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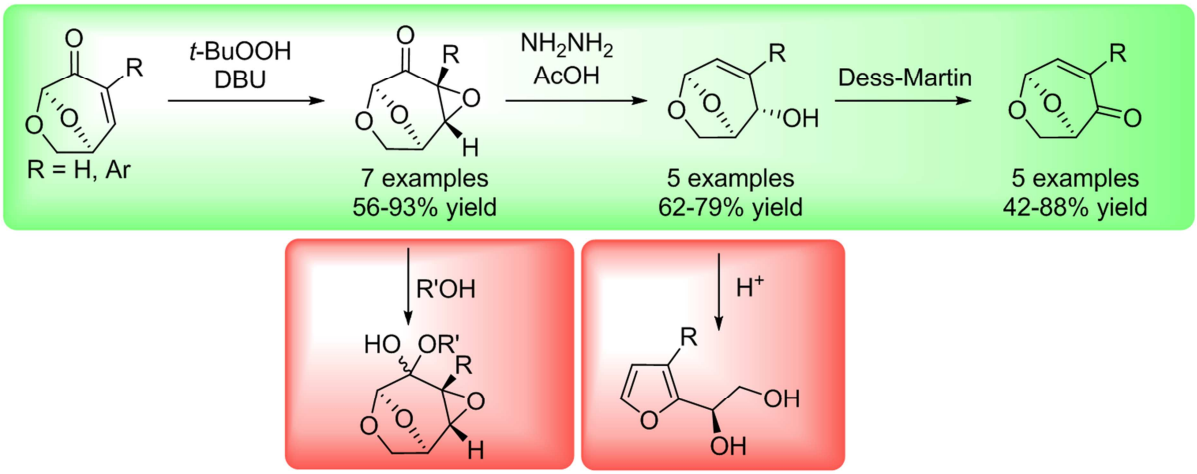

Diastereoselective Weitz-Scheffer Epoxidation of Levoglucosenone for the Synthesis of Isolevoglucosenone and Derivatives

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Abstract

High-yielding epoxidation conditions for the cellulose pyrolysis product (−)-levoglucosenone (LGO) and 3-aryl derivatives of LGO have been developed. The reaction of LGO with hydrogen peroxide/base is known to give a Baeyer-Villiger reaction, however, it was found that the reactions of LGO or derivatives with *tert*-butylhydroperoxide/base affords solely epoxides through the Weitz-Scheffer reaction. A critical parameter in the successful isolation of the epoxide from LGO was to avoid all contact with water or alcohols during and after the reaction. The epoxide products were reacted under Wharton conditions affording allylic alcohols and subsequent oxidation led to isolevoglucosenone or 3-arylisolevoglucosenone derivatives. Previously unreported reactions on isolevoglucosenone were then investigated.

Keywords: Levoglucosenone, epoxide, diastereoselective, hydroperoxide, isolevoglucosenone

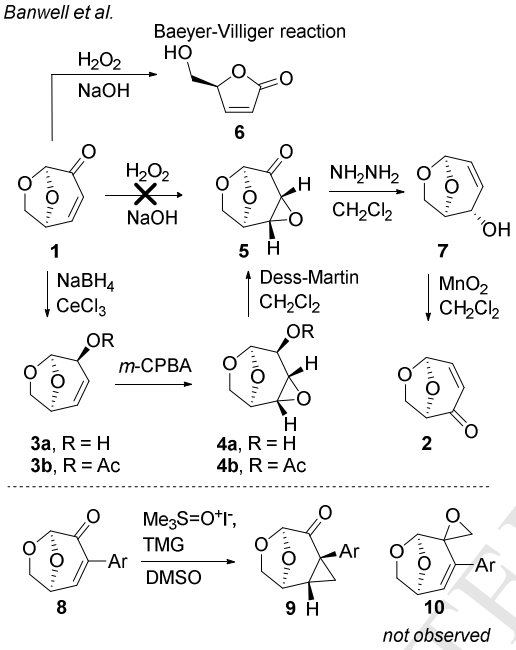
1. Introduction

The cellulose pyrolysis product (−)-levoglucosenone (**1**) has generated interest as a chiral synthon due to its selective formation under acidic conditions and as non-food biomass is used in its production.[1,2,3] It has been used to synthesize chiral materials including catalysts,[4] ligands[5] and auxiliaries,[6] intermediates for the production of pharmaceuticals,[7] and has been used as a scaffold for drug discovery.[8] The high degree of functionality in **1** has allowed for the development of a large set of transformations generating diverse structures. In particular, oxidation chemistry involving the alkene in **1** can be used to produce rare carbohydrates.[9]

Recent reports from the Banwell group have explored epoxidation and allylic transposition reactions on **1** (Scheme 1).[10] The group have used the Wharton reaction as the key step leading to isolevoglucosenone (**2**), a compound which has been investigated by a number of groups,[11] and once readily available may find new applications in synthesis. The authors reported that the attempted Weitz-Scheffer epoxidation of **1** using hydrogen peroxide to give **5** resulted in a Baeyer-Villiger reaction affording **6**, which matches results in our group, and is consistent with recent reports on the Baeyer-Villiger oxidation of **1** using hydrogen peroxide in water.[12] Success in this reaction would have led to an efficient three-step synthesis of the transposition product **2**. The synthesis of α-ketoepoxide **5** was instead achieved by reducing the ketone in **1** to alcohol **3a**, protection as the acetate **3b**, diastereoselective epoxidation affording **4b**, deprotection and subsequent oxidation of alcohol **4a**.[10] The process could be carried out without protection, however the epoxidation was not diastereoselective. Recently, we reported a series of aryl substituted derivatives **8** which were prepared from **1** via Suzuki chemistry.[13] These compounds underwent Johnson-Corey-Chaykovsky cyclopropanation via 1,4-addition of a sulfoxonium ylide and none of the competing epoxidation via 1,2-addition was observed (Scheme 1).[13a] The selectivity observed for the 1,4-addition suggested that these derivatives might also serve as Weitz-Scheffer

epoxidation substrates, and could be used to prepare 3-arylisolevoglucosenone derivatives in a concise manner using Banwell's approach.[10] An investigation into this chemistry has identified Weitz-Scheffer epoxidation conditions compatible with **1** and 3-aryl derivatives **8**, and subsequently, Wharton chemistry has been used for the production of isolevoglucosenone **2** and derivatives.

Scheme 1



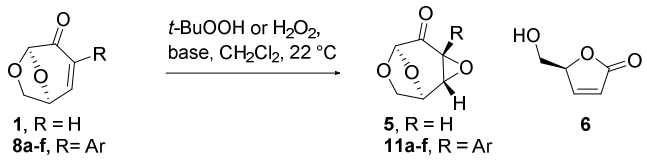
2. Results and Discussion

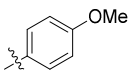
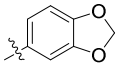
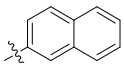
2.1 Weitz-Scheffer epoxidation of levoglucosenone

A series of reactions was performed on **1** to determine whether the Weitz-Scheffer epoxidation could be achieved using literature variants and representative results are presented in Table 1. The reaction of aqueous hydrogen peroxide with **1** using catalytic base afforded the butenolide **6** as expected and no epoxidation product **5** was observed. The epoxidation of isolevoglucosenone can be carried out using H_2O_2 and NaOH, and derivatives have been epoxidised using *tert*-butylhydroperoxide (TBHP) with DBU, a reagent combination known for its selectivity in the epoxidation of cyclic α,β-unsaturated

ketones.[14] Furthermore, kinetic isotope studies of the epoxidation of cyclohex-2-en-1-one have shown that axial approach of the *tert*-butylhydroperoxide nucleophile is favored, which matches nucleophilic additions to the ring-locked conformation of **1**.[15] Switching the oxidant to 70% aqueous TBHP, an encouraging 23% yield of epoxide **5** was obtained without evidence of Baeyer-Villiger reaction. The remaining material was mostly unreacted **1**, and a mixture of epoxides where the ketone had hydrated or formed hemiacetals. These hemiacetals did not revert to ketone with attempted drying by coevaporation with toluene. An improved 82% yield of **5** was obtained using anhydrous TBHP combined with DBU. In the reaction, hemiacetal and hydrate formation was avoided by omitting an aqueous workup, and instead using catalytic 10% Pd/C to decompose residual hydroperoxide and avoiding all contact of solutions of **5** with water or alcohols. The base had a small influence and it was found that DBU was superior to NEt_3 in the epoxidation reaction under the anhydrous reaction conditions. Both possible epoxide diastereomers from the reaction are known and so the diastereoselectivity of the reaction could be readily investigated. There was no evidence in the ^{1}H NMR spectra of the crude materials of the other diasteromer, presumably due to the high facial selectivity of 1,4-additions to **1**. These results are significant when considering the production of isomer **2** from **1**. The direct epoxidation of **1** removes the need for the reduction/protection/oxidation steps on the carbonyl, which although high yielding, add considerable time and handling to the published route to **2**.

Table 1. Epoxidation of **1** and aryl derivatives **8a-f**.



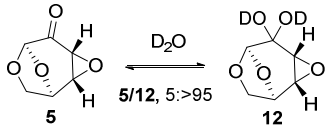
Entry[a]	R	Peroxide (equiv)[b]	Base (equiv)	t (hr)	Product	Yield, (conv.)[c]
1	H	27% H_2O_2 (1.0)	KOH (0.4)	4	**6**	(24)[d]
2	H	*m*-CPBA (1.5)	-	16	**5**	-
3	H	70% TBHP (1.0)	-	15	**5**	-
4	H	70% TBHP (1.0)	KOH (0.1)	24	**5**	(3)
5	H	70% TBHP (1.0)	KOH (1.0)	21	**5**	(23)
6	H	70% TBHP (1.0)	K_2CO_3 (1.0)	16	**5**	(25)
7	H	70% TBHP (2.0)	DBU (1.2)	16	**5**	20
8	H	Anhyd. TBHP (1.1)	DBU (0.2)	16	**5**	82[e]
9	H	Anhyd. TBHP (1.0)	Et_3N (1.0)	16	**5**	(44)[d]
10	H	Anhyd. TBHP (1.0)	TMG (1.0)	16	**5**	74
11	Ph	Anhyd. TBHP (1.5)	DBU (0.2)	3	**11a**	84
12	Ph	70% TBHP (1.1)	KOH (0.4)	3	**11a**	93[f]
13		70% TBHP (1.1)	KOH (0.4)	3	**11b**	84
14		70% TBHP (1.1)	KOH (0.4)	2	**11c**	84
15		70% TBHP (1.1)	KOH (0.4)	2	**11d**	56
16		70% TBHP (1.1)	KOH (0.4)	2	**11e**	31
17		Anhyd. TBHP (1.0)	DBU (0.2)	2	**11e**	79
18	9-Phenanthryl	70% TBHP (1.1)	KOH (0.4)	2	**11f**	93

[a] Reactions performed using **1** (1.0-2.0 mmol) in CH_2Cl_2 (10 mL) at 25 °C. [b] 70% TBHP (*tert*-butylhydroperoxide) solution was in water and anhydrous TBHP was prepared by drying a CH_2Cl_2 solution with anhydrous $MgSO_4$.[c] Isolated yield, percentage conversion determined by ^{1}H NMR relative to unreacted **1**. [d] Remaining material mainly unreacted **1**. [e] 40 mmol scale. [f] 5.0 mmol scale.

The observation of hydration products using aqueous *tert*-butyl hydroperoxide needed confirmation although hydration in this ring-system is well known.[16] The NMR spectra of **5** in D_2O, $CDCl_3$ and d_6-acetone provided conclusive evidence that hydration occurs. Notable

among the changes in the D_2O spectra, the ^{13}C spectrum lacked the carbonyl resonance at δ 192 ppm seen in $CDCl_3$ and had a resonance at δ 88.9 ppm assigned to the ketone hydrate **12** (Scheme 2). The addition of a drop of D_2O to a solution of **5** in $CDCl_3$ immediately resulted in a complex ^1H NMR spectra, containing ketone, hydrate and possibly hemiacetal dimers or oligomers. Hydration of **5** in a d_6-acetone solution in a capped NMR tube was also nearly complete over 8 hours (see Electronic Supporting Information).

Scheme 2



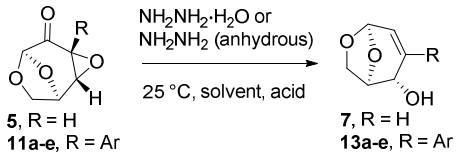
With the success achieved in the epoxidation of **1**, and the lack of the Baeyer-Villiger reaction using TBHP as oxidant, the epoxidations of other aryl derivatives **8a-f** were examined. The epoxidations of electron rich aryl derivatives **8a-d,f** were more tolerant to water and aqueous TBHP using KOH as base afforded excellent yields of the epoxides **11a-d,f**. In all cases, a single stereoisomer was observed due to the facial selectivity enforced by the steric hindrance of the oxymethylene bridge. In the case of the fluoro-substituted **8e**, aqueous TBHP resulted in the formation of hemiacetals which were difficult to separate from the desired product. Substituting the aqueous conditions with anhydrous TBHP gave a good yield of the desired product **11e**, indicating that substrates with electron poor aryl substituents may form hydrates similar to the unsubstituted product **5**.

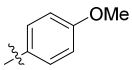
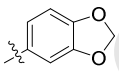
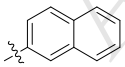
2.2 Wharton reactions of epoxides

With efficient methods developed allowing for the scalable synthesis of epoxide **5** and aryl substituted epoxides **11a-e**, the Wharton reactions could be examined (Table 2). The reactions were mainly performed in acetonitrile, and methanol was avoided due to the

potential formation of hemiacetals. The rearrangement reaction of **5** with anhydrous hydrazine/acetic acid has been reported by Banwell and coworkers and our result of 67% yield starting with **5** mirrored those of the previous report. All attempts at improving the yield using base promoted Wharton conditions failed and only trace amounts of allylic alcohol **7** were obtained. In the case of unsubstituted epoxide **5**, the use of hydrazine hydrate afforded less of the desired rearrangement product, possibly due to the susceptibility of the carbonyl to hydration. An acceptable yield of **13a** was obtained using phenyl substituted epoxide **8a** with hydrazine hydrate (entry 11), and anhydrous conditions slightly improved yields in this reaction (entry 10). The electron-rich substrates **11b,c** and the electron-poor substrate **11e** both afforded good yields of the allylic alcohol products **13b,c** and **13e**.

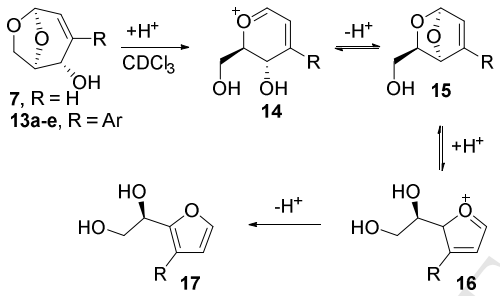
Table 2. Wharton reactions on epoxide **5** and aryl derivatives **11a-e**.



entry	R	NH_2NH_2 (equiv)	Acid (equiv)	Solvent	t (hrs)	Product	Yield (%)
1	H	anhyd. (4.0)	AcOH (5.0)	MeOH	2	**7**	*Lit* 45
2	H	anhyd. (2.0)	AcOH (0.2)	MeCN	5	**7**	31
3	H	hydrate (2.0)	AcOH (0.2)	MeCN	5	**7**	<5
4	H	anhyd. (2.0)	AcOH (2.0)	MeCN	2	**7**	67
5	H	anhyd. (2.0)	AcOH (2.0)	CH_2Cl_2	2	**7**	26
6	H	anhyd. (2.0)	TFA (2.0)	MeCN	2	**7**	17
7	H	hydrate (2.0)	AcOH (2.0)	MeCN	2	**7**	<5
8	Ph	anhyd. (1.1)	AcOH (1.1)	MeOH	2	**13a**	41
9	Ph	anhyd. (2.0)	AcOH (2.0)	MeOH	3	**13a**	51
10	Ph	anhyd. (2.0)	AcOH (2.0)	MeCN	2	**13a**	79
11	Ph	hydrate (2.0)	AcOH (2.0)	MeOH	2	**13a**	65
12		anhyd. (2.0)	AcOH (2.0)	MeCN	2	**13b**	64
13		anhyd. (2.0)	AcOH (2.0)	MeCN	2	**13c**	62
14		hydrate (2.0)	AcOH (2.0)	MeCN	2	**13d**	<5
15		anhyd. (2.0)	AcOH (2.0)	MeCN	2	**13e**	68

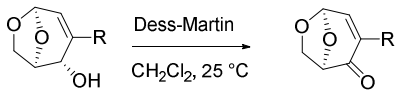
The allylic alcohol products **7** and **13a-e** formed in the Wharton reaction were acid sensitive and underwent rearrangement in $CDCl_3$ (Scheme 3). Near quantitative conversion to furan **17** (R = H)[17] was observed after 8 days, presumably promoted by traces of acid in the solvent. Allylic alcohols **13a-e** with aryl substituents were more stable, taking up to 3 weeks for most of the allylic alcohol to react at ambient temperature. A plausible mechanism for the formation of **17** involves a series of stabilized oxocarbenium ions, with acid-catalyzed ring-opening of the acetal centre in **7** or **13** giving the delocalized oxocarbenium ion **14**, which is then trapped as the intermediate 5,7-dioxabicyclo[2.2.1]hept-2-ene system **15**. Further ring-opening through **16** and aromatisation gives the observed diols.

Scheme 3



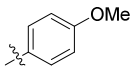
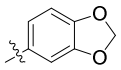
The oxidation of allylic alcohol **7** to isolevoglucosenone (**2**) has been reported using activated MnO_2 in CH_2Cl_2.[10b] In our hands, improved reliability of the oxidation was obtained using Dess-Martin periodinane (DMP). The oxidation of **7** with DMP afforded isolevoglucosenone (**2**) and likewise, oxidation of the 3-substituted derivatives **13a-c,e** gave **18a-c,e** in moderate to excellent yield (Table 3). Starting with **1**, the three-step process gave an overall yield of **2** of 43%, while phenyl substituted **18a** was obtained in 65% yield for the three steps starting with **8a**, which can be obtained from **1** in excellent yield.[13b]

Table 3. The oxidation of allylic alcohols **7** and **13**.



7, R = H
13a-c,e, R = Ar

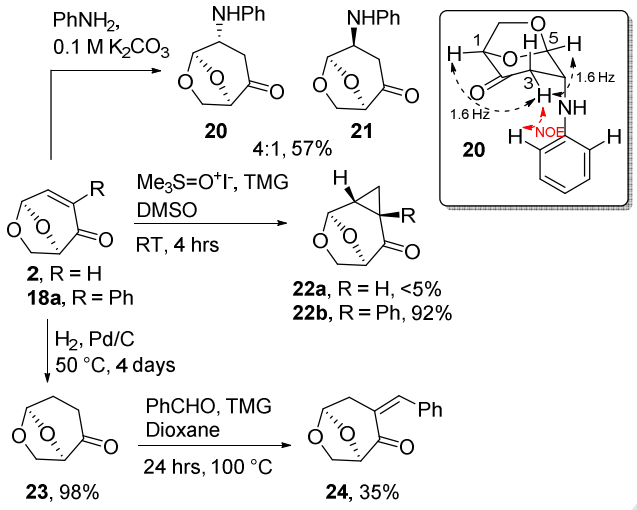
2, R = H
18a-c,e, R = Ar

entry	R	product	yield
1	H	**2**	78
2	Ph	**18a**	88
3		**18b**	64
4		**18c**	42
5		**18e**	52

As gram scale quantities of **2** and **18e** were available, several reactions that could generate novel chiral derivatives were performed (Scheme 4). Aza-Michael addition of aniline to **2** proceeded to give mainly *exo*-addition product **20** and some of the epimer **21** in moderate yield. The stereochemistry was assigned on the basis of coupling constants and NOESY interactions in the major isomer **20**. The equatorial H-3α proton at δ 2.55 ppm had ^4J W-path couplings to H-1 and H-5 and had interactions with the *ortho*-protons on the aromatic ring in the 2D NOESY NMR spectrum. Attempted cyclopropanation of **2** using the Corey-Chaykovsky sulfoxonium ylide[18] with 1,1,3,3-tetramethylguanidine (TMG) gave virtually none of the cyclopropane product **22a**, however, aryl substituted **18a** afforded an excellent yield of a single diastereomer **22b**. The outcomes from the aza-Michael and cyclopropanation reactions agreed with the preferred stereochemical outcome of additions to **2**.[19] The hydrogenation of **2** to give the known dihydrolevoglucosenone **23**[16c] proceeded in near quantitative yield and subsequent reaction with benzaldehyde and TMG afforded the *Z*-aldol condensation product **24**. The alkene geometry was assigned on the basis of crosspeaks

between the vinylic CH and the methylene adjacent to the double bond in the NOESY NMR spectrum. The outcome of this reaction differs to the reaction of the *pseudo*-enantiomer dihydrolevoglucosenone, which affords the *E*-aldol condensation products.[7b, 20]

Scheme 4.



The results presented here provide a method for the direct epoxidation of **1** and some 3-aryl derivatives **8** and their subsequent conversion to substituted isolevoglucosenone derivatives. Levoglucosenone (**1**) is emerging as a versatile starting material in synthesis and this single step, scalable and high yielding synthesis of the epoxide derivative **5** is an important addition to its known reactivity. The exploration of ring-opening reactions of **5** for the preparation of carbohydrate derivatives, and some further transformations on **2** are currently underway.

3. Experimental

3.1 General Experimental

Solvents were dried using literature procedures. ^{1}H NMR spectra recorded in $CDCl_3$ were recorded at 298 K referenced to TMS (δ_H 0 ppm) and ^{13}C NMR spectra were referenced to residual solvent (δ_C 77.0 ppm). ^{1}H and ^{13}C NMR spectra in D_2O were referenced to the internal reference 1,4-dioxane (δ_H 3.75 ppm, δ_H 67.19 ppm). ^{1}H NMR spectra in d_6-acetone

were referenced to residual solvent (δ_H 2.05 ppm). MS were recorded using an *Agilent* 6120 Quadrupole detector. Melting points are uncorrected. HRMS were recorded in positive ESI V mode (source temperature 80 °C, desolvation temperature 150 °C, capillary 2.5 kV). HRMS were recorded on an AB SCIEX 5600 Triple-TOF mass spectrometer. Aryl derivatives **8a-e** were prepared as previously described.[13]

3.2 General procedure for Epoxidation Reactions. Anhydrous *tert*-butylhydroperoxide (TBHP) solution was prepared by adding 70% TBHP in water (1.00 mL) to CH_2Cl_2 (20 mL), standing over anhydrous $MgSO_4$ (~2 grams) for 15 minutes and then decanting the solution. The anhydrous TBHP solution (1.1 eq) was added to a stirred solution of α,β-unsaturated ketone (1.59 - 39.6 mmol) in CH_2Cl_2 (total volume specified below). Alternatively, 70% aqueous TBHP (1.1 eq) was added to the solution of α,β-unsaturated ketone without drying. The solution was cooled via ice bath to 0 °C and then DBU (0.2 eq) or KOH (0.4 eq) was added and the mixture allowed to warm to room temperature over 2-3 hrs and stirring continued as set out in Table 1. When no starting material remained by TLC, the reaction was quenched by the addition of 10% Pd/C (25 mg), the mixture stirred until the evolution of oxygen ceased and a negative test for peroxide was obtained (starch/iodide paper). The solution was then concentrated under reduced pressure and purified as specified below.

(1*R*,2*R*,4*R*,6*R*)-3,7,9-Trioxatricyclo[4.2.1.0^{2,4}]nonan-5-one (5).[11c] The reaction of anhydrous TBHP prepared from 70% aqueous TBHP (6.00 mL, 43.3 mmol) with **1** (5.00 g, 39.6 mmol) in CH_2Cl_2 (200 mL) and DBU (1.18 mL, 7.91 mmol) was performed according to the general procedure. Purification by flash chromatography (1:4 MeCN/EtOAc) afforded **5** as colorless crystals (4.59 g, 82%); R_f (1:4 MeCN/EtOAc) 0.50; ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.18 (d, *J* = 1.8 Hz, 1H, H-6), 5.00 (br dd, *J* = 4.8, 1.9 Hz, 1H, H-1), 4.04 (dd, *J* =

7.4, 0.6 Hz, 1H, H-8β), 3.90 (dd, *J* = 7.4, 4.8 Hz, 1H, H-8α), 3.52 (dd, *J* = 3.7, 1.8 Hz, 1H, H-4), 3.31 (ddd, *J* = 3.7, 1.9, 0.6 Hz, 1H, H-2); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.1 (C-5), 99.8 (C-6), 70.2 (C-1), 65.1 (C-8), 49.9 (C-2), 49.1 (C-4). **(1*R*,2*R*,4*R*,6*R*)-3,7,9-Trioxatricyclo[4.2.1.0^{2,4}]nonane-5,5-diol (12).** ^{1}H NMR (500 MHz, D_2O) δ 5.00 (br d, *J* = 2.5 Hz, 1H, H-6), 4.89 (ddd, *J* = 4.6, 1.6, 0.6 Hz, 1H, H-1), 4.08 (d, *J* = 7.9 Hz, 1H, H-8β), 3.84 (dd, *J* = 7.9, 4.6 Hz, 1H, H-8α), 3.47 (dd, *J* = 4.3, 1.6 Hz, 1H, H-2), 3.18 (ddd, *J* = 4.3, 2.5, 0.6 Hz, 1H, H-4); ^{13}C NMR (125 MHz, D_2O) δ 101.6 (C-6), 88.9 (C-5), 70.4 (C-1), 67.1 (C-8), 53.1 (C-4), 50.5 (C-2).

(1*S*,5*R*)-3-(Phenanthren-9-yl)-6,8-dioxabicyclo[3.2.1]oct-2-en-4-one (8f). 3-Iodolevoglucosenone[13b] (1.5 g, 5.95 mmol), 9-phenanthrylboronic acid (1.98 g, 8.92 mmol), K_3PO_4 (2.53 g, 11.92 mmol), SPhos (49 mg, 0.12 mmol) and $Pd(OAc)_2$ (14 mg, 0.06 mmol) were combined in toluene (15 mL) and refluxed at 110 °C for 45 min in a microwave reactor. The mixture was diluted with H_2O (20 mL), extracted with DCM (30 mL x 3) and the organic phase concentrated. The organic residue was isolated via flash chromatography (1:1 EtOAc:hexanes) then recrystallized from EtOH to afford the product as colorless crystals (1.39 g, 77%); R_f (1:1 EtOAc:hexanes) 0.89; mp 163-172 °C; $[\alpha]_D^{25}$ −168 (*c* 0.6, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.74-8.63 (m, 2H, ArH), 7.88-7.83 (m, 1H, ArH), 7.70-7.53 (m, 6H, ArH), 7.30 (d, *J* = 4.8 Hz, 1H, H-2), 5.61 (s, 1H, H-5), 5.20 (dd, *J* = 4.8, 4.8 Hz, 1H, H-1), 4.10-3.98 (m, 2H, H-7); ^{13}C NMR (125 MHz, $CDCl_3$) δ 188.2 (C-4), 146.1 (C-2), 138.6 (C-3), 131.2 (ArC), 130.7 (ArC), 130.62 (ArC), 130.58 (ArC), 130.4 (ArC), 128.9 (ArC), 128.2 (ArC), 127.3 (ArC), 127.0 (ArC), 126.91 (ArC), 126.89 (ArC), 126.0 (ArC), 123.1 (ArC), 122.7 (ArC), 101.9 (C-5), 72.6 (C-1), 67.0 (C-7); FT-IR (neat) 3062, 2963, 2899, 1699, 1492, 1449, 1351, 1292, 1239, 1106, 1069, 1041, 1003, 748 cm^{-1}; MS (ESI) *m/z* 325.0 $[M+Na]^+$; HRMS (ESI) calc. for $C_{20}H_{14}O_3Na$ $[M + H]^+$, 325.0841; found 325.0839.

(1*R*,2*R*,4*R*,6*R*)-4-Phenyl-3,7,9-trioxatricyclo[4.2.1.0^{2,4}]nonan-5-one (11a). The reaction of 70% aqueous TBHP (0.75 mL, 5.5 mmol) with α,β-unsaturated ketone **8a** (1.00 g, 5.0 mmol) and KOH (0.11 g, 2.0 mmol) in CH_2Cl_2 (12 mL) was performed as per the general procedure. The crude product was purified by flash chromatography (2:3 EtOAc/hexanes) then recrystallized from EtOH to afford the epoxide as colorless crystals (1.01 g, 93%); R_f (2:3 EtOAc/hexanes) 0.60; mp 139-141 °C (EtOH); $[\alpha]_D^{24}$ −22 (*c* 0.78, $CHCl_3$); FT-IR (neat) 1736, 1496, 1485, 1447, 1410, 1335, 1253, 1124, 1096, 1075, 1022 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.39-7.36 (m, 3H, ArH), 7.33-7.30 (m, 2H, ArH), 5.31 (s, 1H, H-6), 5.05 (dd, *J* = 4.6, 1.9 Hz, 1H, H-1), 4.14 (d, *J* = 7.5 Hz, 1H, H-8β), 3.94 (dd, *J* = 7.5, 4.6 Hz, 1H, H-8α), 3.39 (d, *J* = 1.9 Hz, 1H, H-2); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.3 (C-5), 131.7 (ArC), 128.9 (ArC), 128.5 (ArC), 126.5 (ArC), 99.8 (C-6), 70.8 (C-1), 65.5 (C-8), 58.5 (C-4), 58.1 (C-2); MS (EI) *m/z* = 218.1 (M^+, trace), 162.1 (43%), 145.1 (47), 133.1 (46), 115.1 (52), 106.1 (28), 105.1 (100), 89.1 (35), 77.1 (85), 63.1 (26), 51.1 (35); HRMS (ESI) calc. for $C_{12}H_9O_4$ $[M - H]^-$, 217.0501; found 217.0497.

(1*R*,2*R*,4*R*,6*R*)-4-(4-Methoxyphenyl)-3,7,9-trioxatricyclo[4.2.1.0^{2,4}]nonan-5-one (11b). The reaction of 70% aqueous TBHP (0.389 mL, 2.84 mmol) with α,β-unsaturated ketone **8b** (600 mg, 2.58 mmol) and KOH (58 mg, 1.03 mmol) in CH_2Cl_2 (10 mL) was performed as per the general procedure. The crude product was purified by flash chromatography (1:1 EtOAc/hexanes) to afford the epoxide as colorless crystals (539 mg, 84%); R_f (1:1 EtOAc/hexanes) 0.74; mp 144-146 °C; $[\alpha]_D^{23}$ −31 (*c* 0.16, $CHCl_3$); FT-IR (neat) 2973, 1736, 1609, 1510, 1244, 1185, 1127, 1096, 1016, 978, 922 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.26-7.23 (m, 2H, ArH), 6.92-6.89 (m, 2H, ArH), 5.30 (s, 1H, H-6), 5.05 (dd, *J* = 4.5, 2.0 Hz,

1H, H-1), 4.13 (d, *J* = 7.5 Hz, 1H, H-8β), 3.94 (dd, *J* = 7.5, 4.5 Hz, 1H, H-8α), 3.81 (s, 3H, OC$\underline{H}_3$), 3.39 (d, *J* = 2.0 Hz, 1H, H-2); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.6 (C-5), 160.1 (ArC), 128.0 (ArC), 123.6 (ArC), 113.9 (ArC), 99.8 (C-6), 70.8 (C-1), 65.5 (C-8), 58.4 (C-4), 58.1 (C-2), 55.3 (OCH_3); MS (EI) *m/z* = 248.0 (M^+, 19%), 202 (25), 175.1 (29), 174 (34), 163.1 (33), 159.1 (55), 147.1 (31), 145.1 (31), 135 (100), 115 (23), 77 (36); HRMS (ESI) calc. for $C_{13}H_{11}O_5$ $[M - H]^-$, 247.0606; found 247.0601.

(1*R*,2*R*,4*R*,6*R*)-4-(Benzo[*d*][1,3]dioxol-5-yl)-3,7,9-trioxatricyclo[4.2.1.0^{2,4}]nonan-5-one (11c). The reaction of anhydrous TBHP prepared from 70% aqueous TBHP (0.15 mL, 1.07 mmol), α,β-unsaturated ketone **8c** (0.240 g, 0.97 mmol) and DBU (29 µL, 0.19 mmol) in CH_2Cl_2 (10 mL) was performed as per the general procedure. The crude product was purified by flash chromatography (1:1 EtOAc/hexanes) then recrstallized from EtOH to afford the epoxide as a light yellow wax (0.215 g, 84%); R_f (1:1 EtOAc/hexanes) 0.70; $[\alpha]_D^{22}$ −10 (*c* 0.50, $CHCl_3$); FT-IR (neat) 3479, 1971, 2902, 1738, 1609, 1504, 1491, 1445, 1408, 1354, 1300, 1233, 1123, 1097, 1035 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.80-6.79 (m, 3H, ArH), 5.97 (s, 2H, OCH_2O), 5.29 (s, 1H, H-6), 5.04 (dd, *J* = 4.5, 1.9 Hz, 1H, H-1), 4.12 (d, *J* = 7.4 Hz, 1H, H-8β), 3.94 (dd, *J* = 7.4, 4.5 Hz, 1H, H-8α), 3.37 (d, *J* = 1.9 Hz, 1H, H-2); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.3 (C-5), 148.2 (ArC), 147.8 (ArC), 125.3 (ArC), 120.5 (ArC), 108.3 (ArC), 107.2 (ArC), 101.3 (OCH_2O), 99.7 (C-6), 70.8 (C-1), 65.5 (C-8), 58.5 (C-4), 58.0 (C-2); MS (EI) *m/z* = 262 (M^+, 42%), 188 (61), 173 (40), 159 (35), 149 (100), 147 (40), 131 (37), 121 (28), 103 (32), 63 (26); No molecular ion observed by ESI-HRMS.

(1*R*,2*R*,4*R*,6*R*)-4-(Naphthalen-2-yl)-3,7,9-trioxatricyclo[4.2.1.0^{2,4}]nonan-5-one (11d). The reaction of 70% aqueous TBHP (0.600 mL, 4.38 mmol), α,β-unsaturated ketone **8d** (1.0 g,

3.96 mmol) and KOH (90 mg, 1.58 mmol) in CH_2Cl_2 (20 mL) was performed as per the general procedure. The crude product was purified by flash chromatography (2:3 EtOAc/hexanes) to afford the epoxide as colorless crystals (0.596, 56%); R_f (2:3 EtOAc/hexanes) 0.60; mp 191-193 °C; $[\alpha]_D^{25}$ −8 (*c* 0.62, $CHCl_3$); FT-IR (neat) 3064, 2974, 2910, 1736, 1602, 1505, 1481, 1411, 1338, 1284, 1130, 1099, 1061, 817, 746 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.85-7.81 (m, 4H, ArH), 7.52-7.48 (m, 2H, ArH), 7.36-7.34 (m, 1H, ArH), 5.36 (s, 1H, H-6), 5.08 (dd, *J* = 4.6, 1.9 Hz, 1H, H-1), 4.17 (d, *J* = 7.5 Hz, 1H, H-8β), 3.97 (dd, *J* = 7.5, 4.6 Hz, 1H, H-8α), 3.45 (d, *J* = 1.9 Hz, 1H, H-2); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.4 (C-5), 133.3 (ArC), 132.8 (ArC), 129.2 (ArC), 128.3 (ArC), 128.1 (ArC), 127.7 (ArC), 126.7 (ArC), 126.6 (ArC), 126.1 (ArC), 123.6 (ArC), 99.8 (C-6), 70.9 (C-1), 65.6 (C-8), 58.7 (C-4), 58.3 (C-2); MS (EI) *m/z* = 268.1 (M^+, 47%), 195.1 (38), 194.1 (32), 179.1 (25), 165.1 (47), 155.1 (100), 152.1 (33), 139.1 (36), 128.1 (31), 127.1 (91); HRMS (ESI) calc. for $C_{16}H_{11}O_4$ $[M - H]^-$, 267.0657; found 267.0654.

(1*R*,2*R*,4*R*,6*R*)-4-(2-Fluorophenyl)-3,7,9-trioxatricyclo[4.2.1.0^{2,4}]nonan-5-one (11e). The reaction of anhydrous TBHP prepared from 70% aqueous TBHP (0.483 mL, 3.52 mmol), α,β-unsaturated ketone **8e** (0.706 g, 3.21 mmol) and DBU (96 µL, 0.64 mmol) in CH_2Cl_2 (10 mL) was performed as per the general procedure. The crude product was purified by flash chromatography (2:3 EtOAc/hexanes) then recrystallized from *i*-Pr_2O to afford colorless crystals (0.600, 79%); R_f (2:3 EtOAc/hexanes) 0.50; mp 134-136 °C (*i*-Pr_2O); $[\alpha]_D^{26}$ −150 (*c* 0.44, $CHCl_3$); FT-IR (neat) 2968, 2910, 1744, 1618, 1582, 1491, 1451, 1404, 1334, 1259, 1213, 1172, 1124, 1104, 1093, 1056, 1024, 968, 822, 765 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.47-7.44 (m, 1H, ArH), 7.40-7.35 (m, 1H, ArH), 7.20-7.18 (m, 1H, ArH), 7.08-7.04 (m, 1H, ArH), 5.31 (s, 1H, H-6), 5.07 (br dd, *J* = 4.8, 1.9 Hz, 1H, H-1), 4.23 (d, *J* = 7.4 Hz, 1H, H-8β), 3.98 (dd, *J* = 7.4, 4.8 Hz, 1H, H-8α), 3.51 (d, *J* = 1.9 Hz, 1H, H-2); ^{13}C NMR (125

MHz, $CDCl_3$) δ 191.2 (C-5), 160.3 (d, J_{CF} = 247.6 Hz, ArC), 131.0 (d, J_{CF} = 8.1 Hz, ArC), 129.1 (d, J_{CF} = 2.8 Hz, ArC), 124.3 (d, J_{CF} = 3.5 Hz, ArC), 119.8 (d, J_{CF} = 15.0 Hz, ArC), 115.1 (d, J_{CF} = 20.3 Hz, ArC), 99.7 (C-6), 70.4 (C-1), 65.3 (C-8), 56.5 (C-2), 56.1 (C-4); MS (EI) *m/z* = 236.0 (M^+, trace), 163 (33%), 151.1 (22), 147.1 (48), 146.1 (24), 133 (42), 123 (100), 120 (19), 107 (17), 95 (30), 75 (15); HRMS (ESI) calc. for $C_{12}H_8O_4F$ $[M - H]^-$, 235.0407; found 235.0399.

(1*R*,2*R*,4*R*,6*R*)-4-(Phenanthren-9-yl)-3,7,9-trioxatricyclo[4.2.1.0^{2,4}]nonan-5-one (11f). The reaction of 70% aqueous TBHP (0.862 mL, 6.29 mmol), α,β-unsaturated ketone **8f** (1.73 g, 5.72 mmol) and KOH (0.128 g, 2.29 mmol) in CH_2Cl_2 (40 mL) was performed as per the general procedure. The crude product was purified by flash chromatography (2:3 EtOAc/hexanes) to afford the epoxide as a light brown wax (1.70 g, 93%); R_f (3:7 EtOAc/hexanes) 0.56; $[\alpha]_D^{17}$ −95 (*c* 0.21, $CHCl_3$); FT-IR (neat) 2964, 2921, 1784, 1736, 1450, 1340, 1249, 1209, 1127, 1098, 748 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 8.73 (d, *J* = 8.1 Hz, 1H, ArH), 8.67 (d, *J* = 8.2 Hz, 1H, ArH), 7.99 (br s, 1H, ArH), 7.91 (br m, 2H, ArH), 7.70-7.60 (m, 4H, ArH), 5.45 (br s, 1H, H-6), 5.18 (br d, *J* = 4.6 Hz, 1H, H-1), 4.42 (d, *J* = 7.7 Hz, 1H, H-8β), 4.11 (dd, *J* = 7.7, 4.6 Hz, 1H, H-8α), 3.54 (br s, 1H, H-2); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.5 (C-5), 130.9 (ArC), 130.7 (ArC), 130.3 (ArC), 129.3 (ArC), 129.1 (ArC), 127.5 (ArC), 127.3 (ArC), 127.2 (ArC), 127.15 (ArC), 127.0 (ArC), 126.8 (ArC), 123.5 (ArC), 123.4 (ArC), 122.5 (ArC), 100.1 (C-6), 70.9 (C-1), 65.3 (C-8), 59.0 (C-4), 57.2 (C-2); MS (ESI) *m/z* = 341.1 $[M+Na]^+$; HRMS (ESI) calc. for $C_{20}H_{13}O_4$ $[M - H]^-$, 317.0814; found 317.0810.

3.3 General Procedure for the Wharton Reaction. A stirred solution of epoxide **5** or **11a-c,e** in MeCN (4.0 - 6.0 mL/mmol) was cooled to 0 °C using an ice bath and a 1.0 M solution of hydrazine (2 equiv) in THF was added. The solution was allowed to stir for 5 min before addition of glacial AcOH (2 equiv) then subsequently allowed to warm to room temperature. After the time specified in Table 2, the reaction was diluted with sat. $NaHCO_3$ solution, and extracted exhaustively with CH_2Cl_2 (TLC), dried with $MgSO_4$ then concentrated under reduced pressure. The crude product was further purified as specified below.

(1*R*,2*S*,5*R*)-6,8-Dioxabicyclo[3.2.1]oct-3-en-2-ol (7).[10b] The reaction of epoxide **5** (1.00 g, 7.0 mmol) with 1M hydrazine in THF (14 mL, 14.0 mmol) and AcOH (0.80 mL, 14.0 mmol) in MeCN (40 mL) was performed as per the general procedure. Purification by flash chromatography (1:1 EtOAc/hexanes) afforded the title product as a yellow oil which crystallized upon standing at 4 °C (0.60 g, 67%); mp 43-45 °C (Lit. mp 59-60 °C); R_f (4:1 EtOAc/hexanes) 0.61; $[\alpha]_D^{24}$ +138 (*c* 1.0, MeOH) (Lit.[10b] $[\alpha]_D$ +209 (*c* 0.6, MeOH)) ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.03 (ddd, *J* = 9.6, 3.4, 0.6 Hz, 1H, H-4), 5.85 (dddd, *J* = 9.6, 4.4, 1.9, 0.8 Hz, 1H, H-3), 5.52 (br d, *J* = 3.4 Hz, 1H, H-5), 4.67 (dddd, *J* = 6.6, 2.2, 1.9, 1.4 Hz, 1H, H-1), 3.95 (dd, *J* = 7.9, 6.6 Hz, 1H, H-7α), 3.67 (ddd, *J* = 4.4, 1.4, 0.8 Hz, 1H, H-2), 3.46 (dd, *J* = 7.9, 2.2 Hz, 1H, H-7β), 2.25 (br s, 1H, OH); ^{13}C NMR (125 MHz, $CDCl_3$) δ 130.0 (C-3), 126.3 (C-4), 95.4 (C-5), 76.8 (C-1), 67.1 (C-2), 62.6 (C-7). A $CDCl_3$ solution of **7** was observed to react over 8 days to give furan **17** (R = H). **(*R*)-1-(Furan-2-yl)ethane-1,2-diol (17,** R = H**)**.[17] $[\alpha]_D^{15}$ +26 (*c* 1.48, $CHCl_3$); *Lit*[17] +32.0 (c 2.17, CH_2Cl_2); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.39 (dd, *J* = 1.9, 0.9 Hz, 1H, H-5′), 6.36 (dd, *J* = 3.3, 1.9 Hz, 1H, H-4′), 6.32 (ddd, *J* = 3.3, 0.9, 0.6 Hz, 1H, H-3′), 4.81 (ddd, *J* = 6.4, 4.7, 0.6 Hz, 1H, H-1), 3.87 (dd, *J* = 11.4, 6.4 Hz, 1H, H-2), 3.86 (dd, *J* = 11.4, 4.7 Hz, 1H, H-2), 2.66 (br s, 2H, O<u>H</u>); ^{13}C NMR (125 MHz, $CDCl_3$) δ 153.6 (C-2′), 142.3 (C-5′), 110.3 (C-4′), 107.0 (C-3′), 68.3 (C-1), 65.1 (C-2);

MS (EI) *m/z* = 128 (M^+, 67%), 98 (20), 97.1 (M-CH_2OH^+, 100), 95 (15), 81 (14), 69.1 (37), 53.1 (13), 51.1 (12), 41.1 (74), 39.1 (39).

(1*R*,2*S*,5*R*)-3-Phenyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-ol (13a). The reaction of epoxide **11a** (200 mg, 0.92 mmol) with 1M hydrazine in THF (1.83 mL, 1.83 mmol) and AcOH (105 µL, 1.83 mmol) in MeCN (4 mL) was performed as per the general procedure. Purification by flash chromatography (2:3 EtOAc/hexanes) and then recrystallization from acetone/hexanes afforded the title product as fine yellow crystals (149 mg, 79%); R_f (2:3 EtOAc/hexanes) 0.70; mp 108-110 °C (acetone/hexanes); $[\alpha]_D^{28}$ −22 (*c* 0.88, $CHCl_3$); FT-IR (neat) 3380, 2971, 2892, 1632, 1494, 1446, 1358, 1113, 1098, 1072, 1034, 1013, 897, 750 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.56-7.55 (m, 2H, ArH), 7.39-7.31 (m, 3H, ArH), 6.31 (d, *J* = 3.6 Hz, 1H, H-4), 5.71 (d, *J* = 3.6 Hz, 1H, H-5), 4.82 (ddd, *J* = 6.6, 2.0, 1.8 Hz, 1H, H-1), 4.19 (br. d, *J* = 8.7 Hz, 1H, H-2), 3.99 (dd, *J* = 7.9, 6.6 Hz, 1H, H-7β), 3.53 (dd, *J* = 7.9, 2.1 Hz, 1H, H-7α), 2.40 (br d, *J* = 8.7 Hz, 1H, O<u>H</u>); ^{13}C NMR (125 MHz, $CDCl_3$) δ 136.38 (ArC), 136.35 (C-3), 128.7 (ArC), 128.6 (ArC), 125.9 (ArC), 124.0 (C-4), 95.7 (C-5), 77.2 (C-1), 68.4 (C-2), 62.4 (C-7); MS (EI) *m/z* = 204.1 (M^+, 21%), 157.1 (57), 148 (83), 147 (100), 115.1 (49), 105 (20), 103.1 (29), 102.1 (20), 91.1 (22), 77.1 (30); No molecular ion observed by ESI-HRMS.

(1*R*,2*S*,5*R*)-3-(4-Methoxyphenyl)-6,8-dioxabicyclo[3.2.1]oct-3-en-2-ol (13b). The reaction of epoxide **11b** (248 mg, 1.0 mmol) with 1M hydrazine in THF (2.00 mL, 2.0 mmol) and AcOH (0.114 mL, 2.0 mmol) in MeCN (4 mL) was performed as per the general procedure. Purification by flash chromatography (3:2 EtOAc/hexanes) afforded the title product as a pale yellow oil (150 mg, 64%); R_f (3:2 EtOAc/hexanes) 0.80; $[\alpha]_D^{22}$ −17 (*c* 0.53, $CHCl_3$); FT-IR

(neat) 3269, 2958, 2896, 2837, 1729, 1605, 1573, 1512, 1462, 1418, 1357, 1307, 1276, 1243, 1181, 1111, 1098, 1074, 901 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.51-7.48 (m, 2H), 6.92-6.89 (m, 2H), 6.21 (d, *J* = 3.7 Hz, 1H, H-4), 5.69 (d, *J* = 3.7 Hz, 1H, H-5), 4.81 (ddd, *J* = 6.7, 2.2, 1.4 Hz, 1H, H-1), 4.16 (br dd, *J* = 10.2, 1.4 Hz, 1H, H-2), 3.98 (dd, *J* = 8.0, 6.7 Hz, 1H, H-7α), 3.82 (s, 3H, $OC\underline{H}_3$), 3.52 (dd, *J* = 8.0, 2.2 Hz, 1H, H-7β), 2.33 (d, *J* = 10.2 Hz, 1H, $O\underline{H}$); ^{13}C NMR (125 MHz, $CDCl_3$) δ 159.9 (ArC), 135.7 (C-3), 128.7 (ArC), 127.1 (ArC), 122.1 (C-4), 114.1 (ArC), 95.9 (C-5), 77.2 (C-1), 68.5 (C-2), 62.4 (C-7), 55.3 ($O\underline{C}H_3$); MS (EI) *m/z* = 234.1 (M^+, 46%), 203.1 (21), 187.1 (100), 178.1 (84), 177.1 (36), 161 (20), 159.1 (22), 147.1 (20), 133.1 (24), 109.1 (24); HRMS (ESI) calc. for $C_{13}H_{14}O_4Na$ $[M + H]^+$, 257.0790; found 257.0786. A $CDCl_3$ solution of **13b** was observed to react over 21 days to give furan **17** (R = 4-MeOPh). **(*R*)-1-(3-(4-Methoxyphenyl)furan-2-yl)ethane-1,2-diol** (**17,** R = 4-MeOPh). ^1H NMR (500 MHz, $CDCl_3$) δ 7.41 (d, *J* = 1.9 Hz, 1H, H-5′), 7.38-7.35 (m, 2H, ArH), 6.96-6.93 (m, 2H, ArH), 6.51 (d, *J* = 1.9 Hz, 1H, H-4′), 4.91 (dd, *J* = 7.7, 4.3 Hz, 1H, H-1), 4.06 (dd, *J* = 11.5, 7.7 Hz, 1H, H-2), 3.86 (dd, *J* = 11.5, 4.3 Hz, 1H, H-2), 3.83 (s, 3H, $OC\underline{H}_3$); ^{13}C NMR (125 MHz, $CDCl_3$) δ 159.0 (ArC), 147.7 (C-2′), 142.0 (C-5′), 129.3 (ArC), 125.1 (ArC), 124.6 (C-3′), 114.2 (ArC), 111.8 (C-4′), 66.6 (C-1), 65.0 (C-2), 55.3 ($O\underline{C}H_3$); MS (EI) *m/z* = 234.1 (M^+,12%), 216.1 (9), 204.1 (13), 203.1 ($M\text{-}CH_2OH^+$, 100), 187.1 (23), 160 (10), 134.1 (44), 115.1 (17), 91.1 (11), 77.1 (9).

(1*R*,2*S*,5*R*)-3-(Benzo[*d*][1,3]dioxol-5-yl)-6,8-dioxabicyclo[3.2.1]oct-3-en-2-ol (13c). The reaction of epoxide **11c** (256 mg, 0.98 mmol) with 1M hydrazine in THF (1.95 mL, 1.95 mmol) and AcOH (0.112 mL, 1.95 mmol) in MeCN (5 mL) was performed as per the general procedure. Purification by flash chromatography (2:3 EtOAc/hexanes) afforded the title product as a yellow oil (150 mg, 62%); R_f (2:3 EtOAc/hexanes) 0.38; $[\alpha]_D^{26}$ −19 (*c* 0.21, $CHCl_3$); FT-IR (neat) 3432, 2963, 2898, 1729, 1606, 1503, 1488, 1443, 1361, 1245, 1224,

1099, 1070, 1035 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.06 (dd, *J* = 8.1, 1.9 Hz, 1H, 6-ArH), 7.03 (d, *J* = 1.9 Hz, 1H, 2-ArH), 6.80 (d, *J* = 8.1 Hz, 1H, 5-ArH), 6.17 (d, *J* = 3.7 Hz, 1H, H-4), 5.98-5.96 (m, 2H, OC$\underline{H}_2$O), 5.68 (d, *J* = 3.7 Hz, 1H, H-5), 4.80 (ddd, *J* = 6.7, 2.2, 1.2 Hz, 1H, H-1), 4.10 (d, *J* = 1.2 Hz, 1H, H-2), 3.98 (dd, *J* = 8.0, 6.7 Hz, 1H, H-7α), 3.51 (dd, *J* = 8.0, 2.2 Hz, 1H, H-7β), 2.33 (br s, 1H, O$\underline{H}$); ^{13}C NMR (125 MHz, $CDCl_3$) δ 148.1 (ArC), 148.0 (ArC), 136.0 (C-3), 130.7 (ArC), 122.8 (C-4), 119.9 (ArC), 108.4 (ArC), 106.3 (ArC), 101.3 (O$\underline{C}H_2$O), 95.8 (C-5), 77.1 (C-1), 68.6 (C-2), 62.4 (C-7); MS (EI) *m/z* = 248.1 (M^+, 89%), 217.1 (25), 201 (100), 192 (94), 191 (33), 188 (30), 147 (29), 123 (50), 115.1 (25), 89.1 (29); No molecular ion observed by ESI-HRMS. A $CDCl_3$ solution of **13c** was observed to react over 21 days to give furan **17** (R = 3,C-4H_2O_2Ph). **(*R*)-1-(3-(Benzo[*d*][1,3]dioxol-5-yl)furan-2-yl)ethane-1,2-diol** (**17,** R = 3,4-CH_2O_2Ph). ^1H NMR (500 MHz, $CDCl_3$) δ 7.40 (d, *J* = 1.5 Hz, 1H, C-5′), 6.93-6.84 (m, 3H, ArH), 6.48 (d, *J* = 1.5 Hz, C-4′), 5.99 (s, 2H, OC$\underline{H}_2$O), 4.89 (dd, *J* = 7.7, 4.2 Hz, 1H, H-1), 4.05 (dd, *J* = 11.4, 7.7, 1H, H-2), 3.85 (dd, *J* = 11.4, 4.2 Hz, 1H, H-2); ^{13}C NMR (125 MHz, $CDCl_3$) δ 147.9 (C-2′ & ArC), 147.0 (ArC), 142.0 (C-5′), 126.6 (ArC), 124.8 (C-3′), 121.7 (ArC), 111.8 (C-4′), 108.7 (ArC), 108.6 (ArC), 101.1 (O$\underline{C}H_2$O), 66.5 (C-1), 65.0 (C-2); MS (EI) *m/z* = 248.1 (M^+, 26%), 218 (14), 217 (M-CH_2OH^+, 100), 207 (25), 187.1 (26), 171.1 (22), 159.1 (27), 131.1 (23), 115.1 (16), 77.1 (15).

(1*R*,2*S*,5*R*)-3-(2-Fluorophenyl)-6,8-dioxabicyclo[3.2.1]oct-3-en-2-ol (13e) The reaction of epoxide **11e** (75 mg, 0.34 mmol) with 1M hydrazine in THF (680 µL, 0.68 mmol) and AcOH (39 µL, 0.68 mmol) in MeCN (4 mL) was performed as per the general procedure. Purification by flash chromatography (1:1 EtOAc/hexanes) afforded the title product as a colorless wax (48 mg, 68%); R_f (1:1 EtOAc/hexanes) 0.43; $[\alpha]_D^{23}$ +25 (*c* 0.12, $CHCl_3$); FT-IR (neat) 3415, 2975, 2894, 1731, 1611, 1574, 1488, 1448, 1355, 1294, 1238, 1205, 1115, 1098, 1072, 1036, 1013, 758 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.39 (ddd, *J* = 8.2, 7.7, 1.8 Hz,

1H, ArH), 7.32-7.27 (m, 1H, ArH), 7.15 (ddd, *J* = 7.7, 7.6, 1.2 Hz, 1H, ArH), 7.07 (ddd, *J* = 11.4, 8.2, 1.2 Hz, 1H, ArH), 6.24 (d, *J* = 3.7 Hz, 1H, H-4), 5.68 (d, *J* = 3.7 Hz, 1H, H-5), 4.79 (ddd, *J* = 6.7, 2.2, 1.6 Hz, 1H, H-1), 4.19 (br s, 1H, H-2), 4.01 (dd, *J* = 8.0, 6.7 Hz, 1H, H-7α), 3.62 (dd, *J* = 8.0, 2.2 Hz, 1H, H-7β), 2.41 (br s, 1H, OH); ^{13}C NMR (125 MHz, $CDCl_3$) δ 160.5 (d, J_{CF} = 248.7 Hz, ArC), 133.2 (d, J_{CF} = 1.8 Hz, H-3), 129.9 (d, J_{CF} = 9.0 Hz, ArC), 129.8 (d, J_{CF} = 3.6 Hz, ArC), 128.5 (d, J_{CF} = 5.7 Hz, H-4), 124.9 (d, J_{CF} = 12.7 Hz, ArC), 124.3 (d, J_{CF} = 3.6 Hz, ArC), 116.1 (d, J_{CF} = 22.7 Hz, ArC), 95.5 (C-5), 76.9 (C-1), 68.9 (d, J_{CF} = 3.2 Hz, C-2), 62.5 (H-7); MS (EI) *m/z* = 222.1 (M^+, 18%), 175.1 (65), 166 (100), 165 (53), 147.1 (68), 146.1 (39), 133 (68), 121 (36), 120 (34), 109 (29), 101 (29); HRMS (ESI) calc. for $C_{12}H_{11}O_3FNa$ $[M+Na]^+$, 245.0590; found 245.0567. A $CDCl_3$ solution of **13e** was observed to react over 21 days to give furan **17** (R = 2-FPh). **(*R*)-1-(3-(2-Fluorophenyl)furan-2-yl)ethane-1,2-diol** (**17**, R = 2-FPh). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.46 (H-5′), 7.40-7.37 (ArH), 7.34-7.29 (ArH), 7.20-7.17 (ArH), 7.16-7.12 (ArH), 6.53 (H-4′), 4.81 (H-1), 4.03 (H-2), 3.83 (H-2); ^{13}C NMR (125 MHz, $CDCl_3$) δ 149.4 (C-2′), 142.2 (C-5′), 131.1 (ArC), 129.3 (ArC), 124.3 (ArC), 120.4 (ArC), 118.2 (C-3′), 115.8 (ArC), 112.4 (C-4′), 66.6 (C-1), 64.8 (C-2); MS (EI) *m/z* = 222.1 (M^+, 27%), 192.1 (61), 191.1 (M-CH_2OH^+, 100), 175.1 (24), 173 (20), 171.1 (45), 146.1 (21), 133.1 (62), 115.1 (58), 109.1 (24).

3.4 General procedure for the Oxidation of Allylic Alcohols. Dess-Martin periodinane (DMP) (1.05 eq) was added to a solution of allylic alcohol **7, 13a-c,e** in CH_2Cl_2 (20 mL/mmol) and the mixture stirred at ambient temperature for 2-5 hrs as specified in Table 3. The resulting solution was washed with sat. $NaHCO_3$ solution, dried over $MgSO_4$, filtered and concentrated under reduced pressure and the residue was purified by flash chromatography.

(1*R*,5*R*)-6,8-Dioxabicyclo[3.2.1]oct-3-en-2-one (isolevoglucosenone) (2).[10] As per the general procedure, the reaction of allylic alcohol 7 (1.00 g, 7.80 mmol) and DMP (3.48 g, 8.20 mmol) afforded the title product as a yellow oil (0.77 g, 78%); R_f (1:1 EtOAc/hexanes) 0.80; $[\alpha]_D^{23}$ +250 (*c* 1.0, $CHCl_3$) (Lit.[10] $[\alpha]_D$ +445 (*c* 1.0, $CHCl_3$)); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.13 (dd, *J* = 9.8, 3.2 Hz, 1H, H-4), 6.11 (ddd, *J* = 9.8, 1.5, 0.9 Hz, 1H, H-3), 5.82 (dd, *J* = 3.2, 0.9 Hz, 1H, H-5), 4.79 (ddd, *J* = 6.3, 1.5, 1.5 Hz, 1H, H-1), 4.11 (dd, *J* = 8.2, 6.3 Hz, 1H, H-7α), 3.66 (dd, *J* = 8.2, 1.5 Hz, 1H, H-7β); ^{13}C NMR (125 MHz, $CDCl_3$) δ 194.5 (C-2), 147.3 (C-3), 127.1 (C-4), 96.0 (C-5), 79.6 (C-1), 62.7 (C-7).

(1*R*,5*R*)-3-Phenyl-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one (18a). As per the general procedure, the reaction of allylic alcohol **13a** (0.574 g, 2.81 mmol) and DMP (1.25 g, 2.95 mmol) afforded the title product as a colorless oil (0.500 g, 88%); R_f (1:4 EtOAc/hexanes) 0.63; $[\alpha]_D^{22}$ +133 (*c* 1.67, $CHCl_3$); FT-IR (neat) 3057, 2961, 2893, 1698, 1612, 1576, 1492, 1445, 1356, 1325, 1275, 1159, 1112, 1075, 1038, 986, 905, 756, 695 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.43-7.36 (m, 5H, ArH), 7.14 (d, *J* = 3.5 Hz, 1H, H-4), 5.96 (d, *J* = 3.5 Hz, 1H, H-5), 4.94 (dd, *J* = 6.3, 1.4 Hz, 1H, H-1), 4.15 (dd, *J* = 8.2, 6.3 Hz, 1H, H-7α), 3.75 (dd, *J* = 8.2, 1.4 Hz, 1H, H-7β); ^{13}C NMR (125 MHz, $CDCl_3$) δ 193.6 (C-2), 142.3 (C-4), 137.4 (C-3), 132.5 (ArC), 128.9 (ArC), 128.4 (ArC), 128.3 (ArC), 97.1 (C-5), 79.7 (C-1), 62.7 (C-7); MS (EI) *m/z* = 202.1 (M^+,100%), 171.1 (48), 159.1 (33), 145.1 (21), 131.1 (20), 117.1 (24), 115.1 (58), 105.1 (19), 103.1 (65), 77.1 (25); HRMS (ESI) calc. for $C_{12}H_{10}O_3Na$ $[M + Na]^+$, 225.0528; found 225.0505.

(1*R*,5*R*)-3-(4-Methoxyphenyl)-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one (18b). As per the general procedure, the reaction of allylic alcohol **13b** (94 mg, 0.40 mmol) and DMP (179 mg, 0.42 mmol) afforded the title product as a yellow oil (60 mg, 64%); R_f (2:4 EtOAc/hexanes) 0.50; $[\alpha]_D^{21}$ +129 (*c* 0.21, $CHCl_3$); FT-IR (neat) 2958, 2893, 2837, 1763, 1696, 1606, 1572, 1510, 1461, 1356, 1326, 1292, 1268, 1246, 1180, 1158, 1108, 1033 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.41-7.38 (m, 2H, ArH), 7.08 (d, *J* = 3.6 Hz, 1H, H-4), 6.93-6.90 (m, 2H, ArH), 5.94 (d, *J* = 3.6 Hz, 1H, H-5), 4.92 (dd, *J* = 6.3, 1.4 Hz, 1H, H-1), 4.13 (dd, *J* = 8.2, 6.3 Hz, 1H, H-7α), 3.82 (s, 3H, OC<u>H</u>$_3$), 3.73 (dd, *J* = 8.2, 1.4 Hz, 1H, H-7β); ^{13}C NMR (125 MHz, $CDCl_3$) δ 194.1 (C-2), 160.2 (ArC), 140.9 (C-4), 136.8 (C-3), 129.6 (ArC), 124.8 (ArC), 113.9 (ArC), 97.2 (C-5), 79.8 (C-1), 62.7 (C-7), 55.3 (O<u>C</u>H$_3$); MS (EI) *m/z* = 232.1 (M^+, 100%), 202 (37), 201 (65), 187.1 (22), 171 (34), 161 (23), 159 (24), 135 (26), 133.1 (49), 89.1 (22); HRMS (ESI) calc. for $C_{13}H_{12}O_4Na$ $[M + Na]^+$, 255.0633; found 255.0634.

(1*R*,5*R*)-3-(Benzo[*d*][1,3]dioxol-5-yl)-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one (18c). As per the general procedure, the reaction of allylic alcohol **13c** (130 mg, 0.52 mmol) and DMP (233 mg, 0.55 mmol) afforded the title product as a pale yellow wax (54 mg, 42%); R_f (1:4 EtOAc/hexanes) 0.53; $[\alpha]_D^{20}$ +77 (*c* 0.39, $CHCl_3$); FT-IR (neat) 2959, 2898, 1697, 1608, 1488, 1440, 1360, 1230, 1166, 1107, 1032 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.06 (d, *J* = 3.6 Hz, 1H, H-4), 6.94-6.92 (m, 2H, ArH), 6.82 (d, *J* = 8.5 Hz, 1H, ArH), 5.98 (s, 2H, OC<u>H</u>$_2$O), 5.94 (d, *J* = 3.6 Hz, 1H, H-5), 4.92 (dd, *J* = 6.3, 1.5 Hz, 1H, H-1), 4.13 (dd, *J* = 8.2, 6.3 Hz, 1H, H-7α), 3.72 (dd, *J* = 8.2, 1.5 Hz, 1H, H-7β); ^{13}C NMR (125 MHz, $CDCl_3$) δ 193.8 (C-2), 148.3 (ArC), 147.6 (ArC), 141.4 (C-4), 136.9 (C-3), 126.3 (ArC), 122.3 (ArC), 108.7 (ArC), 108.3 (ArC), 101.3 (O<u>C</u>H$_2$O), 97.1 (C-5), 79.7 (C-1), 62.7 (C-7); MS (EI) *m/z* = 246 (M^+, 100%), 216 (28), 215 (76), 188.1 (23), 159 (22), 147 (22), 131.1 (23), 117 (23), 102.1 (17), 89.1 (28); HRMS (ESI) calc. for $C_{13}H_{11}O_5$ $[M + H]^+$, 247.0606; found 247.0535.

(1*R*,5*R*)-3-(2-Fluorophenyl)-6,8-dioxabicyclo[3.2.1]oct-3-en-2-one (18e). As per the general procedure, the reaction of allylic alcohol **13e** (86 mg, 0.39 mmol) and DMP (172 mg, 0.41 mmol) afforded the title product as a colorless wax (45 mg, 52%); R_f (1:4 EtOAc/hexanes) 0.54; $[\alpha]_D^{21}$ +92 (*c* 0.64, $CHCl_3$); FT-IR (neat) 2961, 2900, 1703, 1625, 1572, 1489, 1452, 1353, 1255, 1218, 1158, 1109, 1032, 757 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.38-7.33 (m, 1H, ArH), 7.27-7.24 (m, 1H, ArH), 7.18 (dd, *J* = 3.5, 0.7, 1H Hz, H-4), 7.16-7.14 (m, 1H, ArH), 7.13-7.09 (m, 1H, ArH), 5.96 (d, *J* = 3.5 Hz, 1H, H-5), 4.95 (dd, *J* = 6.3, 1.5 Hz, 1H, H-1), 4.18 (dd, *J* = 8.3, 6.3 Hz, 1H, H-7α), 3.79 (dd, *J* = 8.3, 1.4 Hz, 1H, H-7β); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.3 (C-2), 159.9 (d, J_{CF} = 250 Hz, ArC), 145.0 (d, J_{CF} = 2.7 Hz, C-4), 133.5 (C-3), 130.8 (d, J_{CF} = 2.8 Hz, ArC), 130.6 (d, J_{CF} = 8.2 Hz, ArC), 124.0 (d, J_{CF} = 3.6 Hz, ArC), 120.4 (d, J_{CF} = 15.2 Hz, ArC), 115.8 (d, J_{CF} = 22.1 Hz, ArC), 96.8 (C-5), 79.5 (C-1), 62.8 (C-7); MS (EI) *m/z* = 220.1 (M^+, 100%), 189 (29), 177 (33), 163.1 (22), 135.1 (21), 133 (60), 123 (15), 121 (68), 120 (21), 101 (37); HRMS (ESI) calc. for $C_{12}H_9FO_3Na$ $[M + Na]^+$, 243.0433; found 243.0431.

(1*R*,4*S*/*R*,5*R*)-4-(Phenylamino)-6,8-dioxabicyclo[3.2.1]octan-2-one (20). Isolveoglucosenone **2** (0.250 g, 1.98 mmol) was dissolved in a 0.1 M K_2CO_3 aqueous solution (10 mL) and aniline (199 μL, 2.18 mmol) was added. The mixture was stirred at ambient temperature for 2 hrs and then extracted with CH_2Cl_2 (20 mL × 3). The organic phase was dried over $MgSO_4$, filtered and concentrated under reduced pressure. The crude residue was purified by flash chromatography (1:49 NH_4OH/CH_2Cl_2), giving a 4:1 mixture of **20**/**21** as a yellow solid (0.248 g, 57%); R_f (1:49 NH_4OH/CH_2Cl_2) 0.37; FT-IR (neat) 3373, 2958, 2894, 1729, 1598, 1499, 1311, 1256, 1172, 1121, 1023, 749 cm^{-1}; MS (EI) *m/z* = 219.1

(M^+, 17%), 174.1 (41), 126 (33), 119.1 (50), 118.1 (62), 93.1 (100), 83 (40), 68 (32), 66 (47), 55 (36), 39.1 (30); HRMS (ESI) calc. for $C_{12}H_{14}NO_3$ $[M + H]^+$, 220.0974; found 220.0969. **20**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.21-7.17 (m, 2H, ArH), 6.79-6.75 (m, 1H, ArH), 6.61-6.59 (m, 2H, ArH), 5.61 (br s, 1H, H-5), 4.55 (br d, *J* = 5.3 Hz, 1H, H-1), 4.06 (d, *J* = 8.2 Hz, 1H, H-7β), 4.06-4.04 (m, 1H, C-4), 3.96 (dd, *J* = 8.4, 5.3 Hz, 1H, H-7α), 2.80 (dd, *J* = 17.3, 6.8 Hz, 1H, H-3), 2.52 (dddd, *J* = 17.3, 2.0, 1.5, 1.5 Hz, 1H, H-3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 203.2 (C-2), 145.4 (ArC), 129.6 (ArC), 118.7 (ArC), 113.6 (ArC), 102.1 (C-5), 79.5 (C-1), 66.9 (C-7), 54.1 (C-4), 38.9 (C-3); **21:** ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.25-7.23 (m, 2H, ArH), 6.96-6.93 (m, 1H, ArH), 6.64-6.63 (m, 1H, ArH), 5.67 (d, *J* = 2.2 Hz, 1H, H-5), 4.54 (m, 1H, H-1), 4.11 (m, 1H, H-4), 4.00 (br d, *J* = 8.4 Hz, 1H, H-7), 3.94 (m, 1H, H-7), 2.99 (br dd, *J* = 17.2, 7.5 Hz, 1H, H-3), 2.24 (dd, *J* = 17.2, 7.8 Hz, 1H, H-3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 202.7 (C-2), 145.5 (ArC), 129.6 (ArC), 118.6 (ArC), 113.6 (ArC), 100.7 (C-5), 78.5 (C-1), 67.1 (C-7), 53.9 (C-4), 40.7 (C-3).

(1*R*,2*R*,5*S*,6*R*)-4-Phenyl-8,9-dioxatricyclo[4.2.1.0^{2,4}]nonan-5-one (**22**). To a solution of **2** (0.500 g, 2.47 mmol) and trimethylsulfoxonium iodide (0.652 g, 2.96 mmol) in DMSO (6 mL) was added 1,1,3,3-tetramethlyguanadine (0.371 mL, 2.96 mmol) and the mixture stirred at room temperature for 4 hrs. The resulting solution was diluted with brine (15 mL), then extracted with CH_2Cl_2 (3 × 20 mL), dried over $MgSO_4$ and concentrated under reduced pressure. The residue was purified by flash chromatography (1:4 EtOAc/hexanes), then recrystallized from *i*-Pr_2O to afford the title compound as fine white crystals (0.490 g, 92%); R_f (1:4 EtOAc/hexanes) 0.55; mp 104-106 °C; $[\alpha]_D^{27}$ +62 (*c* 0.13, $CHCl_3$); FT-IR (neat) 2957, 2890, 1706, 1600, 1496, 1472, 1445, 1377, 1351, 1319, 1273, 1224, 1184, 1155, 1127, 1098, 1078, 1066, 1051, 1018, 754, 698 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.34-7.26 (m, 5H, ArH), 5.94 (d, *J* = 1.4 Hz, 1H, H-6), 4.56 (dd, *J* = 5.9, 1.8 Hz, 1H, H-1), 4.01 (dd, *J* = 8.2, 1.8

Hz, 1H, H-8), 3.99 (dd, *J* = 8.2, 5.9 Hz, 1H, H-8), 1.99 (ddd, *J* = 7.5, 5.3, 1.4 Hz, 2H, H-5), 1.90 (dd, *J* = 5.3, 4.8 Hz, 1H, H-3), 1.50 (dd, *J* = 7.5, 4.8 Hz, 1H, H-3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 202.8 (C-2), 137.6 (ArC), 129.9 (ArC), 128.5 (ArC), 127.8 (ArC), 100.2 (C-6), 78.5 (C-1), 67.0 (C-8), 38.4 (C-4), 25.0 (C-5), 17.6 (C-3); MS (EI) *m/z* = 216.1 (M^+, 35%), 173.1 (90), 160.1 (29), 145.1 (100), 129.1 (41), 128.1 (59), 127.1 (45), 117.1 (54), 115.1 (89), 91.1 (31); HRMS (ESI) calc. for $C_{13}H_{12}O_3Na$ $[M + Na]^+$, 239.0684; found 239.0666.

(1*R*,5*R*)-6,8-Dioxabicyclo[3.2.1]octan-2-one (23).[16c] A stirred solution of **2** (0.500 g, 3.96 mmol) and 10% Pd/C (0.843 g, 0.79 mmol) in EtOAc (20 mL) was placed under a H_2 atmosphere and stirred at 50 °C for 4 days. The mixture was filtered and concentrated under reduced pressure to afford the title compound as a yellow oil (0.498 g, 98%); $[\alpha]_D^{20}$ −40 (*c* 1.0, $CHCl_3$) (Lit.[16c] $[\alpha]_D^{25}$ −83 (*c* 0.4, $CHCl_3$)); ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.74 (d, *J* =2.7 Hz, 1H, H-5), 4.51 (d, *J* = 5.6 Hz, 1H, H-1), 3.97 (br d, *J* = 8.2, 1H, H-7β), 3.88 (dd, *J* = 8.2, 5.6 Hz, 1H, H-7α), 2.49-2.46 (m, 2H, H-3), 2.17 (dddd, *J* = 14.0, 8.8, 7.9, 3.0 Hz, 1H), 2.07-2.02 (m, 1H, H-4); ^{13}C NMR (125 MHz, $CDCl_3$) 205.6 (C-2), 100.8 (C-5), 79.3 (C-1), 67.2 (C-7), 31.5 (C-3), 30.7 (C-4).

(1*R*,5*R*)-3-((*Z*)-Benzylidene)-6,8-dioxabicyclo[3.2.1]octan-2-one (24). To a stirred solution of ketone **23** (200 mg, 1.56 mmol) and benzaldehyde (188 μL, 1.87 mmol) in dioxane (15 mL) was added TMG (196 μL, 1.56 mmol) and the mixture heated to reflux for 24 hrs. The solution was concentrated under reduced pressure then purified via flash chromatography (1:4 EtOAc/hexanes) to afford the title compound as a colorless wax (118 mg, 35%); R_f (1:4 EtOAc/hexanes) 0.51; $[\alpha]_D^{20}$ +16 (*c* 0.62, $CHCl_3$); FT-IR (neat) 2955, 2891, 1697, 1595, 1572, 1492, 1446, 1423, 1281, 1253, 1201, 1174, 1125, 1088, 1032 cm^{-1}; ^{1}H NMR (500

MHz, $CDCl_3$) δ 7.77 (dd, *J* = 3.0, 2.0 Hz, 1H, C<u>H</u>Ph), 7.48-7.46 (m, 2H, ArH), 7.44-7.37 (m, 3H, ArH), 5.86 (d, *J* = 3.2 Hz, 1H, H-5), 4.74 (dd, *J* = 5.7, 1.0 Hz, 1H, H-1), 4.05 (dd, *J* = 8.0, 1.0 Hz, 1H, H-7β), 3.96 (dd, *J* = 8.0, 5.7 Hz, 1H, H-7α), 3.15 (ddd, *J* = 17.0, 3.2, 3.0 Hz, 1H, H-4), 2.98 (dd, *J* = 17.0, 2.0 Hz, 1H, H-4); ^{13}C NMR (125 MHz, $CDCl_3$) δ 195.4 (C-2), 140.3 (<u>C</u>HPh), 134.6 (ArC), 130.7 (ArC), 129.8 (ArC), 128.7 (C-3), 127.9 (ArC), 100.7 (C-5), 78.6 (C-1), 67.9 (C-7), 36.3 (C-4); MS (EI) *m/z* = 216.1 (M^+, 14%), 173.1 (74), 170.1 (48), 142.1 (41), 141.1 (22), 129.1 (23), 128.1 (37), 117.1 (83), 116.1 (42), 115.1 (100), 102.1 (34); HRMS (ESI) calc. for $C_{13}H_{12}O_3Na$ $[M + Na]^+$, 239.0684; found 239.0671.

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Captions for Schemes

Scheme 1. Previous synthesis of epoxide **5** from **1** and the Wharton process used for the synthesis of isolevoglucosenone (**2**).

Scheme 2. Hydration of epoxide **5** in D_2O.

Scheme 3. Rearrangement of allylic alcohols to diol **17**.

Scheme 4. Reactions on **2** and **18a**.