Some Aspects of Palladium-Catalyzed Cycloalkenylation: Developments of Environmentally Benign Catalytic Conditions and Demonstration of Tandem Cycloalkenylation

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Received December 20, 2001

The influences of catalysts, substituent groups, and solvents on the palladium-catalyzed cycloalkenylation of cross-conjugated silyl enol ethers of 2-*tert*-butyldimethylsiloxy-5-(2-propenyl)-1,3-cyclohexadiene derivatives have been investigated. The catalytic reaction proceeded smoothly, even in aqueous media. The product ratios were influenced by the structure of substrates as well as solvents. In addition, it was found that the reaction is applicable to a tandem cyclization for the construction of cedrane skeleton.

Introduction

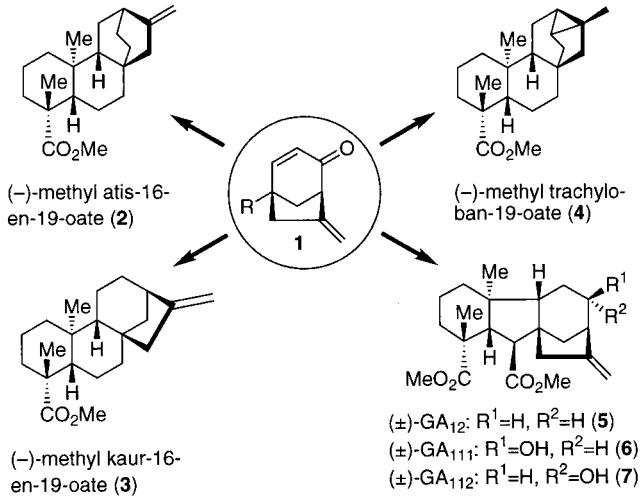
To make natural product syntheses efficient, a large number of transition-metal-mediated carbon−carbon bond formation processes have been developed.[1] In 1979, Ito et al. have discovered that the corresponding silyl enol ethers of alkenyl ketones provide the β,γ-unsaturated cyclic ketones in the presence of Pd(II).[2] This methodology has proven to be a powerful tool for the construction of complex, polycyclic molecules.[3] However, the process employing stoichiometric amounts of $Pd(OAc)_2$ suffers from low yields on large scale. To solve this problem, we developed a novel palladium-catalyzed cycloalkenylation[4] of the olefinic *tert*-butyldimethylsilyl enol ethers, and the methodology was successfully adapted for the syntheses of polycyclic natural products, such as (−)-methyl atis-16-en-19-oate (**2**),[5] (−)-methyl kaur-16-en-19-oate (**3**),[5] (−)-methyl trachyloban-19-oate (**4**),[5] and C_{20} gibberellins (**5**−**7**) (Scheme 1).[6]

The search for improvement of the palladium-catalyzed cycloalkenylation has been continued, with the goal of increasing the diversity of possible substrates and reaction products. In this paper we report some notable results of the above catalytic cyclization.

Results and Discussion

To explore the potential of the palladium-catalyzed cycloalkenylation, several reaction parameters, such as palladium catalysts, substituent groups, and solvents were evaluated. First of all, the effect of varying palladium catalysts was examined. The cycloalkenylation of the silyl enol ether **8** was carried out at 45 °C in the presence of 10 mol % of a palladium catalyst under 1 atm of oxygen in dimethyl sulfoxide (DMSO). As a result of testing, the catalytic reaction with $Pd(OAc)_2$ proceeded nicely to provide the desired bicyclo[3.2.1]octenone **9** in 87% yield (Table 1, entry 1).[4] When $PdCl_2$ was employed, the enone **12** (63%) was obtained as a major product (entry 2). The use of $Pd(OCOCF_3)_2$ gave **9** (40%) along with the dienone **11** (28%) (entry 3), and $Pd(acac)_2$ was less effective in terms of cycloalkenylation (entry 4).

Scheme 1



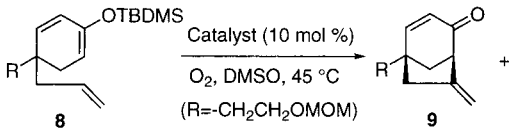
Since a number of bioactive natural products, such as scopadulcic acid B (**13**) and gibberellic acid (**14**), have a substituent group at the angular position of the bicyclo-[3.2.1]ring part, the effect of the substituent groups was next evaluated (Figure 1).

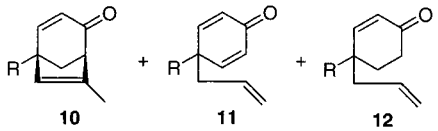
The catalytic cyclization was conducted using a variety of substituted cyclohexadienes. Prior to evaluate the substituent effect, the requisite substrates were prepared as shown in Schemes 2 and 3. Namely, the silyl ether **16** was synthesized from the enone **15**[4] by methylation followed by silylation. The dialkoxide **17** was next prepared from the cross-conjugated silyl enol ether **8**.[4] α-Hydroxylation of **8** followed by *O*-methylation gave rise

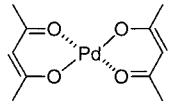
(1) In *Metal-catalyzed Cross-coupling Reactions*; Diederich. F., Stang. P. J., Eds.; Wiley-VCH: Weinheim, 1998.
(2) Ito, Y.; Aoyama, H.; Hirao, T.; Mochizuki, A.; Saegusa, T. *J. Am. Chem. Soc.* **1979**, *101*, 494−496.
(3) Kende, A. S.; Roth, B.; Sanfilippo, P. J.; Blacklock, T. J. *J. Am. Chem. Soc.* **1982**, *104*, 5808−5810. (b) Kende, A. S.; Sanfilippo, P. J. *Synth. Commun.* **1983**, *13*, 715−719. (c) Shibasaki, M.; Mase, T.; Ikegami, S. *J. Am. Chem. Soc.* **1986**, *108*, 2090−2091. (d) Toyota, M.; Nishikawa, Y.; Motoki, K.; Yoshida, N.; Fukumoto, K. *Tetrahedron Lett.* **1933**, *34*, 6099−6102. (e) Toyota, M.; Seishi, T.; Fukumoto, K. *Tetrahedron Lett.* **1993**, *34*, 5947−5950.
(4) Toyota, M.; Wada, T.; Fukumoto, K.; Ihara, M. *J. Am. Chem. Soc.* **1998**, *120*, 4916−4925.
(5) Toyota, M.; Wada, T.; Ihara, M. *J. Org. Chem.* **2000**, *65*, 4565−4570.
(6) Toyota, M.; Odashima, T.; Wada, T.; Ihara, M. *J. Am. Chem. Soc.* **2000**, *122*, 9036−9037.

10.1021/jo011169d CCC: $22.00
Published on Web 04/17/2002

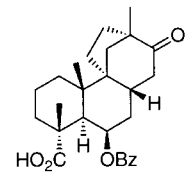
Table 1. Effect of Catalysts on Palladium-Catalyzed Cycloalkenylation



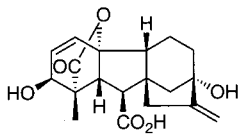


entry	catalyst	products yield (%) 9	10	11	12
1	$Pd(OAc)_2$	87	1	4	0
2	$PdCl_2$	24	4	0	63
3	$Pd(OCOCF_3)_2$	40	0	28	8
4		39	3	0	54

to α-methoxyketone, which was subjected to silylation to provide the compound **17** (Scheme 2).



Scopadulcic acid B (**13**)

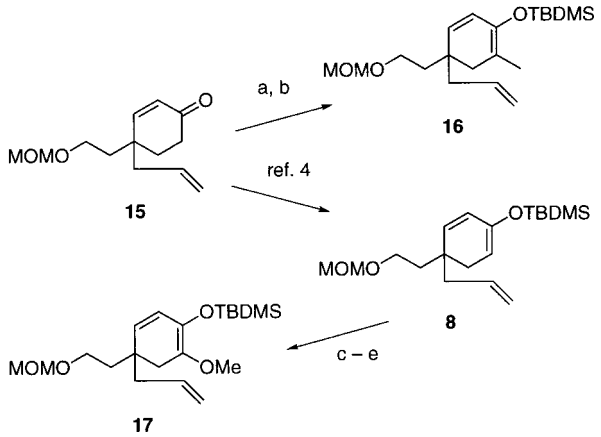


Gibberellic acid (**14**)

Figure 1.

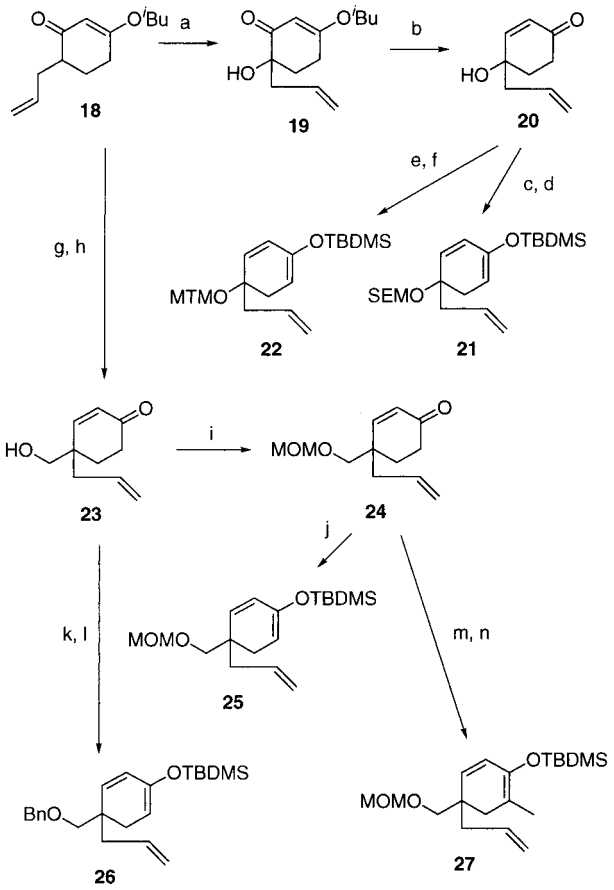
The methylthiomethyl (MTM) ether **22** was synthesized from **18**[7] using Stork−Danheiser's protocol.[7] The compound **18** was subjected to hydroxylation with Vedejs reagent[8] to furnish **19**, which was reduced with $LiAlH_4$. The resulting diol was treated with 15% $HClO_4$ to yield

Scheme 2[a]



[a] Reagents and conditions: (a) LDA, THF, −78 to 0 °C; MeI, −78 to 0 °C (85%). (b) LDA, THF, −78 °C; TBDMSCl, HMPA, −78 °C to room temperature (91%). (c) *m*-CPBA, hexane, −30 °C to room temperature; TBAF, THF, 0 °C to room temperature (67%). (d) MeI, Ag_2O, $CaSO_4$ (83%). (e) LDA, THF, −78 °C; TBDMSCl, HMPA, −78 °C to room temperature (82%).

Scheme 3[a]



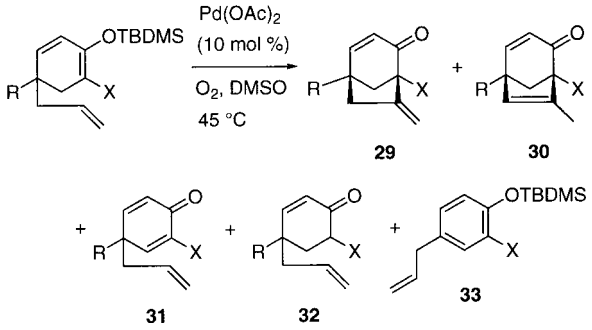
[a] Reagents and conditions: (a) LDA, THF, −78 to 0 °C; MoOPH, −78 to 0 °C (81%). (b) $LiAlH_4$, THF, 0 °C; 15% $HClO_4$, THF, 0 °C (64%). (c) SEMCl, $^iPr_2NET$, CH_2Cl_2, 0 °C (73%). (d) LDA, THF, −78 °C; TBDMSCl, HMPA, −78 °C to room temperature (88%). (e) DMSO, Ac_2O (65%) (f) LDA, THF, −78 °C; TBDMSCl, HMPA, −78 °C to room temperature (62%). (g) LDA, THF, −78 °C; HMPA, $NCCO_2Me$ (93%). (h) $LiAlH_4$, THF, 0 °C; 15% $HClO_4$, THF, 0 °C (83%). (i) MOMCl, $^iPr_2NEt$, CH_2Cl_2 (94%). (j) LDA, THF, −78 °C; TBDMSCl, HMPA, −78 °C to room temperature (90%). (k) NaH, BnBr, DMF, −40 to 0 °C (57%). (l) LDA, THF, −78 °C; TBDMSCl, HMPA, −78 °C to room temperature (76%). (m) LDA, THF, −78 °C to 0 °C; MeI, −78 to 0 °C (72%). (n) LDA, THF, −78 °C; TBDMSCl, HMPA, −78 °C to room temperature (92%).

the alcohol **20**, which was transformed into **22** by etherification and silylation. The 2-(trimethylsilyl)-ethoxymethyl (SEM) ether **21** was prepared from **20** in two steps. The carbinol **23** was synthesized from **18** by carbomethoxylation and reduction, followed by acidic treatment. The compound **23** was led to the silyl enol ether **25** through methoxymethylation followed by silylation. The silyl ether **27** was obtained from **24** by means of methylation followed by silylation. The benzyl ether **26** was also prepared by *O*-benylation and silylation (Scheme 3).

The palladium-catalyzed cycloalkenylations of the silyl enol ethers, synthesized as shown in Schemes 2 and 3, were investigated at 45 °C using 10 mol % of palladium acetate under oxygen atmosphere (1 atm). Generally, the silyl enol ethers bearing long side chains, such as **8** and **28**,[5] provided **29** in good yield (entries 1 and 9). As depicted in Table 2, the catalytic reactions carried out

(7) Stork, G.; Danheiser, R. L. *J. Org. Chem.* **1973**, *38*, 1775−1776.
(8) Vedejs, E.; Larsen, S. *Org. Synth.* **1990**, *7*, 277−282.

Table 2. Substituent Effect on Palladium-Catalyzed Cycloalkenylation



				product yield (%)				
entry	R	X	substrate	**29**	**30**	**31**	**32**	**33**
1	Ph	H	**8**	87[a]	1	4		
2	$-CH_2OMOM$	H	**24**	80	6	4		
3	$-CH_2CH_2OMOM$	Me	**16**	79	9			
4	$-CH_2OMOM$	Me	**27**	79	9	2		
5	$-CH_2CH_2OMOM$	OMe	**27**	46	9	10		
6	$-CH_2OBn$	H	**26**	70	8	3		
7	−OSEM	H	**21**	77	2	6		
8	$-OCH_2SMe$	H	**22**					27
9	$-CH_2CH_2CH_2OPv$	H	**28**	85[b]	8	2		

[a] Reference 4. [b] Reference 5.

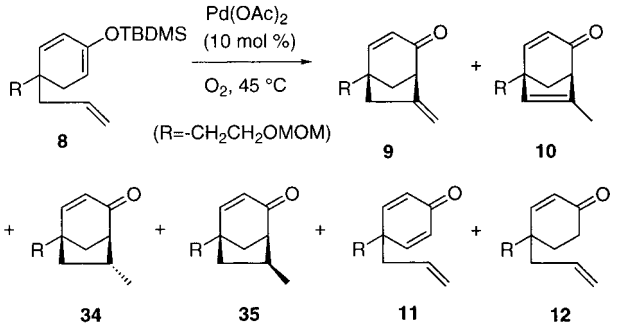
by using 1-methylcyclohexa-1,3-diene derivatives, both **16** and **27**, provided the bicyclic compound **29** in 79% yield (entries 3 and 4). On the other hand, when the reaction was conducted by using **27**, the cyclization yield dropped to 46% (entry 5). The length of the side chains at the C-5 position of the substrates affected the yield little (entries 6 and 7). Interestingly, the sulfur-containing substrate **22** at the side chain afforded exclusively the phenol derivative **33** (entry 8). Probably, **22** acted as catalyst poison because of the strong thiophilicity of transition metals.

Since the trend to get rid of organic solvents is quite common for modern chemical technology, the palladium-catalyzed cycloalkenylation in aqueous media was next investigated (Table 3). First of all, the catalytic reaction of the cross-conjugated silyl enol ether **8** was carried out in water to provide the desired compound **9** in 29% yield together with the enone **12** (25%, entry 1). When a 1:1 mixture of water−DMSO was used as the solvent, the yield of the desired product **1** rose to 59% (entry 2). The results tend to change according to the ratio of water and cosolvent (entry 3). Ultrasonic irradiation proved to be effective in increasing the yield (entry 4). Compared with pyridine, polar solvents, such as DMSO, MeOH, HMPA, and DMF, seem to be suitable as a cosolvent (entries 3, 5, 7−9). When pyridine was used as a cosolvent, the starting material **8** was recovered (entry 9). The yield fell to 29% under additional pressure (3 atm) (entry 6). It is notable that the reduced products **34** and **35** were generated under aqueous media. Details of the reaction mechanism are the subject for future study.

To confirm the structures of **34** and **35**, the reduced products were independently synthesized from **9** in three steps. Namely, hydrogenation of the bicyclic compound **9** gave the corresponding saturated ketones, which were subjected to enol silylation, followed by dehydrosilylation[9] to provide the enones **34** and **35** as a 5:1 mixture of diastereoisomers, as described in Scheme 4.

HPLC eluting with hexanes−EtOAc (2:1) achieved the separation of **34** and **35**. The minor diastereoisomer was

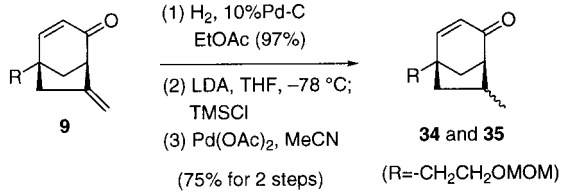
Table 3. Palladium-Catalyzed Cycloalkenylation in Aqueous Media



		product yield (%)					
entry	conditions	**9**	**10**	**34**	**35**	**11**	**12**
1	H_2O, rt	29	2	5	2		25
2	H_2O−DMSO (1:1), 45 °C	59	7	7	2		
3[a]	H_2O−DMSO (9:1), rt	45	5	19	6		
4[a]	H_2O−DMSO (9:1), rt, US[b]	56	6	7	2		
5	H_2O−MeOH (9:1)	41	3	17	7		
6[c]	H_2O−MeOH (9:1)	29	4	4	1	8	
7	H_2O−HMPA (9:1)	42	3	24	5		
8	H_2O−DMF (9:1)	45	3	16	6		
9	H_2O−pyridine (9:1)						

[a] The reaction was carried out at room temperature. [b] Ultrasound. [c] The reaction was carried out under 3 atm of oxygen.

Scheme 4



assigned structure **34** by the $^1H-^1H$ and $^1H-^{13}C$ COSY and NOESY experiment shown in Figure 2. On the other hand, the structure of the major product **35** was established on the basis of NOESY correlation between the methine hydrogen at the ethano bridge and one of the hydrogens at the methano bridge (Figure 2).

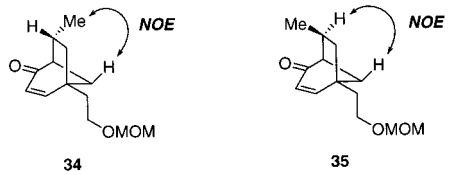
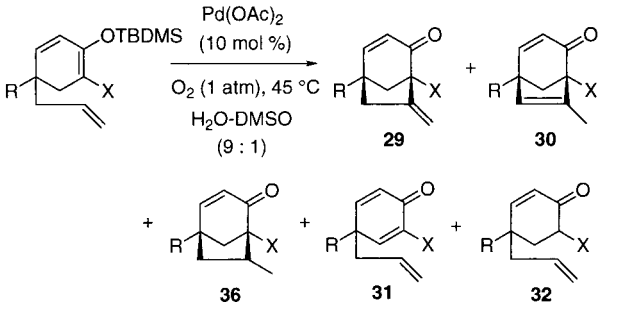


Figure 2.

The palladium-catalyzed cycloalkenylation of highly substituted silyl enol ethers in aqueous media was investigated (Table 4). As results, the catalytic reactions employing **16**, **26**, and **28** provided the bicyclo[3.2.1]-octenone **29** in moderate yields (entries 2, 5, and 7). Contrary to expectation, extension of the reaction to the substrates **25**, **27**, and **21** gave poor results (entries 1, 3, and 6). The yield was also lowered when the hydrogen at the C1 position of the starting material was replaced by a methoxyl group (entry 4). Some points, such as the reason for the generation of **36**, are still unclear; however, the potential of the palladium-catalyzed cycloalkenylation in aqueous media remains to be explored. (Table 4).

(9) Ito, Y.; Hirao, T.; Saegusa, T. *J. Org. Chem.* **1978**, *43*, 1011−1013.

Table 4. Palladium-Catalyzed Cycloalkenylation in Aqueous Medium



				product yield (%)				
entry	R	X	substrate	**29**	**30**	**36**	**31**	**32**
1	$-CH_2OMOM$	H	**25**	21	1			8
2	$-CH_2CH_2OMOM$	Me	**16**	44	3	15[a]		
3	$-CH_2OMOM$	Me	**27**	29	4			trace
4	$-CH_2CH_2OMOM$	OMe	**27**	14	5		5	
5	$-CH_2OBn$	H	**26**	41	2	6		6
6	−OSEM	H	**21**	20	1			
7	$-CH_2CH_2CH_2OPv$	H	**28**	50	3	13	3	3

[a] A 9:1 mixture of diastereoisomers.

Our efforts were next directed toward the transformation of the bicyclo[3.2.1]octenone **1** into the tricyclo[5.3.1]-undecane derivative, the AB ring system of crispolide (**38**)[10] as shown in Figure 3.

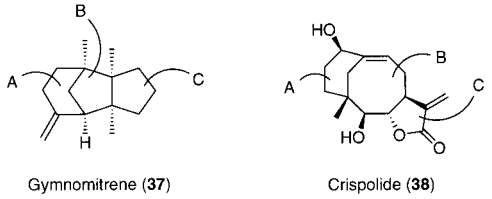
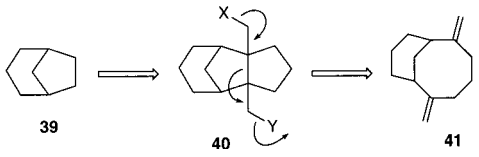


Figure 3.

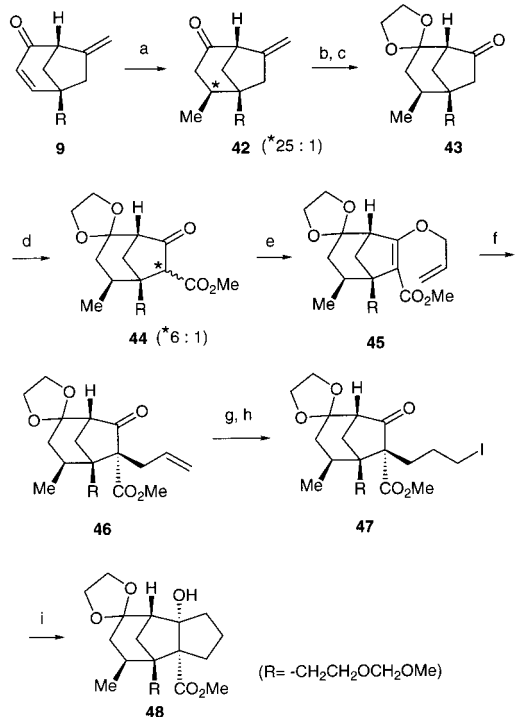
We envisioned that the tricyclo[5.3.1.$0^{2,6}$]undecane derivative, the basic carbon framework of gymnomitrene (**37**),[11] which might be available from the bicyclo[3.2.1]-octane **39**, could be converted to the bicyclo[5.3.1]-undecane compound **41**, the AB carbon framework of crispolide (**38**), by the Grob fragmentation through **40** depicted in Scheme 5.

Scheme 5



The synthesis of the tricyclo[5.3.1.$0^{2,6}$]undecane **48** is summarized in Scheme 6. Starting from the bicyclo[3.2.1]-octane derivative **9**, methylation was stereoselectively conducted with lithium dimethylcuprate to afford the ketone **42** as a major stereoisomer. After separation of the diastereomeric mixture by recrystallization, ketalization of **42** followed by Johnson−Lemieux oxidation[12] provided the ketone **43**, which was treated with Mander reagent in the presence of LDA to give rise to the keto ester **44** as a 6:1 mixture of diastereomers. The stereoisomeric mixture **44** was next subjected to allylation to furnish the α,β-unsaturated ester **45**, which was heated at 160 °C in a sealed tube to lead to the keto ester **46** as a sole product. Hydroboration−oxidation of the olefin **46** was regioselectively performed to yield the corresponding alcohol, which was converted to the iodide **47** by means of Samuelsson's protocol.[13] Since tin radical-initiated cyclization of **47** did not produce the desired compound **48**, samarium-mediated reductive cyclization was adopted to give the tricyclo[5.3.1.$0^{2,6}$]undecane **48** in 92% yield (Scheme 6).

Scheme 6[a]



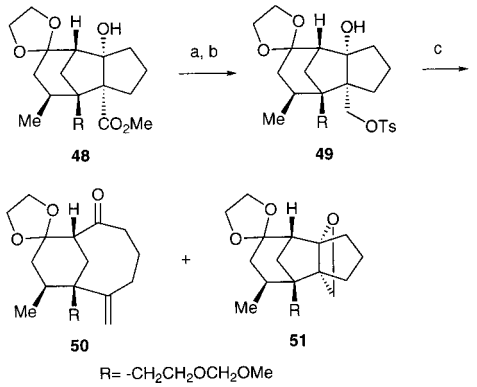
[a] Reagents and conditions: (a) Me_2CuLi, Et_2O, −50 °C (89%). (b) $HOCH_2CH_2OH$, PPTS, C_6H_6, reflux (93%). (c) OsO_4, $NaIO_4$, Et_2O-H_2O (96%). (d) LDA, THF, −78 °C; $NCCO_2Me$ (82%). (e) NaH, HMPA; $CH_2=CHCH_2Br$ (94%). (f) toluene, 160 °C, in sealed tube (91%). (g) disiamylborane, THF, 0 °C; H_2O_2, NaOH (76%). (h) I_2, Ph_3P, imidazole, THF−MeCN (92%). (i) SmI_2, THF−HMPA (92%).

Having developed a viable route to the basic carbon framework of gymnomitrene (**37**), we focused on the ring opening (Grob fragmentation[14]) of **48**. Base-promoted ring opening of **48** afforded no desired compound; however, the tosylate **49**, prepared from **48** by reduction with $LiAlH_4$ followed by tosylation, was subjected to basic treatment to provide the tricyclo[5.3.1]undecane derivative **50** together with oxetane **51**. The use of potassium *tert*-butoxide (KO^tBu) afforded **50** in 30% yield with **51** (47%). When potassium hexamethyldisilazide (KHMDS) was used as a base, the yield of **50** slightly rose to 32% (Scheme 7).

Analyses of the $^1H-^1H$ COSY experiments of **48**, **50**, and **51** enabled the assignment of all protons of each

(10) Appendino. G.; Gariboldi, P.; Nano, G. M. *Phytochem*. **1982**, *21*, 1099−1102.
(11) Connolly, J. D.; Harding, A. E.; Thornton, I. M. S. *J. Chem. Soc., Chem. Commun*. **1972**, 1320−1321.
(12) Lemieux, R. U.; Johnson, W. S. *J. Org. Chem*. **1956**, *21*, 478−479.
(13) Garegg, P. J.; Samuelsson, B. *Synthesis* **1979**, 469−470.
(14) Grob, C. A.; Baumann, W. *Helv. Chim. Acta* **1955**, *38*, 594−610.

Scheme 7[a]



[a] Reagents and conditions: (a) $LiAlH_4$, THF, reflux (81%). (b) TsCl, pyridine (95%). (c) Method A: KO^{t}Bu, THF, 0 °C to room temperature; **50** (30%), **51** (47%). Method B: $KN(TMS)_2$, THF, 0 °C to room temperature; **50** (32%), **51** (44%).

compounds. In addition, the relative stereochemistries were established on the basis of NOESY correlations, as described in Figure 4. Interestingly, the highly strained pentacyclic compound **51** was unexpectedly generated in moderate yield.

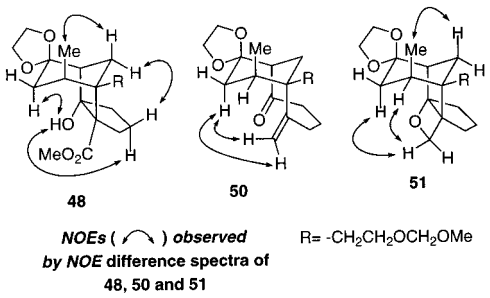


Figure 4.

To explore the potential of the catalytic cycloalkenylation, one-pot construction of cedrane skeleton by means of tandem cycloalkenylation was next examined. The unique tricyclo[5.3.1.$0^{1,5}$]undecane ring system of cedrene (**52**)[15] and cedrol (**53**)[15] prompted a considerable number of synthetic investigations on this sesquiterpene family (Figure 5).[16]

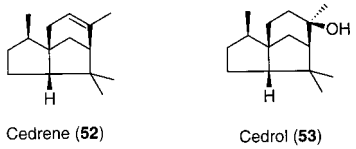


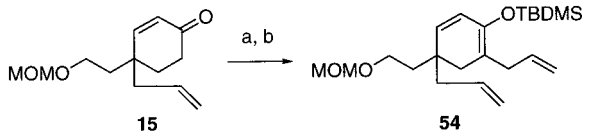
Figure 5.

The requisite diallyl substrate (**54**) for the tandem process was synthesized from **15** through allylation followed by silyl enolization, as shown in Scheme 8.

First of all, the tandem cycloalkenylation reaction of **54** was conducted at room temperature in DMSO using 1 equiv of $Pd(OAc)_2$ to provide the desired tricyclic product **55** in 24% yield, together with the monocyclized compound **57** (40%) (entry 1). Among the reaction conditions examined, the use of a catalytic amount of $Pd(OAc)_2$

(15) Stork, G.; Breslow, R. *J. Am. Chem. Soc.* **1953**, *75*, 3291.
(16) Mehta, G.; Srikrishna, A. *Chem. Rev.* **1997**, *97*, 671−719.

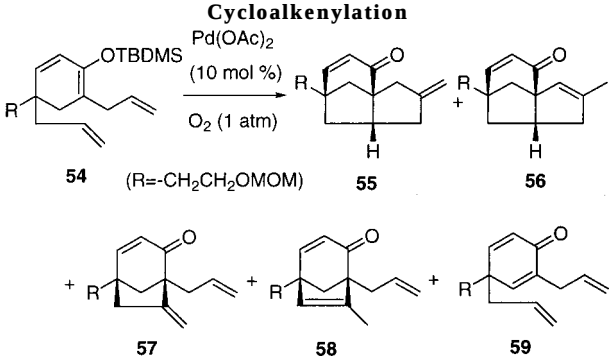
Scheme 8[a]



[a] Reagents and conditions: (a) LDA, THF, −78 to 0 °C; CH_2=$CHCH_2Br$, −78 °C to room temperature (54%). (b) LDA, THF, −78 °C; TBDMSCl, THF, HMPA, −78 °C to room temperature (89%).

(10 mol %) was found to be the best condition; the palladium-catalyzed cycloalkenylation of **54** was carried out at room temperature in DMSO under 1 atm of oxygen atmosphere to give rise to the desired tricyclic product **55** in 30% yield (entry 2). Heating of the reaction mixture accelerates the β-elimination from the monocyclized product, providing **57** (entries 3 and 4). A small amount of **55** was obtained under aqueous media (entries 5 and 6). An important advantage of the present synthetic route is that the second cyclization product **55** was obtained by a one-pot procedure, along with **57** generated by the β-elimination of the corresponding monocyclized intermediate (Table 5).

Table 5. Palladium-Catalyzed Tandem Cycloalkenylation



		product yield (%)				
entry	conditions	**55**	**56**	**57**	**58**	**59**
1[a]	DMSO, rt	24		40		20
2	DMSO, rt	30		58		trace
3	DMSO, 45 °C	18	4	64	2	
4	DMSO, 60 °C		2	42	trace	
5	H_2O−DMSO (9:1), rt	4		19		5
6	H_2O−DMSO (9:1), 45 °C	6		34	2	1

[a] The reaction was performed using 100 mol % of $Pd(OAc)_2$.

All protons and carbons of the tricyclic compound **55** were assigned by $^1H-^1H$ COSY and $^1H-^{13}C$ COSY experiments. The relative configuration of **55** was established on the basis of NOESY correlations between α-protons, as depicted in Figure 6.

In conclusion, we have developed a convenient, novel process to construct highly functionalized bicyclo[3.2.1]-

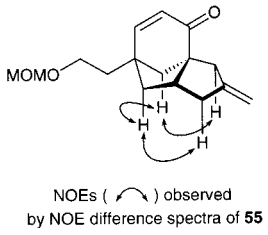


Figure 6.

octane derivatives, potential synthons for the syntheses of polycyclic natural products such as scopadulcic acid B (**13**) and gibberellic acid (**14**). Although the product yields are moderate, the palladium-catalyzed cycloalkenylations proceed in aqueous media to give the desired bicyclo-[3.2.1]octane compounds. The above characteristics make this process an environmentally attractive one, which should find widespread synthetic utility. Finally, the catalytic cycloalkenylation turned out to be adaptable to a tandem process. The tricyclic compound **55**, the basic framework of cedrene (**52**) and cedrol (**53**), was prepared through the above protocol.

Experimental Section

General. Unless otherwise noted, all reactions were performed in oven-dried glassware, sealed with a rubber septum under an atmospheree of argon. Anhydrous tetrahydrofuran (THF) and dichloromethane (CH_2Cl_2) were purchased from Kanto Chemical Co., Inc. Toluene, pyridine, and diisopropylamine ($^iPr_2NH$) were distilled from CaH_2. Hexamethylphosphoramide (HMPA) and dimethyl sulfoxide (DMSO) were distilled from CaH_2 under reduced pressure. Benzene (C_6H_6) and methanol (MeOH) were distilled under argon immediately prior to use. Unless otherwise mentioned, materials were obtained from commercial suppliers and used without further purification. Organic extracts were dried by being stirred over anhydrous $MgSO_4$, filtered through Celite, and concentrated under reduced pressure with the aid of a rotary evaporator. Flash chromatography was carried out using Merck 60 (230−400 mesh) or Cica 60 (spherical/40−100 μm) silica gel. Reactions and chromatography fractions were analyzed by employing precoated silica gel 60 F_{254} plates (Merck). Compounds were visualized using an ultraviolet lamp (254 nm) and/or by staining with *p*-anisaldehyde (in EtOH), phosphomolybdic acid (in EtOH), or ammonium molybdate (in 10% H_2SO_4). IR spectra were recorded as films on NaCl plates unless otherwise noted. ^{1}H NMR spectra were measured as $CDCl_3$ solutions at 300 MHz. Chemical shifts are expressed in ppm downfield from internal tetramethylsilane or relative internal $CHCl_3$. *J* values are in hertz.

(±)-2-*tert*-Butyldimethylsilyloxy-1-methyl-5-(2-methoxymethoxyethyl)-5-(2-propenyl)cyclohexa-1,3-diene (16). To a stirred solution of LDA, prepared from $^iPr_2NH$ (0.71 mL, 5.05 mmol) and butyllithium (1.56 M in hexane, 3.24 mL, 5.05 mmol), in THF (25.0 mL) cooled to −78 °C was added dropwise a THF solution of the ketone **15**[4] (943.8 mg, 4.21 mmol). After 30 min, the mixture was allowed to warm to 0 °C and continued to stir for 1 h. The mixture was cooled to −78 °C, and then MeI (0.79 mL, 12.62 mmol) was added dropwise. The mixture was allowed to warm to 0 °C, and the mixture was stirred for an additional 4 h. The reaction was quenched by addition of saturated aqueous $NaHCO_3$ solution. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with saturated aqueous $NaHCO_3$ solution and brine. After drying of the solvent, followed by concentration, column chromatography of the residue with hexanes−EtOAc (4:1) as an eluent afforded 655 mg (85%) of the corresponding ketone as a colorless oil. IR (neat) cm^{-1}: 1683. ^{1}H NMR δ: 6.70 (0.4H, dd, J = 10.2, 2.2 Hz), 6.67 (0.6H, dd, J = 10.2, 2.2 Hz), 5.93 (1H, d, J = 10.2 Hz), 5.88−5.67 (2H, m), 5.17−5.08 (2H, m), 4.61 (1.2H, s), 4.58 (0.8H, s), 3.66 (1.2H, t, J = 7.0 Hz), 3.64−3.50 (0.8H, m), 3.37 (1.8H, s), 3.34 (1.2H, s), 2.66−2.50 (1H, m), 2.42−2.15 (2H, m), 2.01−1.65 (3H, m), 1.12 (3H, d, J = 6.6 Hz). MS *m*/*z*: 238 (M$^+$). Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.56; H, 9.30. Found: C, 70.75; H, 9.19.

To a stirred solution of LDA, prepared from $^iPr_2NH$ (0.19 mL, 1.34 mmol) and butyllithium (1.57 M in hexane, 0.85 mL, 1.33 mmol), in THF (10 mL) cooled to −78 °C was added dropwise a solution of the above substrate (315 mg, 1.41 mmol) in THF (2 mL). After 45 min, a solution of TBDMSCl (424 mg, 2.81 mmol) and HMPA (0.37 mL, 2.11 mmol) in THF (2 mL) was added at −78 °C, and the resulting mixture was allowed to warm to room temperature. The reaction was quenched by addition of saturated aqueous $NaHCO_3$ solution. After separation, the aqueous layer was extracted three times with hexane. The combined organic layers were washed with saturated aqueous $NaHCO_3$ solution and brine. After drying of the solvent followed by evaporation, the crude product was purified by flash column chromatography with a 20:1 mixture of hexanes−EtOAc (with 2% of triethylamine) as an eluent. The silyl enol ether **16** (328 mg, 91%) was obtained as a colorless oil. ^{1}H NMR δ: 5.85−5.70 (1H, m), 5.67 (1H, d, J = 9.9 Hz), 5.39 (1H, dd, J = 9.9, 0.5 Hz), 5.07−4.97 (2H, m), 4.59 (2H, s), 3.57 (2H, t, J = 7.5 Hz), 3.35 (3H, s), 2.19−2.02 (4H, m), 1.78−1.58 (5H, m), 0.95 (9H, s), 0.10 (6H, s). ^{13}C NMR δ: 141.08, 134.80, 132.78, 125.63, 117.42, 111.04, 96.39, 64.50, 55.05, 43.62, 39.15, 38.10, 36.74, 25.64, 17.91, 16.16, −4.27. MS *m*/*z*: 352 (M$^+$). Anal. Calcd for $C_{20}H_{36}O_3Si$: C, 68.13; H, 10.29. Found: C, 68.04; H, 10.14.

(±)-2-*tert*-Butyldimethylsilyloxy-1-methoxy-5-(2-methoxymethoxyethyl)-5-(2-propenyl)cyclohexa-1,3-diene (17). To a stirred solution of the silyl enol ether **8** (5.14 g, 15.17 mmol) in hexane (50.0 mL) was added *m*-CPBA (65%, 4.03 g, 15.17 mmol) in one portion at −30 °C. After 15 min of stirring at −30 °C, the mixture was stirred at room temperature for 2 h. The mixture was filtered, and then the filtrate was concentrated. The residue was dissolved in THF (50 mL). To the solution was added tetrabutylammonium fluoride (TBAF) (1.0 M in THF, 18.37 mL, 18.37 mmol) at 0 °C, and then the resulting mixture was stirred for 30 min at 0 °C. The mixture was allowed to warm to room temperature and continued to stir at room temperature for 3 h. The solvent was evaporated, and the residue was dissolved in EtOAc. The solution was washed with saturated aqueous NH_4Cl solution and brine. After drying of the solvent, followed by evaporation, the crude product was purified by column chromatography with hexanes−EtOAc (2:1) as an eluent to give 2.43 g (67% for two steps) of the corresponding hydroxy ketone as a colorless oil. IR (neat) cm^{-1}: 3420, 1685. ^{1}H NMR δ: 6.80 (0.5H, dd, J = 10.1, 2.2 Hz), 6.77 (0.5H, dd, J = 10.1, 2.2 Hz), 6.04 (1H, d, J = 10.1 Hz), 5.92−5.63 (1H, m), 5.21−5.08 (2H, m), 4.62 (1H, s), 4.57 (1H, s), 4.42 (0.5H, t, J = 5.4 Hz), 4.37 (0.5H, t, J = 5.4 Hz), 3.69 (1H, t, J = 6.7 Hz), 3.65−3.50 (2H, m), 3.37 (1.5H, s), 3.33 (1.5H, t, J = 0.5 Hz), 2.40−2.20 (3H, m), 2.02−1.78 (3H, m). MS *m*/*z*: 195 (M$^+$ − 45). Anal. Calcd for $C_{13}H_{20}O_4$: C, 64.98; H, 8.39. Found: C, 64.97; H, 8.20.

A mixture of the above hydroxy ketone (1.06 g, 4.39 mmol), MeI (10 mL), Ag_2O (1.22 g, 5.27 mmol), and a small amount of anhydrous $CaSO_4$ was stirred in a sealed tube at room temperature for 24 h. Ag_2O (1.22 g, 5.27 mmol) was added to the mixture, and then the mixture was stirred for an additional 24 h. The mixture was filtered, and then the filtrate was concentrated. Column chromatography of the crude product with hexanes−EtOAc (2:1) as an eluent gave rise to 931.8 mg (83%) of the methoxy ketone as a colorless oil. IR (neat) cm^{-1}: 1693. ^{1}H NMR δ: 6.69 (0.4H, dd, J = 10.2, 1.9 Hz), 6.66 (0.6H, dd, J = 10.2, 1.9 Hz), 5.93 (1H, d, J = 10.2 Hz), 5.89−5.65 (1H, m), 5.22−5.08 (2H, m), 4.62 (1.2H, s), 4.57 (0.8H, s), 3.97 (0.4H, dd, J = 12.6, 5.5 Hz), 3.97 (0.6H, dd, J = 12.6, 5.5 Hz), 3.67 (1.2H, td, J = 6.6, 1.6 Hz), 3.65−3.51 (0.8H, m), 3.55 (1.2H, s), 3.54 (1.8H, s), 3.38 (1.2H, s), 3.33 (1.8H, s), 2.42−2.10 (3H, m), 2.03−1.79 (3H, m). MS *m*/*z*: 254 (M$^+$). Anal. Calcd for $C_{14}H_{22}O_4$: C, 66.12; H, 8.72. Found: C, 66.01; H, 8.79.

The silyl enol ether **17** was obtained in 82% yield according to the procedure described before. ^{1}H NMR δ: 5.86−5.72 (1H, m), 5.66 (1H, d, J = 9.9 Hz), 5.20 (1H, d, J = 9.9 Hz), 5.10−5.01 (2H, m), 4.60 (2H, s), 3.59 (2H, t, J = 7.4 Hz), 3.58 (3H, s), 3.35 (3H, s), 2.31 (1H, d, J = 1.4 Hz), 2.17 (2H, t, J = 7.4 Hz), 1.81−1.61 (2H, m), 0.94 (9H, s), 0.12 (6H, s). ^{13}C NMR δ: 136.50, 134.59, 130.61, 128.76, 126.08, 117.82, 96.42, 64.41, 56.11, 55.09, 43.54, 38.60, 38.04, 34.08, 26.12, 25.61, 18.00, −4.71. HRMS calcd for $C_{20}H_{36}O_4Si$ (M$^+$): 368.2383. Found: 368.2407.

(±)-5-Isobutoxy-2-hydroxy-2-(2-propenyl)cyclohex-5-en-1-one (19). To a stirred solution of LDA, prepared from

$^{i}Pr_2NH$ (2.44 mL, 17.42 mmol) and butyllithium (1.56 M in hexane, 11.17 mL, 17.42 mmol), in THF (25 mL) cooled to −78 °C was added dropwise a THF solution of the ketone **18**[7] (3.30 g, 15.83 mmol). After 30 min, the mixture was allowed to warm to 0 °C and continued to stir at 0 °C for 1 h. The mixture was cooled to −78 °C, and then oxodiperoxymolybdenum−pyridine−hexamethylphosphoric triamide (MoOPH) (10.3 g, 23.75 mmol) was added in one portion. The resulting mixture was stirred at −78 °C for 1 h and at 0 °C for 1 h. The reaction was quenched by addition of saturated aqueous Na_2SO_3 solution. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with 10% HCl solution and brine, followed by drying and concentration. Column chromatography of the residue with hexanes−EtOAc (5:1) as an eluent furnished 2.88 (81%) of the hydroxy ketone **19** as a colorless oil. IR (neat) cm^{-1}: 3450, 1650. ^1H NMR δ: 5.94−5.80 (1H, m), 5.34 (1H, d, J = 1.4 Hz), 5.18−5.09 (2H, m), 3.79 (1H, s), 3.68−3.58 (2H, m), 2.62−2.40 (2H, m), 2.34 (2H, d, J = 7.7 Hz), 2.18 (1H, ddd, J = 13.2, 5.2, 2.5 Hz), 2.12−1.90 (2H, m), 0.99 (6H, d, J = 6.9 Hz). ^{13}C NMR δ: 201.21, 177.68, 132.80, 118.73, 98.98, 75.31, 73.84, 41.39, 31.30, 27.64, 27.18, 18.95, 18.92 MS *m/z*: 224 (M^+). Anal. Calcd for $C_{13}H_{20}O_3$: C, 69.61; H, 8.98. Found: C, 69.81; H, 9.17.

(±)-4-Hydroxy-4-(2-propenyl)cyclohex-2-en-1-one (20). A THF solution of the hydroxy ketone **19** (2.31 g, 10.28 mmol) was added dropwise to a solution of $LiAlH_4$ (780.3 mg, 20.56 mmol) in THF (40 mL) at 0 °C. After stirring for 45 min, the reaction was quenched by successive addition of 0.84 mL of water, 0.84 mL of 15% NaOH solution, and 2.52 mL of water. After being stirred for 30 min, two spoonful of $MgSO_4$ were added, and then the mixture was stirred for an additional 15 min. The mixture was filtered, and then the filtrate was concentrated. The residue was dissolved in 20 mL of THF. To the solution was added dropwise aqueous 15% $HClO_4$ solution (20 mL) at 0 °C with continuous stirring. After 10 min, the mixture was neutralized by addition of saturated aqueous K_2CO_3 solution. The mixture was extracted three times with Et_2O. The combined organic layers were washed with brine and dried. After removal of the solvent, the crude product was purified by flash column chromatography with hexanes−EtOAc (3:1) as an eluent to give 994.7 mg (64% for two steps) of the enone **20** as a colorless oil. IR (neat) cm^{-1}: 3414, 1668. ^1H NMR δ: 6.76 (1H, dt, J = 10.2, 0.8 Hz), 5.95 (1H, dt, J = 10.2, 0.8 Hz), 5.94−5.83 (1H, m), 5.31−5.21 (2H, m), 2.70−2.38 (4H, m), 2.21−2.04 (2H, m), 2.47 (1H, s). MS *m/z*: 152 (M^+). Anal. Calcd for $C_9H_{12}O_2$: C, 71.02; H, 7.94. Found: C, 71.03; H, 7.97.

(±)-2-*tert*-Butyldimethylsilyloxy-5-(2-propenyl)-5-[2-(trimethylsilyl)ethoxymethoxy]cyclohexa-1,3-diene (21). To a solution of alcohol **20** (462.8 mg, 3.04 mmol) in CH_2Cl_2 (15 mL) were added successively SEMCl (0.67 mL, 3.95 mmol) and $^{i}Pr_2NEt$ (1.06 mL, 6.08 mmol) at 0 °C. The resulting mixture was stirred at room temperature for 4 days. The mixture was quenched by addition of saturated aqueous NH_4Cl solution. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with brine, dried, and concentrated. Purification of the crude product by flash column chromatography with hexanes−EtOAc (6:1) as an eluent afforded 584.7 mg (73%) of the corresponding SEM ether as a colorless oil. IR (neat) cm^{-1}: 1680. ^1H NMR δ: 5.86 (1H, d, J = 10.3, Hz), 6.01 (1H, d, J = 10.3, Hz), 5.90−5.80 (1H, m), 5.18−5.11 (2H, m), 4.80 (2H, J = 0.8 Hz), 3.66−3.61 (2H, m), 2.68−2.00 (6H, m), 0.93−0.87 (2H, m), 0.01 (9H, s). MS *m/z*: 209 (M^+ − 73). Anal. Calcd for $C_{15}H_{26}O_3Si$: C, 63.78; H, 9.27. Found: C, 63.59; H, 9.30.

The silyl enol ether **21** (88%) was synthesized from the above ketone according to the procedure described before. ^1H NMR δ: 5.90−5.76 (1H, m), 5.87 (1H, dd, J = 9.9, 2.4 Hz), 5.67 (1H, d, J = 9.9 Hz), 5.09−5.02 (2H, m), 4.94−4.87 (1H, m), 4.72 (2H, dd, J = 13.7, 6.7 Hz), 3.62 (2H, dd, J = 9.3, 7.7 Hz), 2.60−2.35 (3H, m), 3.35 (3H, s), 2.31 (1H, d, J = 1.4 Hz), 2.17 (2H, t, J = 7.4 Hz), 1.81−1.61 (4H, m), 0.94−0.88 (2H, m), 0.92 (9H, s), 0.12 (6H, s), 0.01 (9H, s). ^{13}C NMR δ: 146.75, 133.98, 130.79, 129.00, 117.82, 102.658, 90.10, 74.81, 65.10, 45.18, 33.38, 25.56, 18.00, −1.57, −4.63. HRMS calcd for $C_{17}H_{30}O_3Si_2$ (M^+ − 58): 338.1733 Found: 338.2127.

2-*tert*-Butyldimethylsiloxy-5-methylthiomethoxy-5-(2-propenyl)cyclohexa-1,3-diene (22). A mixture of the hydroxy ketone **20** (81.7 mg, 0.51 mmol), acetic anhydride (3 mL, 32 mmol), and DMSO (3 mL, 42 mmol) was stirred at room temperature for 47 h. After removal of the excess reagents, the residue was extracted three times with Et_2O. The combined ethereal layers were washed with brine, dried, and evaporated to yield an oil, which was chromatographed with hexanes−EtOAc (5:1) as an eluent to provide the corresponding methyl thiomethyl ether (51.8 mg, 65%). IR (neat) cm^{-1}: 1680. ^1H NMR δ: 6.90 (1H, d, J = 10.4 Hz), 5.89−5.84 (1H, m), 5.20−5.13 (2H, m), 4.62 (2H, s), 2.71−2.20 (5H, m), 2.20 (3H, s), 2.11−2.01 (1H, m). ^{13}C NMR δ: 198.69, 151.74, 132.29, 130.83, 119.12, 75.58, 68.23, 42.20, 34.23, 31.26, 14.28. HRMS calcd for $C_{11}H_{16}O_2S$ (M^+): 212.0870. Found: 212.0913.

The silyl enol ether **22** (62%) was prepared from the above ketone according to the procedure described before. IR (neat) cm^{-1}: 1645. ^1H NMR δ: 5.91, (1H, dd, J = 10.2, 2.3 Hz), 5.81−5.57 (1H, m), 5.53 (1H, dd, J = 10.2, 0.6), 5.05−4.98 (2H, m), 4.97−4.89 (1H, m), 4.41 (2H, s), 2.43 (2H, d, J = 4.7 Hz), 2.36−2.33 (2H, m), 2.11 (3H, s), 0.88 (9H, s), 0.08 (6H, s). ^{13}C NMR δ: 146.74, 133.82, 129.93, 128.98, 118.02, 102.85, 74, 69, 45.96, 32.42, 25.57, 17.86, 14.37, −4.58. HRMS calcd for $C_{15}H_{25}OSi$ (M^+): 249.1645. Found: 249.1945.

(±)-4-Oxo-1-(2-propenyl)-2-cyclohexene-1-methanol (23). To a stirred solution of LDA, prepared from $^{i}Pr_2NH$ (6.25 mL, 44.60 mmol) and butyllithium (1.50 M in hexane, 28.50 mL, 42.74 mmol), in THF (150 mL) cooled to −78 °C was added dropwise a THF solution of the ketone **18**[7] (7.74 g, 37.17 mmol). The mixture was stirred at −78 °C for 45 min. To the mixture were successively added HMPA (7.44 mL, 42.74 mmol) and methyl cyanoformate (3.54 mL, 44.60 mmol), and the resulting mixture was stirred at −78 °C for an additional 45 min. The reaction was quenched by addition of water. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with brine, dried, and concentrated. Flash column chromatography of the residue with hexanes−EtOAc (3:1) as an eluent furnished 9.19 g (93%) of the corresponding keto ester as a colorless oil. IR (neat) cm^{-1}: 1725, 1655. ^1H NMR δ: 5.82−5.68 (1H, m), 5.36 (1H, s), 5.14−5.07 (2H, m), 3.71 (3H, s), 3.60 (2H, d, J = 6.6 Hz), 2.77−2.50 (3H, m), 2.44−2.32 (2H, m), 2.07−1.91 (2H, m), 0.97 (6H, d, J = 6.6 Hz). ^{13}C NMR δ: 195.12, 177.14, 171.87, 133.48, 118.58, 101.78, 74.69, 55.41, 52.13, 38.44, 27.90, 27.42, 25.93, 18.73. MS *m/z*: 266 (M^+). Anal. Calcd for $C_{15}H_{22}O_4$: C, 67.64; H, 8.33. Found: C, 67.72; H, 8.26.

A THF solution of the above keto ester (14.06 g, 52.79 mmol) was added dropwise to a solution of $LiAlH_4$ (2.21 g, 58.33 mmol) in THF (130 mL) at 0 °C. The mixture was stirred at 0 °C for 30 min and at room temperature for 20 min. The reaction was quenched by successive addition of 2.21 mL of water, 2.21 mL of 15% NaOH solution, and 6.63 mL of water. After being stirred for 30 min, two spoonfuls of $MgSO_4$ were added, and then the mixture was stirred for an additional 30 min. The mixture was filtered. After the filtrate was concentrated, the residue was dissolved in 80 mL of THF. To the solution was added dropwise aqueous 15% $HClO_4$ solution (20 mL) at 0 °C, and then the mixture was stirred at room temperature for 30 min. The mixture was neutralized at 0 °C by addition of saturated aqueous K_2CO_3 solution. The mixture was extracted three times with EtOAc. The combined organic layers were washed with brine and dried. After removal of the solvent, the crude product was purified by flash column chromatography with hexanes−EtOAc (1:1) as an eluent to give 7.29 g (83% for two steps) of the enone **23** as a colorless oil. IR (neat) cm^{-1}: 3393, 1668. ^1H NMR δ: 6.78 (1H, d, J = 10.3), 6.05 (1H, d, J = 10.3), 5.89−5.74 (1H, m), 5.20−5.13 (2H, m), 3.66−3.55 (2H, m), 2.57−2.42 (2H, m), 2.31 (2H, d, J = 7.4 Hz), 2.04−1.86 (2H, m), 1.60 (1H, s). ^{13}C NMR δ: 200.28, 155.76, 133.02, 129.12, 118.63, 66.51, 40.73, 39.42, 33.38, 27.82. HRMS calcd for $C_{10}H_{14}O_2$ (M^+): 166.0994. Found: 166.0998.

(±)-4-Methoxymethoxymethyl-4-(2-propenyl)cyclohex-2-en-1-one (24). To a solution of the alcohol **23** (3.02 g, 18.16 mmol) in CH_2Cl_2 (100 mL) were added successively $^iPr_2NEt$ (2.75 mL, 36.33 mmol) and MOMCl (9.49 mL, 54.49 mmol) at 0 °C. The resulting mixture was stirred at room temperature for 12 h. The solvent was evaporated, and then the residue was dissolved in hexane. To the solution was added saturated aqueous $KHSO_4$ solution, and then the mixture was separated. The organic layer was washed with saturated aqueous $KHSO_4$ solution and saturated aqueous $NaHCO_3$ solution. After drying of the solvent followed by evaporation, the crude product was purified by flash column chromatography with hexanes−EtOAc (4:1) as an eluent to give rise to 3.56 g (94%) of the methoxymethyl (MOM) ether **24** as a colorless oil. IR (neat) cm^{-1}: 1680. ^1H NMR δ: 6.77 (1H, d, J = 10.3 Hz), 6.02 (1H, d, J = 10.3 Hz), 5.86−5.72 (1H, m), 5.16−5.10 (2H, m), 4.63 (2H, s), 3.46 (2H, dd, J = 17.0, 9.3 Hz), 3.37 (3H, s), 2.49 (2H, t, J = 6.9 Hz), 2.32 (2H, d, J = 7.7 Hz), 2.05−1.87 (2H, m). ^{13}C NMR δ: 199.19, 154.58, 133.02, 129.38, 118.90, 96.57, 71.96, 55.17, 39.94, 39.59, 33.56, 28.58. HRMS calcd for $C_{11}H_{16}O_2$ (M^+): 180.1150. Found: 180.1145.

(±)-2-*tert*-Butyldimethylsilyloxy-1-methyl-5-methoxymethoxymethyl-5-(2-propenyl)cyclohexa-1,3-diene (25). The silyl enol ether **25** (90%) was obtained from **24** according to the procedure described before. ^1H NMR δ: 5.85−5.70 (1H, m), 5.72 (1H, d, J = 9.9 Hz), 5.04 (1H, d, J = 9.9 Hz), 5.06−4.99 (2H, m), 4.61 (2H, s), 3.35 (3H, s), 3.33 (2H, dd, J = 13.8, 9.2 Hz), 2.21−2.01 (4H, m), 1.64 (3H, s), 0.96 (9H, s), 0.10 (6H, s). ^{13}C NMR δ: 141.21, 134.93, 130.79, 126.62, 117.47, 111.08, 96.85, 72.37, 55.19, 40.24, 39.07, 36.43, 25.75, 18.04, 16.33, −4.17. MS m/z: 338 (M^+). Anal. Calcd for $C_{19}H_{34}O_3Si$: C, 66.62; H, 9.94. Found: C, 66.53; H, 10.03.

(±)-5-Benzyloxymethyl-2-*tert*-butyldimethylsilyloxy-5-(2-propenyl)cyclohexa-1,3-diene (26). To a solution of the alcohol **23** (210.4 mg, 1.27 mmol) in DMF (3 mL) cooled to −40 °C was added NaH (60% in oil, 85.0 mg, 2.13 mmol). After 30 min, the mixture was allowed to warm gradually to 0 °C and then continued to stir at 0 °C for 1 h. The reaction was quenched by addition of saturated aqueous NH_4Cl solution. The mixture was extracted three times with Et_2O. The combined ethereal layers were washed with brine, dried, and concentrated. Flash chromatography of the residue with hexanes−EtOAc (8:1) as an eluent afforded 186.5 mg (57%) of the corresponding benzyl ether as a colorless oil. IR (neat) cm^{-1}: 1682. ^1H NMR δ: 7.39−7.27 (5H, m), 6.79 (1H, d, J = 10.3 Hz), 5.99 (1H, d, J = 10.3 Hz), 5.82−5.68 (1H, m), 5.14−5.07 (2H, m), 4.52 (2H, s), 3.37 (2H, dd, J = 16.5, 9.1 Hz), 2.45 (2H, t, J = 7.0 Hz), 2.32 (2H, dd, J = 7.4, 1.1 Hz), 2.04−1.84 (2H, m). ^{13}C NMR δ: 199.52, 154.91, 138.08, 133.28, 129.32, 128.42, 127.71, 127.50, 118.87, 74.21, 73.30, 40.03, 33.69, 28.68. MS m/z: 256 (M^+). Anal. Calcd for $C_{17}H_{20}O_2$: C, 79.65; H, 7.86. Found: C, 79.28; H, 7.62.

The silyl enol ether **26** (76%) was prepared from the above ketone according to the procedure described before. ^1H NMR δ: 7.35−7.26 (5H, m), 5.84−5.70 (1H, m), 5.71 (1H, dd, J = 9.9, 2.0 Hz), 5.60 (1H, d, J = 9.9 Hz), 5.05−4.98 (2H, m), 4.76 (1H, td, J = 4.5, 2.2 Hz), 4.50 (2H, s), 3.27 (2H, dd, J = 23.3, 8.8 Hz), 2.31−2.09 (4H, m), 0.91 (9H, s), 0.11 (6H, d, J = 1.4 Hz)). ^{13}C NMR δ: 147.44, 138.84, 135.06, 134.16, 128.38, 127.50, 126.28, 117.44, 101.25, 74.12, 73.22, 39.80, 38.76, 29.59, 25.61, 17.94, −4.62. HRMS calcd for $C_{23}H_{34}O_2Si$ (M^+): 370.2328 Found: 370.2318.

(±)-2-*tert*-Butyldimethylsilyloxy-1-methyl-5-methoxymethoxymethyl-5-(2-propenyl)cyclohexa-1,3-diene (27). To a stirred solution of LDA, prepared from $^iPr_2NH$ (0.44 mL, 3.15 mmol) and butyllithium (2.66 M in hexane, 1.14 mL, 3.02 mmol), in THF (13.0 mL) cooled to −78 °C was added dropwise a THF solution of the ketone **24** (529.4 mg, 2.52 mmol). After 30 min, the mixture was allowed to warm to 0 °C and continued to stir for 30 min. The mixture was cooled to −78 °C, and then MeI (0.78 mL, 12.59 mmol) was added dropwise. After 2 h of stirring at −78 °C, the mixture was allowed to warm to 0 °C and stirred at 0 °C for an additional 2 h. The reaction was quenched by addition of saturated aqueous NH_4Cl solution. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with saturated aqueous NH_4Cl solution and brine. After drying of the solvent followed by concentration, column chromatography of the residue with hexanes−EtOAc (6:1) as an eluent afforded 406.4 mg (72%) of the corresponding methyl ketone as a colorless oil. IR (neat) cm^{-1}: 1683. ^1H NMR δ: 6.74 (0.6H, dd, J = 10.2, 1.9 Hz), 6.64 (0.4H, dd, J = 10.2, 2.2 Hz), 6.00 (1H, d, J = 10.2 Hz), 5.98 (1H, d, J = 10.2 Hz), 5.89−5.68 (1H, m), 5.16−5.08 (2H, m), 4.63 (1.2H, s), 4.62 (0.8H, s), 3.55 (0.8H, dd, J = 12.2, 9.5 Hz), 3.38 (1.2H, dd, J = 31.8, 9.3 Hz), 3.37 (1.2H, s), 3.36 (1.8H, s), 2.70−2.54 (1H, m), 2.47−2.18 (2H, m), 2.02−1.86 (1H, m), 1.79−1.60 (1H, m), 1.13 (1.2H, dd, J = 6.6 Hz), 1.12 (1.8H, d, J = 6.6 Hz). MS m/z: 194 (M^+ − 30). Anal. Calcd for $C_{13}H_{20}O_3$: C, 69.61; H, 8.99. Found: C, 69.61; H, 9.04.

The silyl enol ether **27** (92%) was synthesized from the above ketone according to the procedure described before. ^1H NMR δ: 5.85−5.70 (1H, m), 5.72 (1H, d, J = 9.9 Hz), 5.04 (1H, d, J = 9.9 Hz), 5.06−4.99 (2H, m), 4.61 (2H, s), 3.35 (3H, s), 3.33 (2H, dd, J = 13.8, 9.2 Hz), 2.21−2.01 (4H, m), 1.64 (3H, s), 0.96 (9H, s), 0.10 (6H, s). ^{13}C NMR δ: 141.21, 134.93, 130.79, 126.62, 117.47, 111.08, 96.85, 72.37, 55.19, 40.24, 39.07, 36.43, 25.75, 18.04, 16.33, −4.17. MS m/z: 338 (M^+). Anal. Calcd for $C_{19}H_{34}O_3Si$: C, 66.62; H, 9.94. Found: C, 66.53; H, 10.03.

General Procedure for Palladium-Catalyzed Cycloalkenylation (Tables 2 and 3). To a solution of the TBDMS enol ether in DMSO or aqueous media (0.1 M) was added palladium catalyst (10 mol %) at room temperature. The resulting mixture was stirred under 1 atm of oxygen at the temperature as shown in Tables 2 and 3. The reaction was monitored by TLC. After completion of the reaction, the mixture was diluted with Et_2O and filtered to remove palladium black. Water was added to the filtrate, and the layers were separated. The aqueous layer was extracted three times with Et_2O. The combined ethereal layers were washed with ice-cold 10% HCl solution, saturated aqueous $NaHCO_3$ solution, and brine. After drying of the solvent followed by evaporation, the crude product was purified by column chromatography with hexanes−EtOAc as an eluent. All the products were obtained as a colorless oil.

(±)-1,7-Dimethyl-5-(2-methoxymethoxyethyl)-*cis*-bicyclo[3.2.1]octa-3,6-dien-2-one (30: X = Me, R = $-CH_2CH_2OMOM$). IR (neat) cm^{-1}: 1683. ^1H NMR δ: 7.24 (1H, dd, J = 9.6, 1.9 Hz), 6.02 (1H, br s), 5.37 (1H, d, J = 9.6 Hz), 4.62 (2H, s), 3.66 (2H, t, J = 6.8 Hz), 3.36 (3H, s), 2.49 (1H, d, J = 9.6), 2.25 (1H, dd, J = 9.9, 1.9), 2.08−1.84 (2H, m), 1.62 (3H, d, J = 1.6 Hz), 1.22 (3H, s). ^{13}C NMR δ: 201.89, 159.83, 145.47, 139.72, 121.65, 96.52, 64.64, 61.74, 0.61.45, 0.55.27, 49.50, 35.20, 16.44, 12.75. MS m/z: 236 (M^+). Anal. Calcd for $C_{14}H_{20}O_3$: C, 71.16; H, 8.53. Found: C, 71.16; H, 8.60.

(±)-1-Methyl-7-methylidene-5-(2-methoxymethoxyethyl)-*cis*-bicyclo[3.2.1]oct-3-en-2-one (29: X = Me, R = $-CH_2CH_2OMOM$). IR (neat) cm^{-1}: 1683. ^1H NMR δ: 7.10 (1H, dd, J = 9.6, 2.1 Hz), 5.83 (1H, d, J = 9.6 Hz), 5.09−5.07 (2H, m), 4.62 (2H, s), 3.67 (2H, td, J = 6.6, 0.8 Hz), 3.36 (3H, s), 2.58 (1H, ddd, J = 15.6, 2.5, 2.5 Hz), 2.47 (1H, ddd, J = 15.6, 4.0, 1.8 Hz), 2.10 (1H, dd, J = 11.3, 2.5 Hz), 2.06−1.84 (2H, m), 1.67 (1H, dd, J = 11.3, 2.2 Hz), 1.32 (3H, s). ^{13}C NMR δ: 200.00, 157.90, 149.78, 126.49, 111.20, 96.49, 64.87, 57.69, 55.27, 52.19, 43.71, 43.64, 37.22, 17.68. MS m/z: 236 (M^+) Anal. Calcd for $C_{14}H_{20}O_3$: C, 71.16; H, 8.53. Found: C, 71.16; H, 8.48.

(±)-5-Benzyloxymethyl-7-methylidene-*cis*-bicyclo[3.2.1]-oct-3-en-2-one (29: X = H, R = $-CH_2OBn$). IR (neat) cm^{-1}: 1681. ^1H NMR δ: 7.41−7.28 (5H, m), 7.16 (1H, dd, J = 9.9, 1.9 Hz), 5.84 (1H, dd, J = 9.6, 1.6 Hz), 5.29 (1H, br s), 5.05 (1H, br s), 4.59 (2H, s), 3.56 (2H, dd, J = 11.0, 9.1 Hz), 3.47 (1H, d, J = 4.9 Hz), 2.48 (1H, dt, J = 15.9, 2.5 Hz), 2.38 (1H, dd, J = 15.9, 1.6 Hz), 2.14 (1H, dd, J = 11.2, 2.5 Hz), 1.83 (1H, ddd, J = 11.2, 5.0, 1.9 Hz). ^{13}C NMR δ: 198.91, 156.43, 145.08, 138.11, 128.53, 127.83, 127.60, 126.66, 112.40, 74.27, 73.45, 58.46, 47.61, 42.76, 39.52. HRMS calcd for $C_{17}H_{18}O_2$ (M^+): 254.1307. Found: 254.1295.

(±)-5-Benzyloxymethyl-7-methyl-*cis*-bicyclo[3.2.1]octa-3,6-dien-2-one (30: X = H, R = −CH_2OBn). IR (neat) cm^{-1}: 1683. ^1H NMR δ: 7.41−7.24 (5H, m), 7.29 (1H, dd, J = 9.8, 1.6 Hz), 6.05 (1H, q, J = 1.6 Hz), 5.40 (1H, dd, J = 9.8, 1.6 Hz), 4.60 (2H, s), 3.55 (2H, dd, J = 12.4, 9.1 Hz), 3.17 (1H, dd, J = 4.0, 1.2 Hz), 2.58−2.45 (2H, m), 1.79 (3H, d, J = 1.6 Hz). ^{13}C NMR δ: 157.50, 143.57, 138.20, 136.98, 137.02, 128.56, 127.86, 127.69, 122.30, 73.51, 72.72, 61.79, 53.57, 53.35, 15.47. HRMS calcd for $C_{17}H_{18}O_2$ (M^+): 254.1307. Found: 254.1295.

(±)-4-Benzyloxymethyl-4-(2-propenyl)cyclohexa-2,5-dien-1-one (31: X = H, R = −CH_2OBn). IR (neat) cm^{-1}: 1664. ^1H NMR δ: 7.40−7.22 (5H, m), 6.87 (1H, d, J = 10.2 Hz), 6.87 (1H, dd, J = 11.3, 4.7 Hz), 6.35 (1H, d, J = 10.2 Hz), 6.35 (1H, dd, J = 11.3, 4.7 Hz), 5.65−5.40 (1H, m), 5.10−5.00 (2H, m), 4.52 (2H, s), 3.45 (2H, s), 2.46 (2H, d, J = 7.4 Hz). ^{13}C NMR δ: 168.59, 151.88, 137.74, 132.06, 130.65, 128.57, 127.95, 127.63, 119.12, 74.51, 73.57, 39.68, 33.85. HRMS calcd for $C_{17}H_{18}O_2$ (M^+): 254.1307. Found: 254.1295.

(±)-3-[7-Methyl-2-oxo-*cis*-bicyclo[3.2.1]octa-3,6-dien-5-yl]propyl 2,2-Dimethylpropanoate (30: X = H, R = −$CH_2CH_2CH_2OPv$). IR (neat) cm^{-1}: 1729, 1683. ^1H NMR δ: 7.13 (1H, dd, J = 9.6, 1.6 Hz), 5.94 (1H, d, J = 1.6 Hz), 5.38 (1H, dd, J = 9.6, 1.9 Hz), 4.13−4.09 (2H, m), 3.16 (1H, dd, J = 4.0, 1.6 Hz), 2.50 (1H, d, J = 9.6 Hz), 2.45 (1H, dd, J = 4.4, 1.6 Hz), 1.78 (3H, d, J = 1.64 Hz), 1.75−1.61 (3H, m), 1.21 (9H, s). ^{13}C NMR δ: 200.05, 178.67, 159.71, 143.12, 138.97, 122.23, 64.20, 62.00, 54.76, 51.90, 38.66, 31.61, 27.08, 24.61, 15.42. MS m/z: 276 (M^+). Anal. Calcd for $C_{17}H_{24}O_3$: C, 73.88; H, 8.75. Found: C, 73.67; H, 8.82.

(±)-3-[1-Oxo-4-(2-propenyl)cyclohexa-2,5-dien-4-yl]propyl 2,2-Dimethylpropanoate (31: X = H, R = −$CH_2CH_2CH_2OPv$). IR (neat) cm^{-1}: 1728, 1667. ^1H NMR δ: 6.72 (1H, d, J = 10.3 Hz), 6.72 (1H, dd, J = 11.2, 4.9 Hz), 6.36 (1H, d, J = 10.3 Hz), 6.36 (1H, dd, J = 11.2, J = 4.9 Hz), 5.65−5.51 (1H, m), 5.08−5.01 (2H, m), 3.99 (2H, t, J = 6.5 Hz), 2.37 (2H, d, J = 7.4 Hz), 1.74−1.68 (2H, m), 1.54−1.41 (2H, m), 1.19 (9H, s). ^{13}C NMR δ: 186.49, 178.63, 153.85, 132.05, 130.67, 119.13, 63.84, 45.41, 44.02, 38.68, 34.96, 27.10, 23.95. HRMS calcd for $C_{17}H_{24}O_3$ (M^+): 276.1725. Found: 276.1766.

(±)-7-Methylidene-5-methoxymethoxymethyl-*cis*-bicyclo[3.2.1]oct-3-en-2-one (29: X = H, R = −CH_2OMOM) IR (neat) cm^{-1}: 1683. ^1H NMR δ: 7.15 (1H, dd, J = 9.6, 1.9 Hz), 5.86 (1H, dd, J = 9.6, 1.9 Hz), 5.30 (1H, br s), 5.07 (1H, br s), 4.68 (2H, s), 3.66 (2H, dd, J = 15.2, 9.4 Hz), 3.49 (1H, d, J = 4.9 Hz), 3.40 (3H, s), 2.48−2.41 (2H, m), 2.16 (1H, dd, J = 11.3, 2.2 Hz), 1.85 (1H, ddd, J = 11.3, 4.9, 1.9 Hz). MS m/z: 208 (M^+). Anal. Calcd for $C_{12}H_{13}O_3$: C, 69.21; H, 7.74. Found: C, 69.15; H, 7.92.

(±)-7-Methyl-5-methoxymethoxymethyl-*cis*-bicyclo-[3.2.1]oct-3,6-dien-2-one (30: X = H, R = −CH_2OMOM). IR (neat) cm^{-1}: 1683. ^1H NMR δ: 7.28 (1H, dd, J = 9.9, 1.6 Hz), 6.04 (1H, q, J = 1.9 Hz), 5.42 (1H, dd, J = 9.9, 1.6 Hz), 4.67 (2H, s), 3.65 (2H, dd, J = 13.1, 9.4 Hz), 3.40 (3H, s), 3.19 (1H, dd, J = 4.1, 1.5 Hz), 2.58−2.48 (2H, m), 1.80 (3H, d, J = 1.9 Hz). ^{13}C NMR δ: 199.90, 157.09, 143.77, 136.79, 136.73, 122.38, 96.75, 70.30, 61.77, 55.26, 53.01, 15.44. HRMS calcd for $C_{12}H_{16}O_3$ (M^+): 208.1099. Found: 208.1107.

(±)-4-Methoxymethoxymethyl-4-(2-propenyl)cyclohexa-2,5-dien-1-one (31: X = H, R = −CH_2OMOM). IR (neat) cm^{-1}: 1666. ^1H NMR δ: 6.86 (1H, d, J = 10.4 Hz), 6.85 (1H, dd, J = 11.2, 4.8 Hz), 6.36 (1H, d, J = 10.4 Hz), 6.37 (1H, dd, J = 11.2, 4.8 Hz), 5.66−5.52 (1H, m), 5.10−5.04 (2H, m), 4.60 (2H, s), 3.55 (2H, s), 3.34 (3H, s), 2.65 (2H, dt, J = 7.4, 1.0 Hz). ^{13}C NMR δ: 186.36, 151.62, 131.85, 130.80, 119.25, 96.69, 72.16, 55.49, 46.14, 39.74. HRMS calcd for $C_{12}H_{16}O_3$ (M^+): 208.1099. Found: 208.1066.

(±)-1-Methoxy-7-methyl-5-(2-methoxymethoxyethyl)-*cis*-bicyclo[3.2.1]octa-3,6-dien-2-one (30: X = OMe, R = −CH_2CH_2OMOM). IR (neat) cm^{-1}: 1689. ^1H NMR δ: 7.24 (1H, dd, J = 9.6, 1.6 Hz), 6.07 (1H, dd, J = 1.6, 0.8 Hz), 5.51 (1H, d, J = 9.6 Hz), 4.63 (2H, s), 3.69 (2H, t, J = 6.5 Hz), 3.37 (3H, s), 3.36 (3H, s), 2.71 (1H, d, J = 9.1 Hz), 2.52 (1H, dd, J = 9.1, 1.6 Hz), 2.12−1.90 (2H, m), 1.69 (3H, d, J = 1.6 Hz). ^{13}C NMR δ: 197.25, 160.03, 144.44, 139.10, 123.00, 99.17, 96.55, 64.41, 57.51, 53.35, 52.27, 50.07, 35.57, 11.68. HRMS calcd for $C_{14}H_{20}O_4$ (M^+): 252.1362. Found: 252.1324.

(±)-2-Methoxy-4-(2-methoxymethoxyethyl)-4-(2-propenyl)cyclohexa-2,5-dien-1-one (31, X = OMe, R = −CH_2CH_2OMOM). IR (neat) cm^{-1}: 1666. ^1H NMR δ: 6.80 (1H, dd, J = 9.9, 2.5 Hz), 6.35 (1H, d, J = 9.9 Hz), 5.67 (1H, d, J = 2.5 Hz), 5.65−5.53 (1H, m), 5.09−5.01 (2H, m), 4.50 (2H, s), 3.67 (3H, s), 3.37 (2H, td, J = 6.9, 2.2 Hz), 3.29 (3H, s), 2.40 (2H, d, J = 7.4 Hz), 2.02 (2H, td, J = 6.9, 2.2 Hz). ^{13}C NMR δ: 181.53, 154.37, 151.97, 132.22, 129.15, 120.36, 119.18, 96.55, 64.08, 55.23, 54.79, 45.00, 44.75, 39.24. HRMS calcd for $C_{14}H_{20}O_4$ (M^+): 252.1362. Found: 252.1318.

(±)-1-Methoxy-7-methylidene-5-(2-methoxymethoxyethyl)-*cis*-bicyclo[3.2.1]oct-3-en-2-one (29: X = OMe, R = −CH_2CH_2OMOM). IR (neat) cm^{-1}: 1694. ^1H NMR δ: 7.13 (1H, dd, J = 9.6, 2.1 Hz), 5.93 (1H, d, J = 9.6 Hz), 5.38 (1H, dd, J = 3.0, 1.9 Hz), 5.22 (1H, br s), 4.62 (2H, s), 3.69 (2H, t, J = 6.3 Hz), 3.39 (3H, s), 3.36 (3H, s), 2.46 (1H, ddd, J = 17.0, 2.6, 2.6 Hz), 2.42 (1H, ddd, J = 15.8, 4.0, 1.8 Hz), 2.24 (1H, dd, J = 10.6, 2.1 Hz), 2.09−1.88 (3H, m). ^{13}C NMR δ: 196.42, 157.90, 144.10, 127.02, 113.07, 96.55, 90.74, 64.64, 55.37, 52.36, 46.35, 43.72, 41.78, 37.71. MS m/z: 252 (M^+). Found: 252.1346. Anal. Calcd for $C_{14}H_{20}O_4$: C, 66.65; H, 7.99. Found: C, 66.32; H, 7.79.

(±)-7-Methyl-5-[2-(trimethylsilyl)ethoxymethoxy]-*cis*-bicyclo[3.2.1]octa-3,6-dien-2-one (30: X = H, R = OSEM). IR (neat) cm^{-1}: 1683. ^1H NMR δ: 7.36 (1H, dd, J = 10.2, 2.2 Hz), 6.21−6.18 (1H, m), 5.31 (1H, dd, J = 10.2, 2.2 Hz), 4.86 (2H, dd, J = 10.7, 7.4 Hz), 3.76−3.62 (2H, m), 3.25 (1H, dd, J = 4.4, 2.2 Hz), 2.83 (1H, dd, J = 4.4, 2.2 Hz), 2.76 (1H, d, J = 9.3 Hz), 1.80 (3H, d, J = 1.9 Hz), 0.98−0.92 (2H, m), 0.03 (9H, s). ^{13}C NMR δ: 199.06, 158.50, 142.83, 137.12, 120.59, 90.91, 87.20, 65.51, 61.26, 56.55, 18.05, 15.74, −1.57. HRMS calcd for $C_{12}H_{15}O_3$ (M^+ − 73): 207.1021. Found: 207.0838.

(±)-4-(2-Propenyl)-4-[2-(trimethylsilyl)ethoxymethoxy]-cyclohexa-2,5-dien-1-one (31: X = H, R = OSEM). IR (neat) cm^{-1}: 1670. ^1H NMR δ: 6.82 (1H, d, J = 10.2 Hz), 6.82 (1H, dd, J = 11.4, 3.1 Hz), 6.28 (1H, d, J = 10.2 Hz), 6.28 (1H, dd, J = 11.4, 5.0 Hz), 5.78−5.64 (1H, m), 5.16−5.05 (2H, m), 4.61 (2H, s), 3.68−3.62 (2H, m), 2.50 (2H, dt, J = 7.1, 1.1 Hz), 0.95−0.89 (2H, m), 0.03 (9H, s). ^{13}C NMR δ: 185.72, 150.53, 130.99, 129.97, 119.80, 91.59, 74.83, 65.72, 43.96, 17.97, −1.61. HRMS calcd for $C_{15}H_{24}O_3Si$ (M^+): 280.1495. Found: 280.1483.

4-*tert*-Butyldimethylsiloxyallylbenzene (33: X = H). ^1H NMR δ: 7.03 (2H, d, J = 9.0 Hz), 6.98 (2H, d, J = 9.0 Hz), 6.02−5.90 (1H, m), 5.10−5.00 (2H, m), 3.33 (2H, d, J = 7.0 Hz), 0.98 (9H, s), 0.18 (6H, s).

(±)-7-Methylidene-5-[2-(trimethylsilyl)ethoxymethoxy]-*cis*-bicyclo[3.2.1]oct-3-en-2-one (29: X = H, R = OSEM). IR (neat) cm^{-1}: 1694. ^1H NMR δ: 7.27 (1H, dd, J = 10.2, 2.5 Hz), 5.82 (1H, dd, J = 10.2, 1.8 Hz), 5.27 (1H, br s), 5.10 (1H, br s), 4.86 (2H, dd, J = 9.5, 7.6 Hz), 3.77−3.62 (2H, m), 3.51 (1H, d, J = 5.2 Hz), 2.78 (1H, ddd, J = 15.6, 2.7, 2.7 Hz), 2.64 (1H, ddd, J = 15.6, 4.5, 2.5 Hz), 2.43 (1H, dd, J = 10.7, 2.5 Hz), 2.15 (1H, ddd, J = 10.7, 5.5, 2.5 Hz), 0.95 (2H, t, J = 8.5 Hz), 0.03 (9H, s). ^{13}C NMR δ: 197.68, 157.34, 142.01, 126.34, 113.38, 91.64, 82.88, 65.61, 58.02, 44.57, 41.38, 18.00, −1.58. MS (EI) m/z: 207 (M^+ − 73). Anal. Calcd for $C_{15}H_{24}O_3Si$: C, 64.24; H, 8.63. Found: C, 64.24; H, 8.61.

(±)-2-Methyl-4-methoxymethoxymethyl-4-(2-propenyl)-cyclohexa-2,5-dien-1-one (31: X = Me, R = −CH_2OMOM). IR (neat) cm^{-1}: 1667. ^1H NMR δ: 6.84 (1H, dd, J = 9.9, 3.0 Hz), 6.64−6.62 (1H, m), 6.35 (1H, d, J = 9.9 Hz), 5.64−5.44 (1H, m), 5.10−5.02 (2H, m), 4.59 (2H, s), 3.51 (2H, d, J = 1.1 Hz), 3.34 (3H, s), 2.42 (2H, d, J = 7.1 Hz), 1.92 (3H, d, J = 1.4 Hz). ^{13}C NMR δ: 151.39, 146.90, 132.29, 130.43, 118.90, 96.68, 72.42, 55.37, 45.95, 39.87. HRMS calcd for $C_{13}H_{18}O_3$ (M^+): 222.1256. Found: 222.1249.

(±)-1-Methyl-7-methylidene-5-methoxymethoxymethyl-*cis*-bicyclo[3.2.1]oct-3-en-2-one (29: X = Me, R = −CH_2OMOM). IR (neat) cm^{-1}: 1683. ^1H NMR δ: 7.12 (1H, dd, J = 9.6, 1.9 Hz), 5.89 (1H, d, J = 9.9 Hz), 5.11−5.09 (2H, m), 4.68 (2H, s), 3.64 (2H, dd, J = 14.3, 9.3 Hz), 3.40 (3H, s), 2.61 (2H, dt, J = 15.6, 2.5 Hz), 2.45 (1H, dq, J = 15.6, 1.9 Hz),

2.08 (1H, dd, J = 11.0, 2.5 Hz), 1.73 (1H, dd, J = 11.0, 2.2 Hz), 1.34, (3H, s). ^{13}C NMR δ: 200.00, 155.61, 149.42, 127.07, 111.54, 96.72, 71.99, 57.63, 55.27, 49.90, 45.68, 40.64, 17.71. MS m/z: 222 (M^+). Anal. Calcd for $C_{13}H_{18}O_3$: C, 70.24; H, 8.16. Found: C, 69.99; H, 8.26.

(±)-1,7-Dimethyl-5-methoxymethoxymethyl-*cis*-bicyclo-[3.2.1]octa-3,6-dien-2-one (30: X = Me, R = −CH$_2$OMOM). IR (neat) cm^{-1}: 1681. ^{1}H NMR δ: 7.25 (1H, dd, J = 9.6, 1.9 Hz), 6.06 (1H, br s), 5.44 (1H, d, J = 9.6 Hz), 4.69 (2H, s), 3.64 (2H, dd, J = 11.3, 9.3 Hz), 3.40 (3H, s), 2.50 (1H, d, J = 9.9 Hz), 2.30 (1H, dd, J = 9.6, 1.9 Hz), 1.64 (3H, d, J = 1.6 Hz), 1.25 (3H, s). ^{13}C NMR δ: 201.69, 156.81, 164.40, 137.20, 122.36, 96.77, 70.36, 61.33, 59.59, 55.24, 51.65, 16.33, 12.81. MS m/z: 222 (M^+). Anal. Calcd for $C_{13}H_{18}O_3$: C, 70.24; H, 8.16. Found: C, 70.14, H, 8.11.

(±)-5-(2-Methoxymethoxyethyl)-7-methyl-*cis*-bicyclo-[3.2.1]oct-3-en-2-ones (34 and **35).** A mixture of the enone **9** (168 mg, 0.754 mmol) and catalytic amounts of 10% Pd−C in EtOAc (1 mL) was stirred under 1 atm of hydrogen at room temperature for 12 h. After the catalyst was filtered off, the filtrate was concentrated to provide the crude product. Flash column chromatography of the residue with hexanes−EtOAc (5:1) as an eluent afforded 163 mg (97%) of the corresponding ketone as a colorless oil. IR (neat) cm^{-1}: 1708. ^{1}H NMR δ: 4.62 (2H, s), 3.61 (2H, td, J = 7.1, 1.1 Hz), 3.37 (3H, s), 2.57−1.29 (14H, m), 1.05 (0.2H, d, J = 6.9 Hz), 0.98 (0.8H, d, J = 7.1 Hz). MS m/z: 226 (M^+). Anal. Calcd for $C_{13}H_{22}O_3$: C, 68.99; H, 9.80. Found: C, 68.93; H, 9.81.

To a stirred solution of LDA, prepared from ^{i}Pr$_2$NH (0.01 mL, 0.74 mmol) and butyllithium (2.66 M in hexane, 0.26 mL, 0.69 mmol), in THF (2 mL) cooled to −78 °C was added dropwise a solution of the above ketone (56 mg, 0.25 mmol) in THF (1 mL). After 30 min, the mixture was allowed to warm to 0 °C and continued to stir at 0 °C for an additional 1 h. The mixture was cooled to −78 °C, and then TMSCl (0.11 mL, 0.87 mmol) was added dropwise. After being stirred at −78 °C for 45 min, the mixture was quenched by addition of saturated aqueous $NaHCO_3$ solution at 0 °C. After separation, the aqueous layer was extracted three times with Et$_2$O. The combined organic layers were washed with saturated aqueous $NaHCO_3$ solution, dried, and concentrated. The crude product was dissolved in acetonitrile. To the solution was added palladium(II) acetate (83 mg, 0.37 mmol), and the resulting mixture was stirred at room temperature for 48 h. After dilution with Et$_2$O, the mixture was filtered. The filtrate was washed with ice-cold 10% HCl solution, saturated aqueous $NaHCO_3$ solution, and brine. After drying of the solvent followed by concentration, the crude product was purified by flash column chromatography with hexanes−EtOAc (5:1) as an eluent to give 42 mg (75% for two steps) of the enones **34** and **35** as a 5:1 mixture of the diastereoisomers. The mixture was separated by HPLC to provide each analytical samples of the isomers **34** and **35**.

(1*R,5*S**,7*R**)-5-(2-Methoxymethoxyethyl)-7-methyl-bicyclo[3.2.1]oct-3-en-2-one (34).** IR (neat) cm^{-1}: 1683. ^{1}H NMR (500 MHz) δ: 7.11 (1H, dd, J = 10.0, 2.0 Hz), 5.76 (1H, dd, J = 10.0, 2.0 Hz), 4.59 (2H, s), 3.66−3.58 (2H, m), 3.34 (3H, s), 2.51 (1H, dd, J = 4.6, 1.5 Hz), 2.07−1.93 (4H, m), 1.86−1.81 (1H, m), 1.70 (1H, ddd, J = 11.5, 5.0, 2.0 Hz), 1.26−1.21 (1H, m), 1.16 (3H, d, J = 6.5 Hz). ^{13}C NMR (125 MHz) δ: 203.38, 159.89, 126.06, 96.55, 65.24, 58.43, 55.37, 47.12, 45.36, 42.05, 37.74, 33.66 22.06. HRMS calcd for $C_{13}H_{19}O_3$ ($M^+ - 1$): 223.1334. Found: 223.1322.

(1*R,5*S**,7*S**)-5-(2-Methoxymethoxyethyl)-7-methyl-bicyclo[3.2.1]oct-3-en-2-one (35).** IR (neat) cm^{-1}: 1683. ^{1}H NMR δ: 7.23 (1H, dd, J = 9.5, 2.0 Hz), 5.83 (1H, dd, J = 9.5, 2.0 Hz), 4.57 (2H, s), 3.63−3.55 (2H, m), 3.32 (3H, s), 2.86 (1H, br t, J = 5.8 Hz), 2.61−2.52 (1H, m), 2.05 (1H, dd, J = 11.2, 2.2 Hz), 2.00 (1H, dd, J = 13.00, 10.2 Hz), 1.95−1.89 (1H, m), 1.82−1.76 (1H, m), 1.62 (1H, ddd, J = 11.2, 4.5, 1.7 Hz), 1.33 (1H, ddd, J = 13.0, 4.5, 2.2 Hz), 0.88 (3H, d, J = 7.5 Hz). ^{13}C NMR δ: 202.85, 161.51, 127.55, 96.50, 65.09, 56.62, 55.32, 49.91, 45.52, 43.17, 37.83, 33.29, 18.53. HRMS calcd for $C_{13}H_{20}O_3$ (M^+): 224.1412. Found: 224.1432.

(±)-1,7-Dimethyl-5-(2-methoxymethoxyethyl)-*cis*-bicyclo[3.2.1]oct-3-en-2-one (36: X = Me, R = −CH$_2$CH$_2$OMOM). IR (neat) cm^{-1}: 1671. ^{1}H NMR δ: 7.24 (0.9H, dd, J = 9.6, 2.2 Hz) 7.13 (0.1H, dd, J = 9.6, 2.2 Hz), 5.87 (0.9H, d, J = 9.6 Hz), 5.84 (0.1H, d, J = 9.6 Hz), 4.61 (2H, s), 3.64 (2H, td, J = 6.6, 2.6 Hz), 3.35 (3H, s), 2.21−2.07 (2H, m), 2.00 (1H, dd, J = 11.3, 2.2 Hz), 1.98−1.76 (2H, m), 1.57 (1H, dd, 11.3, 2.2), 1.42 (1H, dd, J = 8.0, 2.5 Hz), 1.20 (3H, s), 1.01 (0.3H, d, J = 7.1 Hz), 0.82 (2.7H, d, J = 6.9). MS m/z: 238 (M^+). Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.56; H, 9.30. Found: C, 70.34; H, 9.31.

(±)-5-Benzyloxymethyl-7-methyl-*cis*-bicyclo[3.2.1]oct-3-en-2-one (36: X = H, R = −CH$_2$OBn). IR (neat) cm^{-1}: 1682. ^{1}H NMR δ: 7.40−7.30 (5H, m), 7.18 (1H, dd, J = 9.6, 2.1 Hz), 5.82 (1H, dd, J = 9.6, 1.6 Hz), 4.58 (2H, s), 3.52 (2H, dd, 13.9, 8.9 Hz), 2.55 (1H, d, J = 3.0 Hz), 2.15−1.97 (3H, m), 1.76 (1H, ddd, J = 11.5, 4.9, 2.1 Hz), 1.28 (1H, dd, J = 12.1, 4.9 Hz), 1.17 (3H, d, J = 6.9). HRMS calcd for $C_{17}H_{20}O_2$ (M^+): 256.1463. Found: 256.1448.

(±)-3-[7-Methyl-2-oxo-*cis*-bicyclo[3.2.1]octa-3-en-5-yl]-propyl 2,2-Dimethylpropanoate (36: X = H, R = −CH$_2$CH$_2$CH$_2$OPv). IR (neat) cm^{-1}: 1727, 1683. ^{1}H NMR δ: 7.00 (1H, dd, J = 9.6, 2.2 Hz), 5.82 (1H, dd, J = 9.6, 1.6 Hz), 4.08 (2H, t, J = 6.2 Hz), 2.53 (1H, dd, J = 4.2, 1.5 Hz), 2.12−1.93 (3H, m), 1.78−1.54 (6H, m), 1.21 (9H, s), 1.18 (3H, d, J = 6.9 Hz). ^{13}C NMR δ: 203.59, 159.58, 126.75, 64.31, 58.26, 48.00, 44.97, 41.56, 38.70, 34.17, 33.75, 27.11, 25.17, 21.95. HRMS calcd for $C_{17}H_{26}O_3$ (M^+): 278.1882. Found: 278.1897.

(1*S,4*R**,5*R**)-5-(2-Methoxymethoxyethyl)-4-methyl-7-methylidenebicyclo[3.2.1]octan-2-one (42).** Methyllithium (1.14 M in Et$_2$O, 33.30 mL, 37.97 mmol) was added dropwise to a solution of CuBr·SMe$_2$ (3.90 g, 18.98 mmol) in Et$_2$O (150 mL) at 0 °C. After stirring for 30 min, the mixture was cooled to −50 °C, and then a solution of the enone **9** (3.84 g, 17.26 mmol) in Et$_2$O (10 mL) was added dropwise. After being stirred at −50 °C for 2 h, the mixture was quenched by addition of saturated aqueous NH_4Cl solution. The two layers were separated. The organic layer was washed with brine, dried, and concentrated. Column chromatography of the residue with hexanes−EtOAc (4:1) as an eluent furnished the adduct **42** (3.67 g, 89%) as a colorless oil. IR (neat) cm^{-1}: 1715. ^{1}H NMR δ: 5.01 (1H, br s), 4.91 (1H, br s), 4.62 (2H, s), 3.63−3.56 (2H, m), 3.38 (3H, s), 3.16 (1H, d, J = 5.2 Hz), 2.78 (1H, dd, J = 15.7, 8.0 Hz), 2.62 (1H, dd, J = 17.4, 1.5 Hz), 2.53 (1H, ddd, J = 17.4, 2.6, 2.6 Hz), 2.31−2.11 (1H, m), 2.03−1.82 (3H, m), 1.71−1.57 (2H, m), 0.99 (3H, d, J = 7.2 Hz). ^{13}C NMR δ: 209.94, 149.14, 107.99, 96.32, 54.39, 59.72, 54.99, 44.16, 43.03, 42.74, 38.84, 37.35, 36.29, 16.64. MS m/z: 238 (M^+). Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.55; H, 9.30. Found: C, 70.60; H, 9.25.

(1*S,4*R**,5*R**)-5-(2-Methoxymethoxyethyl)-4-methyl-bicyclo[3.2.1]octan-2,7-dione 2-Ethylene Acetal (43).** A mixture of the ketone **42** (3.66 g, 15.37 mmol), ethylene glycol (8.57 mL, 153.74 mmol), and PPTS (96.6 mg, 0.38 mmol) in anhydrous benzene (150 mL) was refluxed using a Dean−Stark trap for 10 h. After being cooled to room temperature, to the mixture was added water. The two layers were separated, and then the aqueous layer was extracted three times with Et$_2$O. The combined organic layers were washed with saturated aqueous $NaHCO_3$ solution and brine. Drying of the solvent followed by evaporation provided the crude product, which was purified by column chromatography with hexanes−EtOAc (3:1) as an eluent to give 4.05 g (93%) of the acetal as a colorless oil. ^{1}H NMR (500 MHz) δ: 4.99 (1H, br s), 4.86 (1H, br s), 4.60 (2H, s), 4.00−3.85 (4H, m), 3.59−3.47 (2H, m), 3.36 (3H, s), 2.50 (1H, d, J = 5.0 Hz), 2.34 (1H, dd, J = 17.0, 2.5 Hz), 2.25 (1H, ddd, J = 17.0, 2.5, 2.5 Hz), 2.06 (1H, dd, J = 11.5, 2.5 Hz), 1.97−1.91 (2H, m), 1.83−1.74 (1H, m), 1.51 (1H, dd, J = 9.0, 6.0 Hz), 1.48 (1H, dd, J = 9.0, 6.0 Hz), 1.35 (1H, d, J = 1.42 Hz), 1.27 (1H, ddd, J = 11.8, 5.5, 1.5 Hz), 1.06 (3H, d, J = 7.3 Hz). ^{13}C NMR (125 MHz) δ: 151.19, 110.74, 107.45, 96.52, 64.81, 64.70, 63.69, 55.25, 51.35, 43.80, 43.49, 37.29, 36.49, 36.47, 35.53, 16.24. MS m/z: 282 (M^+). Anal. Calcd for $C_{16}H_{26}O_4$: C, 68.05; H, 9.28. Found: C, 68.20; H, 9.38.

To a solution of the above olefin (1.77 g, 6.26 mmol) in Et_2O (62.6 mL) were added water (31.3 mL), $NaIO_4$ (13.38 g, 62.57 mmol), and OsO_4 (1% w/v in THF, 15.91 mL, 0.63 mmol). The resulting mixture was stirred at room temperature for 19 h. The mixture was filtered. The filtrate was washed with brine, dried, and concentrated. The crude product was chromatographed with hexanes−EtOAc (1:1) as an eluent to give 1.71 g (96%) of the ketone **43** as a colorless oil. IR (neat) cm^{-1}: 1740. ^1H NMR δ: 4.60 (2H, s), 3.98−3.92 (4H, m), 3.64−3.48 (2H, m), 3.35 (3H, s), 2.43 (1H, d, J = 5.5 Hz), 2.39−2.29 (2H, m), 2.17 (1H, d, J = 19.2 Hz), 2.03−1.86 (3H, m), 1.66−1.49 (3H, m), 2.14 (3H, d, J = 7.1 Hz). ^{13}C NMR δ: 216.29, 108.28, 96.49, 64.67, 64.18, 64.00, 55.65, 55.24, 50.17, 41.80, 37.60, 37.31, 34.65, 33.85, 15.92. MS m/z: 284 (M^+). Anal. Calcd for $C_{15}H_{24}O_5$: C, 63.65; H, 8.50. Found: C, 63.42; H, 8.55.

(1*S,4*R**,5*R**)-Methyl 2,2-Ethylenedioxy-5-(2-methoxymethoxyethyl)-4-methyl-7-oxobicyclo[3.2.1]octane-6-carboxylate (44).** To a solution of LDA, prepared from $^iPr_2NH$ (6.47 mL, 3.61 mmol) and butyllithium (1.54 M in hexane, 2.20 mL, 3.39 mmoL), in THF (12 mL) cooled to −78 °C was added dropwise a THF solution of the ketone **43** (642.0 mg, 2.26 mmol). After being stirred at −78 °C for 1 h, HMPA (0.59 mL, 3.39 mmol) and methyl cyanoformate (0.29 mL, 3.61 mmol) were added dropwise. The mixture was allowed to warm to room temperature and stirred at room temperature for 4 h. The reaction was quenched at 0 °C by addition of water. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with brine, dried, and concentrated. Column chromatography of the residue with hexanes−EtOAc (3:1) as an eluent afforded 633.5 mg (82%) of the keto ester **44** as a colorless oil. IR (neat) cm^{-1}: 1745, 1735. ^1H NMR δ: 4.55 (2H, s), 4.01−3.91 (4H, m), 3.74 (3H, s), 3.69−3.53 (2H, m), 3.34 (3H, s), 3.26 (1H, s), 2.52 (1H, dd, J = 5.2, 1.6 Hz), 2.45−2.38 (1H, m), 2.37 (1H, d, J = 12.9 Hz), 2.24 (1H, dd, J = 15.1, 6.9 Hz), 1.98 (1H, ddd, J = 14.5, 5.8, 5.8 Hz), 1.81−1.71 (1H, m), 1.63 (1H, ddd, J = 12.6, 5.8, 2.1 Hz), 1.56 (1H, ddd, J = 14.5, 2.1, 1.2 Hz), 1.15 (3H, d, J = 7.1 Hz). MS m/z: 342 (M^+). Anal. Calcd for $C_{17}H_{26}O_7$: C, 59.64; H, 7.65. Found: C, 59.62; H, 7.64.

(1*S,4*R**,5*R**)-Methyl 2,2-Ethylenedioxy-5-(2-methoxymethoxyethyl)-4-methyl-2-oxo-7-(2-propenyloxy)bicyclo[3.2.1]oct-6-ene-6-carboxylate (45).** To a stirred solution of NaH (60% in oil, 234.2 mg, 5.86 mmol) in HMPA (7.0 mL) was added a solution of the keto ester **44** (1.54 g, 4.50 mmol) in HMPA (7.0 mL) at 0 °C. The mixture was stirred until evolution of gas ceased. Allyl bromide (0.51 mL, 5.86 mmol) was added at 0 °C, and then the resulting mixture was stirred at room temperature for 19 h. The reaction was quenched by addition of saturated aqueous NH_4Cl solution. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with brine, dried, and concentrated. Flash column chromatography of the residue with hexanes−EtOAc (3:1) furnished 1.62 g (94%) of the enol ether 45 as a colorless oil. IR (neat) cm^{-1}: 1680. ^1H NMR δ: 6.03−5.90 (1H, m), 5.40 (1H, ddd, J = 17.0, 3.3, 1.6 Hz), 5.24 (1H, ddd, J = 17.0, 3.3, 1.6 Hz), 4.79−4.72 (1H, m), 4.63−4.54 (1H, m), 4.56 (2H, s), 4.01−3.82 (4H, m), 3.71 (3H, s), 3.55−3.41 (2H, m), 3.33 (3H, s), 2.74 (1H, d, J = 4.9 Hz), 2.21−2.07 (3H, m), 2.01 (1H, d, J = 11.5 Hz), 1.81−1.66 (2H, m), 1.44−1.39 (1H, m), 1.09 (3H, d, J = 7.7 Hz). MS m/z: 382 (M^+). Anal. Calcd for $C_{20}H_{30}O_7$: C, 62.81; H, 7.91. Found: C, 62.85; H, 7.87.

(1*S,4*R**,5*R**,6*R**)-Methyl 2,2-Ethylenedioxy-5-(2-methoxymethoxyethyl)-4-methyl-7-oxo-6-(2-propenyl)bicyclo[3.2.1]octane-6-carboxylate (46).** A solution of the enol ether **45** (1.62 g, 4.23 mmol) in anhydrous toluene (40 mL) was stirred in a sealed tube at 160 °C for 12 h. After evaporation of the solvent, the crude product was purified by column chromatography with hexanes−EtOAc (3.1) as an eluent to lead to 1.48 g (91%) of the ketone **46**. IR (neat) cm^{-1}: 1745, 1715. ^1H NMR δ: 5.93−5.79 (1H, m), 5.11−5.06 (2H, m), 4.64 (2H, dd, J = 7.7, 6.6 Hz), 4.00−3.89 (4H, m), 3.69 (3H, s), 3.62−3.44 (2H, m), 3.38 (1H, s), 2.80 (1H, dd, J = 13.7, 7.4 Hz), 2.47−2.39 (2H, m), 2.26 (1H, d, J = 13.2 Hz), 2.22 (1H, dd, J = 15.4, 6.9 Hz), 2.06−1.83 (3H, m), 1.71 (1H, ddd, J = 13.2, 5.8, 1.9 Hz), 1.48 (1H, dd, J = 15.4, 1.5 Hz), 1.20 (3H, d, J = 7.1 Hz). MS m/z: 382 (M^+). Anal. Calcd for $C_{20}H_{30}O_7$: C, 62.81; H, 7.91. Found: C, 62.87; H, 7.98.

(1*S,4*R**,5*R**,6*R**)-Methyl 2,2-Ethylenedioxy-6-(3-iodopropyl)-5-(2-methoxymethoxyethyl)-4-methyl-7-oxobicyclo[3.2.1]octane-6-carboxylate (47).** To a solution of the olefin **46** (352.7 mg, 0.92 mmol) in THF (6 mL) cooled to 0 °C was added dropwise a THF solution of disiamylborane (0.55 M, 2.0 mL, 1.10 mmol), prepared from BH_3·SMe_2 (10 M in THF, 0.40 mL, 4.00 mmol) and 2-methyl-2-butene (0.88 mL, 8.30 mmol), in THF (6 mL). The mixture was stirred at 0 °C for 2 h. To the mixture were added 15% NaOH solution (1 mL) and 30% H_2O_2 solution (1 mL), and then the mixture was stirred for 1.5 h. To the mixture was added brine. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with brine, dried, and concentrated. The crude product was purified by flash column chromatography with hexanes−EtOAc (1:3) as an eluent to give rise to 279.5 mg (76%) of the corresponding alcohol as a colorless oil. IR (neat) cm^{-1}: 3500, 1750, 1715. ^1H NMR δ: 4.63 (2H, dd, J = 8.0, 6.6 Hz), 4.01−3.86 (5H, m), 3.72 (3H, s), 3.64−3.47 (3H, m), 3.38 (3H, s), 2.45 (1H, dd, J = 5.5, 2.2 Hz), 2.33−2.13 (3H, m), 2.03−1.81 (4H, m), 1.76−1.65 (2H, m), 1.51−1.38 (3H, m), 1.20 (3H, d, J = 7.1 Hz). MS m/z: 400 (M^+). Anal. Calcd for $C_{20}H_{32}O_8$: C, 59.98; H, 8.05. Found: C, 60.06; H, 8.01.

To a stirred solution of the above alcohol (60.0 mg, 0.15 mmol) in a mixture of THF (3 mL) and MeCN (1 mL) were added successively Ph_3P (118.0 mg, 0.45 mmol), imidazole (30.6 mg, 0.45 mmol), and I_2 (76.1 mg, 0.30 mmol) at 0 °C, and then it was allowed to warm to room temperature and continued to stir at room temperature for 2 h. The reaction was quenched by addition of saturated aqueous $Na_2S_2O_3$ solution. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with brine, dried, and concentrated. The crude product was purified by flash column chromatography with hexanes−EtOAc (4:1) as an eluent to give 70.5 mg (92%) of the iodide **47** as a white crystal (needles, recrystallization from Et_2O−hexane), mp 80−82 °C. IR (KBr) cm^{-1}: 1750, 1715. ^1H NMR δ: 4.64 (2H, s), 3.99−3.89 (5H, m), 3.73 (3H, s), 3.52−3.47 (1H, m), 3.39 (3H, s), 3.14 (2H, t, J = 6.2 Hz), 2.46(1H, dd, J = 5.8, 2.2 Hz), 2.33−2.15 (4H, m), 1.97−1.88 (3H, m), 1.73−1.63 (3H, m), 1.48 (1H, d, J = 13.7 Hz), 1.20 (3H, d, J = 7.1 Hz). MS m/z: 510 (M^+). Anal. Calcd for $C_{20}H_{31}O_7I$: C, 47.07; H, 6.12; I, 24.87. Found: C, 47.01; H, 6.23; I, 24.85.

(1*S,2*S**,6*R**,7*R**,8*R**)-Methyl 10,10-Ethylenedioxy-2-hydroxy-7-(2-methoxymethoxyethyl)-8-methyl-10-oxotricyclo[5.3.1.0^{2,6}]undecane-6-carboxylate (48).** A solution of iodoethane (646.6 mg, 2.29 mmol) in THF (16 mL) was added to Sm powder (449.0 mg, 2.99 mmol) with vigorous stirring at room temperature. The mixture was continued to stir at room temperature for 2 h. HMPA (2.60 mL, 14.93 mmol) was added, and then the resulting mixture was stirred for 30 min. A solution of the iodide **47** (287.2 mg, 0.56 mmol) in THF (4 mL) was added dropwise, and the mixture was stirred for 30 min. The reaction was quenched by addition of saturated aqueous NH_4Cl solution. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with water, 3% $Na_2S_2O_3$ solution, and brine. After drying of the solvent followed by evaporation, the crude product was purified by flash column chromatography with hexanes−EtOAc (1:1) as an eluent to provide 209.5 mg (92%) of the tricyclic compound **48** as a colorless oil. IR (neat) cm^{-1}: 3550, 1730. ^1H NMR δ: 4.90 (1H, s), 4.57 (2H, s), 3.99−3.83 (4H, m), 3.69 (3H, s), 3.57−3.47 (2H, m), 3.34 (3H, s), 2.63 (1H, br dq, J = 7.3, 7.3 Hz), 2.24 (1H, dd, J = 14.6, 7.3 Hz), 2.12 (1H, ddd, J = 13.2, 5.0, 2.7 Hz), 2.09 (1H, ddd, J = 13.0, 6.3, 2.8 Hz), 2.05 (1H, d, J = 13.2 Hz), 2.01−1.96 (1H, m), 1.94 (1H, dd, J = 4.8, 1.8 Hz), 1.85−1.56 (5H, m), 1.43 (1H, d, J = 1.3 Hz), 1.40 (1H, br s), 1.14 (3H, d, J = 7.3 Hz). ^{13}C NMR δ: 176.00, 110.46, 96.37, 90.68, 66.02, 64.82, 64.38, 63.36, 55.09, 52.09, 51.48, 48.45, 45.98, 39.40, 36.40, 33.59, 32.72, 31.40, 24.98, 17.69. HRMS calcd for $C_{20}H_{30}O_6$ (M^+ − 18): 366.2042. Found: 366.2035.

(1*S,2*S**,6*R**,7*R**,8*R**)-2-Hydroxy-7-(2-methoxymethoxyethyl)-8-methyl-6-p-toluenesulfoxymethyltricyclo[5.3.1.0^{2,6}]undecan-10-one 10-Ethylene Acetal (49).** To a stirred solution of $LiAlH_4$ (62.0 mg, 1.64 mmol) in THF (30 mL) was added a solution of the ester **48** (209.5 mg, 0.54 mmol) in THF (10 mL) at 0 °C. After being stirred at 0 °C for 15 min, the mixture was refluxed for 4 h. The mixture was quenched by successive addition of 0.06 mL of water, 0.06 mL of 15% NaOH solution, and 0.18 mL of water. After being stirred for 30 min, a spoonful of $MgSO_4$ was added, and then the mixture was stirred for an additional 30 min. The mixture was filtered. The filtrate was concentrated to give the crude product, which was purified by column chromatography with hexanes−EtOAc (1:1) as an eluent to give 158.3 (81%) of the diol as a white crystal (prisms, recrystallization from Et_2O), mp 86.0−87.5 °C. IR (KBr) cm^{-1}: 3500. ^{1}H NMR δ: 4.59 (2H, s), 4.12 (1H, dd, J = 11.5 Hz), 4.08 (1H, s), 3.99−3.86 (4H, m), 3.57−3.41 (3H, m), 3.34 (3H, s), 2.77 (1H, dd, J = 10.4, 2.7 Hz), 2.42 (1H, dd, J = 14.8, 7.1 Hz), 2.08−1.86 (6H, m), 1.76−1.57 (5H, m), 1.49 (1H, dd, J = 14.8, 1.6 Hz), 1.36 (1H, ddd, J = 13.0, 5.2, 1.9 Hz), 1.09 (3H, d, J = 7.1 Hz). MS m/z: 338 (M$^+$ − 18). Anal. Calcd for $C_{19}H_{32}O_6$: C, 64.02; H, 9.05. Found: C, 64.09; H, 9.04.

To a stirred solution of the above diol (73.8 mg, 0.21 mmol) in pyridine (1 mL) was added TsCl (78.9 mg, 0.41 mmol) at 0 °C. After 30 min, the mixture was allowed to warm to room temperature, and the mixture was continued to stir at room temperature for 19 h. The mixture was diluted with Et_2O. The resulting mixture was washed with saturated aqueous $NaHCO_3$ solution and brine. After drying of the solvent, followed by concentration, flash column chromatography of the residue with hexanes−EtOAc (1:1) as an eluent afforded 100.6 mg (95%) of the tosylate **49**. IR (KBr) cm^{-1}: 3503. ^{1}H NMR δ: 7.82 (2H, d, J = 8.2 Hz), 7.34 (2H, d, J = 8.0 Hz), 4.56 (2H, s), 4.16 (1H, d, J = 10.7 Hz), 3.96 (1H, d, J = 10.7 Hz), 3.93−3.83 (4H, m), 3.67 (1H, s), 3.60−3.36 (2H, m), 3.35 (3H, s), 2.45 (3H, s), 2.15−1.25 (14H, m), 1.04 (3H, d, J = 7.1 Hz). ^{13}C NMR δ: 144.62, 132.99, 129.83, 128.13, 110.46, 96.42, 89.04, 71.22, 65.46, 63.90, 58.83, 55.15, 51.16, 46.94, 46.26, 37.69, 35.34, 33.88, 32.76, 30.30, 23.30, 21.51, 18.02. HRMS calcd for $C_{26}H_{38}O_8S$ (M$^+$ − 172): 338.2093. Found: 338.2082.

Ring Expansion Reaction. Method I. To a solution of the tosylate **49** (48.6 mg, 0.095 mmol) in THF (3 mL) was added KO^{t}Bu (21.0 mg, 0.19 mmol) at 0 °C. After being stirred at 0 °C for 15 min, the mixture was quenched at 0 °C by addition of water. The resulting mixture was extracted three times with Et_2O. The combined organic layers were washed with brine, dried, and concentrated. Column chromatography of the crude product with hexanes−EtOAc (1:1 v/v) as an eluent afforded 9.5 mg (30%) of **50** and 15.2 mg (47%) of **51**.

Method II. To a solution of the tosylate **49** (50.5 mg, 0.099 mmol) in THF (2 mL) was added potassium hexamethyldisilazide (KHMDS) (0.5 M in toluene, 0.40 mL, 0.198 mmol) at 0 °C. After being stirred at 0 °C for 30 min, the mixture was quenched at 0 °C by addition of saturated aqueous NH_4Cl solution. The resulting mixture was extracted three times with Et_2O. The combined organic layers were washed with brine, dried, and concentrated. Column chromatography of the crude product with hexanes−EtOAc (1:1) as an eluent afforded 10.7 mg (32%) of **50** and 14.8 mg (44%) of **51**.

(1*S,7*R**,8*R**)-7-(2-Methoxymethoxyethyl)-8-methyl-6-methylidenebicyclo[5.3.1]undecan-2,10-dione 10-Ethylene Acetal (50).** IR (neat) cm^{-1}: 1705. ^{1}H NMR δ: 5.09 (1H, br s), 4.99 (1H, br s), 4.53 (2H, s), 4.03−3.79 (4H, m), 3.34 (H, ddd, J = 10.0, 10.0, 5.6 Hz), 3.31 (3H, s), 3.18 (1H, ddd, J = 10.0, 10.0, 5.6 Hz), 2.70 (1H, ddd, J = 12.0, 12.0, 3.8 Hz), 2.41−2.14 (7H, m), 2.12−1.96 (3H, m), 1.68−1.50 (2H, m), 1.40 (1H, d, J = 13.6 Hz), 1.18 (3H, d, J = 7.2 Hz). ^{13}C NMR δ: 210.94, 148.58, 116.16, 109.04, 96.39, 64.74, 63.85, 62.96, 56.14, 55.05, 42.78, 39.82, 35.25, 33.22, 32.13, 30.82, 30.12, 28.94, 17.15. HRMS calcd for $C_{19}H_{30}O_5$ (M$^+$): 338.2093. Found: 338.2068.

(1*S,2*S**,6*R**,7*R**,8*R**)-2,6-Epoxymethano-7-(2-methoxymethoxyethyl)-8-methyltricyclo[5.3.1.0^{2,6}]undecan-10-one 10-Ethylene Acetal (51).** ^{1}H NMR δ: 4.55 (2H, s), 4.36 (1H, dd, J = 7.1, 1.2 Hz), 4.08 (1H, d, J = 7.1 Hz), 4.01−3.82 (4H, m), 3.49 (1H, ddd, J = 9.6, 9.6, 5.2 Hz), 3.29 (3H, s), 3.25 (1H, ddd, J = 9.6, 9.6, 6.0 Hz), 2.80 (1H, dd, J = 15.2, 8.4 Hz), 2.25−2.13 (3H, m), 2.04−1.95 (3H, m), 1.83 (1H, ddd, J = 14.8, 10.0, 5.2 Hz), 1.75−1.68 (1H, m), 1.59 (1H, dd, J = 15.3, 1.5 Hz), 1.57−1.48 (2H, m), 1.32−1.22 (1H, m), 1.20 (3H, d, J = 6.8 Hz), 1.12 (1H, ddd, J = 12.8, 5.2, 2.0 Hz). ^{13}C NMR δ: 110.68, 101.83, 96.38, 71.19, 64.69, 64.43, 63.80, 57.22, 55.10, 50.94, 45.31, 39.48, 37.78, 35.58, 33.45, 32.44, 30.02, 26.06, 19.13. HRMS calcd for $C_{19}H_{30}O_5$ (M$^+$): 338.2093. Found: 338.2073.

(±)-2-*tert*-Butyldimethylsilyloxy-5-(2-methoxymethoxyethyl)-1,5-di-2-propenylcyclohexa-1,3-diene (54). To a stirred solution of LDA, prepared from ^{i}Pr$_2$NH (0.21 mL, 1.49 mmol) and butyllithium (1.52 M in hexane, 0.94 mL, 1.42 mmol), in THF (15 mL) cooled to −78 °C was added dropwise a THF solution of the ketone **15** (290.0 mg, 1.29 mmol). After 30 min, the mixture was allowed to warm to 0 °C and continued to stir at 0 °C for 1 h. The mixture was cooled to −78 °C, and then allyl bromide (0.17 mL, 1.94 mmol) was added dropwise at 0 °C. The mixture was allowed to warm to room temperature, and then the mixture was further stirred for 20 h. The reaction was quenched at 0 °C by addition of saturated aqueous NH_4Cl solution. After separation, the aqueous layer was extracted three times with Et_2O. The combined organic layers were washed with saturated aqueous NH_4Cl solution and brine. After drying of the solvent followed by concentration, column chromatography of the residue with hexanes−EtOAc (3:1) as an eluent afforded 183.4 mg (54%) of the corresponding diallyl ketone as a colorless oil. IR (neat) cm^{-1}: 1683. ^{1}H NMR δ: 6.72 (0.5H, dd, J = 9.6, 2.2 Hz), 6.69 (0.5H, dd, J = 9.6, 2.2 Hz), 5.94 (1H, d, J = 9.6), 5.89−5.67 (2H, m), 5.18−5.02 (4H, m), 4.61 (1H, s), 4.58 (1H, s), 3.67−3.50 (2H, m), 3.64 (1H, t, J = 6.9 Hz), 3.37 (1.5H, s), 3.34 (1.5H, s), 2.78−2.68 (1H, m), 2.61−2.48 (1H, m), 2.39−2.16 (2H, m), 2.11−1.60 (5H, m). MS m/z: 264 (M$^+$). Anal. Calcd for $C_{16}H_{24}O_3$: C, 72.69; H, 9.15. Found: C, 72.76; H, 9.37.

The silyl enol ether **54** was prepared from the above ketone according to the procedure described before. ^{1}H NMR δ: 5.84−5.63 (2H, m), 5.70 (1H, d, J = 9.9 Hz), 5.43 (1H, d, J = 9.9 Hz), 5.09−4.98 (4H, m), 4.59 (2H, s), 3.56 (2H, t, J = 7.5 Hz), 3.35 (3H, s), 2.84 (2H, d, J = 6.6 Hz), 2.20−2.04 (4H, m), 1.78−1.56 (2H, m), 0.94 (9H, s), 0.11 (6H, s). ^{13}C NMR δ: 141.45, 136.09, 134.74, 133.84, 125.34, 117.58, 115.88, 112.18, 96.42, 64.44, 55.09, 43.13, 37.65, 36.65, 36.25, 34.19, 25.65, 17.94, −4.13. MS m/z: 352 (M$^+$). Anal. Calcd for $C_{22}H_{38}O_3Si$: C, 69.79; H, 10.12. Found: C, 69.91; H, 9.86.

(±)-5-(2-Methoxymethoxyethyl)-7-methylidene-1-(2-propenyl)-*cis*-bicyclo[3.2.1]oct-3-en-2-one (57). IR (neat) cm^{-1}: 1683. ^{1}H NMR δ: 7.10 (1H, dd, J = 9.6, 2.2 Hz), 5.84 (1H, d, J = 9.6 Hz), 5.83−5.69 (1H, m), 5.14−5.00 (4H, m), 4.62 (2H, s), 3.67 (2H, td, J = 6.6, 1.6 Hz), 3.36 (3H, s), 2.80 (1H, dd, J = 14.3, 7.1 Hz), 2.56−2.37 (3H, m), 2.06−1.83 (3H, m), 1.69 (1H, dd, J = 11.3, 2.2 Hz). ^{13}C NMR δ: 198.87, 157.77, 148.05, 134.71, 126.81, 117.63, 111.89, 96.52, 64.92, 60.72, 55.34, 48.26, 43.84, 43.63, 37.30, 35.31. MS m/z: 262 (M$^+$). Anal. Calcd for $C_{16}H_{22}O_3$: C, 73.25; H, 8.45. Found: C, 73.22; H, 8.53.

(±)-5-(2-Methoxymethoxyethyl)-7-methyl-1-(2-propenyl)-*cis*-bicyclo[3.2.1]octa-3,6-dien-2-one (58). IR (neat) cm^{-1}: 1676. ^{1}H NMR δ: 7.23 (1H, dd, J = 9.6, 1.6 Hz), 6.05 (br s), 5.77−5.63 (1H, m), 5.36 (1H, d, J = 9.6 Hz), 5.13−5.03 (2H, m), 4.62 (2H, s), 3.66 (2H, t, J = 6.9 Hz), 3.36 (3H, s), 2.72-(1H, ddt, J = 14.0, 6.9, 1.2 Hz), 2.40 (1H, d, J = 10.2 Hz), 2.28 (1H, ddt, J = 14.0, 6.9, 1.2 Hz), 2.27 (1H, dd, J = 10.2, 1.6 Hz), 2.06−1.85 (2H, m), 1.64 (3H, d, J = 1.6 Hz). ^{13}C NMR δ: 200.58, 159.80, 144.24, 140.73, 134.25, 121.94, 117.79, 96.52, 64.63, 64.47, 57.61, 55.27, 49.41, 35.22, 34.23, 12.69. HRMS calcd for $C_{16}H_{22}O_3$ (M$^+$): 262.1589. Found: 262.1614.

(±)-4-(2-Methoxymethoxyethyl)-2,4-di-2-propenylcyclohexa-2,5-dien-1-one (59). IR (neat) cm^{-1}: 1664, 1635. ^{1}H NMR δ: 6.76 (1H, dd, J = 9.9, 3.0 Hz), 6.54−6.52 (1H, m), 6.32 (1H, d, J = 9.9 Hz), 5.91−5.77 (1H, m), 5.63−5.49 (1H, m), 5.12−4.99 (4H, m), 4.49 (2H, s), 3.34 (2H, t, J = 6.9 Hz), 3.29 (3H, s), 3.10−3.05 (2H, m), 2.36 (2H, d, J = 7.4 Hz), 1.98 (2H, t, J = 6.9 Hz). ^{13}C NMR δ: 186.10, 153.43, 149.48, 138.56,

135.48, 132.19, 129.80, 119.07, 116.78, 96.57, 64.14, 55.23, 44.31, 44.28, 38.71, 33.11. MS *m/z*: 262 (M^+). Anal. Calcd for $C_{16}H_{22}O_3$: C, 73.25; H, 8.46. Found: C, 73.13; H, 8.20.

(1*S,5*S**,7*S**)-7-(2-Methoxymethoxyethyl)-3-methylidenetricyclo[5.3.1.0^{1,5}]undec-8-en-10-one (55).** IR (neat) cm^{-1}: 1681. ^1H NMR (500 MHz) δ: 7.40 (1H, dd, J = 9.5, 2.2 Hz), 5.82 (1H, d, J = 9.5 Hz), 4.81 (br s), 4.77 (br s), 4.53 (2H, s), 3.60−3.52 (2H, m), 3.28 (3H, s), 3.07 (1H, d, J = 16.0 Hz), 2.67 (1H, dd, J = 16.0, 10.0 Hz), 2.26−2.20 (1H, m), 2.11−2.04 (2H, m), 1.96 (1H, d, J = 15.0 Hz), 1.94−1.77 (2H, m), 1.82 (1H, dd, J = 11.5, 2.0 Hz), 1.53 (1H, dd, J = 11.5, 2.0 Hz), 1.45 (1H, dd, J = 12.5, 5.5 Hz). ^{13}C NMR (125 MHz) δ: 202.35, 159.17, 151.24, 126.58, 107.26, 96.51, 61.15, 64.41, 55.34, 48.51, 48.05, 45.14, 44.14, 40.01, 37.60, 36.10. HRMS calcd for $C_{16}H_{22}O_3$ (M^+): 262.1589. Found: 262.1532.

(1*S,5*S**,7*S**)-7-(2-Methoxymethoxyethyl)-3-methyltricyclo[5.3.1.0^{1,5}]undec-2,8-dien-10-one (56).** IR (neat) cm^{-1}: 1681. ^1H NMR δ: 7.88 (1H, dd, J = 9.6, 2.2 Hz), 5.84 (1H, d, J = 9.6 Hz), 5.52 (br s), 4.61 (2H, s), 3.63 (2H, td, J = 6.6, 1.9 Hz), 3.35 (3H, s), 2.66−2.53 (2H, m), 2.31−1.83 (5H, m), 2.58 (3H, br s), 1.69−1.61 (1H, m), 1.52 (1H, dd, J = 11.3, 2.2 Hz). ^{13}C NMR δ: 204.45, 158.74, 142.81, 126.58, 124.12, 96.54, 72.61, 65.05, 55.32, 50.36, 50.13, 45.48, 43.52, 43.39, 37.62, 16.85. HRMS calcd for $C_{16}H_{22}O_3$ (M^+): 262.1589. Found: 262.1564.

Supporting Information Available: Spectra for obtained compounds. This material is available free of charge via the Internet as http://pubs.acs.org.

JO011169D