyflavones were not detected in roots of most species indicates the selectivity of enzymes towards either 4'-deoxyflavones or 4'-hydroxyflavones (or their respective

precursors), as well as organ-specific regulation of biosynthetic gene expression.

We found that *S. racemosa* accumulates the highest concentrations of oroxylin A, and its 7-glucuronide, oroxyloside, in its leaves, among all organs of all species (Figure 3; Table 1). *S. wrightii* also accumulated notable amounts of oroxylin A and oroxyloside in its stem, but not in its leaves. Oroxylin A is a 4'-deoxyflavone which has been demonstrated to exhibit memory enhancement and neuroprotective

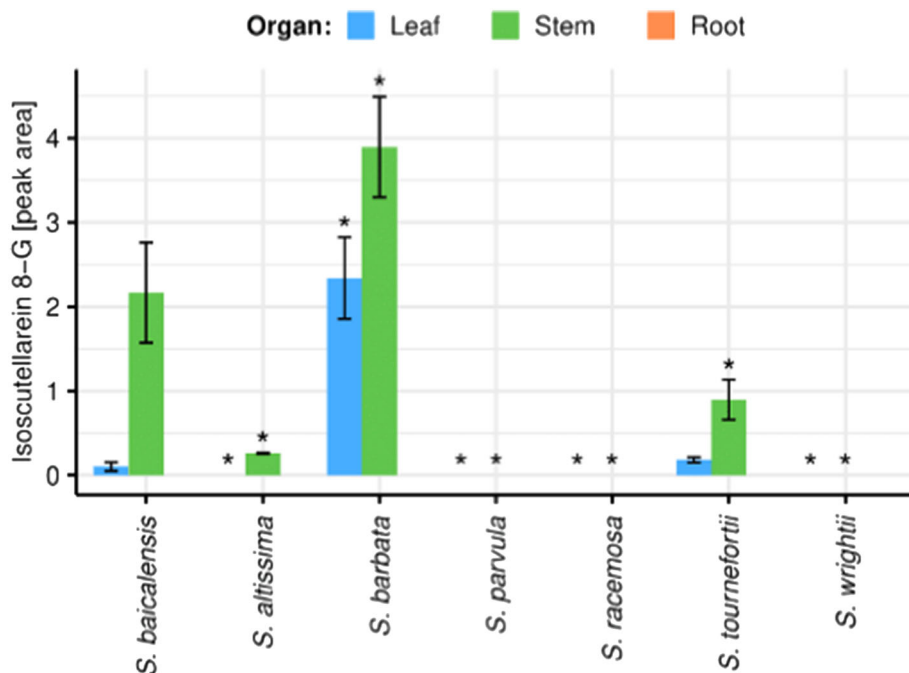


FIGURE 6 Organ-specific isoscutellarein 8-glucuronide peak areas in seven *Scutellaria* species, as determined via High Performance Liquid Chromatography (HPLC). Peak areas were averaged from tissue samples taken from three biological replicates, and error bars represent standard error. Asterisk (*) indicates p value $< .05$ relative to *S. baicalensis* for the same organ and flavone

effects in rat models (Jeon et al., 2011, 2012). The most likely route for oroxylin A biosynthesis is the methylation of baicalein at its 6-OH group (Figure 1) (Elkin et al., 2018). Although previous works have identified a variety of *O*-methyltransferases (OMTs) in plants, the enzymes with high specificity for the 6-OH group in flavonoids are rare, as this reaction is biochemically unfavorable (Zhang et al., 2016). Work in sweet basil (*Ocimum basilicum*), a species also in the Lamiaceae family with *Scutellaria*, identified a methyltransferase capable of specific methylation of the 6-OH group of scutellarein (Berim et al., 2012). Scutellarein is a 4'-hydroxyflavone identical in structure to baicalein apart from its 4'-OH group. To ensure the proper orientation of its substrate, and thus its regioselectivity, the *O. basilicum* OMT uses a threonine residue to form a hydrogen bond with the 4'-OH group of scutellarein. However, as baicalein has no 4'-OH group, it would be impossible for a regioselective OMT in *S. racemosa* or *S. wrightii* to rely on this interaction during the methylation of baicalein. Research by Zhang et al. (2016) in a liverwort species (*Plagiochasma appendiculatum*) identified a methyltransferase (PaF6OMT) that is capable of methylation of the 6-OH group in baicalein. As this OMT has not yet been structurally characterized, how it achieves its specificity remains unknown. Future work in *S. racemosa* and *S. wrightii* should be directed towards characterizing its biosynthesis of oroxylin A, with specific attention paid to the potential specialization of OMTs in the pathway. Overall, *S. racemosa* and *S. wrightii* are promising targets for biotechnology improvement due to the significant bioactive effects of oroxylin A and oroxyloside. Considering that both species occur in warm area (Texas and South America) (Krings & Neal, 2001; Nelson & Goetze, 2010), accumulation of oroxylin A and oroxyloside in these species may indicate the physiological relevance of oroxylin A and oroxyloside in these species.

Isoscutellarein 8-G was first detected in the liverwort species *Marchantia berteroana* (Markham & Porter, 1975). Following this initial report, Miyaichi, Imoto, et al. (1988) and Miyaichi, Kizu, et al. (1988) detected the flavone in the aerial parts of *S. indica* and *S. baicalensis*. Aside from these works, few other studies have reported isoscutellarein 8-G in *Scutellaria*, though several have detected its aglycone and 7-O-glycosylated forms (Karimov & Botirov, 2017). This rarity in detection may be a result of its low abundance relative to other glycosylated flavones in *Scutellaria*. A potential reason for this low abundance is its unique glycosylation at the 8-O position. Flavone 7-O glycosylation is more common in *Scutellaria* due to the presence of a hydroxyl group at the 7-O position in all flavones synthesized via the core flavone pathway (Figure 1). On the other hand, 8-O glycosylation first requires the activity of an 8-hydroxylase to add the free hydroxyl group to which the carbohydrate will be attached. As the purpose of glycosylation is typically to increase the stability of the flavone for long term storage (Slámová et al., 2018), it is possible that 8-O glycosylation provides slightly greater stability as compared to 7-O glycosylation. Therefore, it would be preferable to glycosylate isoscutellarein at the 8-O position, even though a free hydroxyl group is also present at the 7-O position. Several species may have evolved regioselective glycosyltransferase enzymes for this purpose. Researchers working with a glycosyltransferase from *Bacillus cereus* demonstrated that a single amino acid substitution could alter the primary site of quercetin glycosylation with high specificity (Chiu et al., 2016). Perhaps, a similar mutation occurs in several *Scutellaria* species to allow the biosynthesis of isoscutellarein 8-G. Alternatively, it is possible that the glycosyltransferase enzymes of these species which accumulate isoscutellarein 8-G have less strict regioselectivity, and are capable of glycosylation at both 7-G and 8-G positions. Quantification of isoscutellarein 7-G alongside isoscutellarein 8-G would



provide valuable insight regarding these theories. Based on current understanding of flavone biosynthesis, we propose a possible route of isoscutellarein and isoscutellarein 8-G production from apigenin (Figure S7). Further organ-specific transcriptome study is required to identify enzymes responsible for of isoscutellarein and isoscutellarein 8-G production.

Our quantification of isoscutellarein 8-G across the seven *Scutellaria* species we analyzed revealed an intriguing pattern. Isoscutellarein 8-G was entirely absent in the species of *S. parvula*, *S. racemosa*, and *S. wrightii*, all of which accumulate high concentrations of 4'-deoxyflavones such as oroxylin A and oroxyloside in their aerial parts. This specific example is representative of a broader pattern—species with high accumulation of 4'-deoxyflavones in their aerial parts accumulated low concentrations of 4'-hydroxyflavones. This substitution of 4'-hydroxyflavones with 4'-deoxyflavones potentially indicates an evolution to utilize 4'-deoxyflavones to fulfill the physiological roles which 4'-hydroxyflavones do in other species. Works in species outside of *Scutellaria* have demonstrated the anti-herbivory effects of several 4'-hydroxyflavones we quantified here (Gallon et al., 2019; Sosa et al., 2004). However, little is known about the physiological role that 4'-deoxyflavones play in plants. Further research should be devoted to exploring the role of 4'-deoxyflavones in plant growth and stress response to better understand the evolutionary advantage their biosynthesis and accumulation offers.

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AUTHOR CONTRIBUTIONS

B.C.A., Y.D., and J.K. designed the research project; B.C.A., D.L., G.M. R, and Y.S. performed the experiments and analyzed the data; B.C.A., Y.D., and J.K. wrote the manuscript.

CONFLICT OF INTEREST

The authors declare no competing interest.

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SUPPORTING INFORMATION

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