JOC Article

Diels−Alder Reactions of 4-Triflyloxy-2,6,6-trimethyl-2,4-cyclohexadienone. An Expedient Methodology for the Synthesis of Bicyclo[2.2.2]oct-5-en-2-ones and Bicyclo[2.2.2]octa-5,7-dien-2-ones

Yu-Shiang Lin,[†] Shi-Yi Chang,[†] Ming-Shyong Yang,[†] Chitneni Prasad Rao,[†] Rama Krishna Peddinti,[†] Yow-Fu Tsai,[‡] and Chun-Chen Liao*,[†]

Department of Chemistry, National Tsing Hua University, Hsinchu 300, Taiwan, and Graduate Institute of Pharmacognosy, Taipei Medical University, Taipei 110, Taiwan

ccliao@mx.nthu.edu.tw

Received September 30, 2003

The synthesis of 4-triflyloxy-2,6,6-trimethyl-2,4-cyclohexadienone (**13**), bicyclo[2.2.2]octenones **1a**−**j** and **15a**−**j**, and bicyclo[2.2.2]octadienones **2a**−**f**, **6a**−**d**, and **11a**−**f** is described. The 2,4-cyclohexadienones **4** and **13** were used for the first time as nondimerizing and easily accessible alternatives to 2,6,6-trimethyl-2,4-cyclohexadienone **12** in Diels−Alder reactions with acetylene derivatives **5a**−**d** to prepare the adducts **6a**−**d** and **11a**−**e** in excellent yields. Compounds **11a**−**d** were initially prepared by the alcoholysis of **6a**−**d** to afford bicyclo[2.2.2]octene-2,5-diones **7a**−**d** followed by treatment of **7a**−**d** with *N*-phenyltriflimide in the presence of LHMDS at −78 °C. Diels−Alder reaction of **13** with an acetylene equivalent, phenyl vinyl sulfoxide, was also studied. A detailed study of the Diels−Alder reactions of various olefinic dienophiles **14a**−**j** with **13** has been carried out to furnish cycloadducts **15a**−**j** in high yields. Reductive removal of triflyloxy group of vinyl triflates **11a**−**f** and **15a**−**j** was performed in the presence of $[Pd(PPh_3)_2Cl_2-Bu_3N-HCO_2H]$ to obtain the desired bicyclo[2.2.2]octadienones **2a**−**f** and bicyclo[2.2.2]octenones **1a**−**j**, respectively, in good overall yields.

Introduction

The Diels−Alder reaction is a widely used protocol in organic synthesis since it generates a wide variety of polyfunctionalized cyclic compounds with up to four new contiguous stereogenic centers in a highly stereoselective and predictable manner in a single laboratory operation.[1−3] A large number of dienes and dienophiles with a plethora of functionalities has been used to construct various types of ring structures.[2] Bicyclo[2.2.2]octenones (**1**), which have a wide range of applications in the synthesis of natural products,[3,4] can be accessed easily by using the Diels−Alder reaction of 2,4-cyclohexadienones with activated alkenes.[2,5] Similarly, bicyclo[2.2.2]octadienones (**2**) can be conveniently generated by reaction of activated alkynes with 2,4-cyclohexadienones.[6−10] Both bicyclo[2.2.2]octadienones and bicyclo[2.2.2]octenones can undergo interesting and useful photochemical reactions, viz., di-π-methane (DPM) and oxa-di-π-methane (ODPM) rearrangements, and 1,3-acyl migration and ODPM rearrangement, respectively.[11]

Unlike bicyclo[2.2.2]octenones, the only general method for preparing bicyclo[2.2.2]octadienones is the Diels−

[†] National Tsing Hua University.
[‡] Taipei Medical University.

(1) Carruthers, W. *Cycloaddition Reactions in Organic Synthesis*; Pergamon: Oxford, 1990.

(2) (a) Fringuelli, F.; Taticchi, A. *The Diels−Alder Reaction: Selected Practical Methods*; Wiley: Chichester, UK, 2002. (b) Fǎllis, A, G,; Lu, Y.-F. *Advances in Cycloadditions*; JAI Press, Inc.: Greenwich, CT, 1993; Vol. 3, Chapter 1, pp 1−66. (c) Oppolzer, W. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: New York, 1991; Vol. 5, Chapter 4.1, pp 316−399.

(3) (a) Corey, E. J. *Angew. Chem., Int. Ed.* **2002**, *41*, 1650−1667. (b) Nicolaou, K. C.; Snyder, S. A.; Montagnon, T.; Vassilikogiannakis, G. E. *Angew. Chem., Int. Ed.* **2002**, *41*, 1668−1698. (c) Stocking, E. M.; Williams, R. M. *Angew. Chem., Int. Ed.* **2003**, *42*, 3078−3115.

(4) (a) Desimoni, G.; Tacconi, G.; Barco, A.; Pollini, G. P. *Natural Products Synthesis Through Pericyclic Reactions*; ACS Monograph Series 180; American Chemical Society: Washington, DC, 1983. (b) Ho, T.-L. *Carbocyclic Ring Construction in Terpene Synthesis*; VCH: Weinheim, 1988.

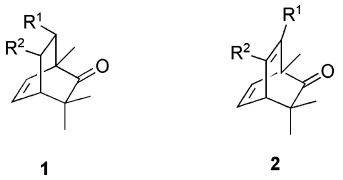
(5) (a) Singh, V. *Acc. Chem. Res.* **1999**, *32*, 324−333. (b) Quideau, S.; Pouységu, L. *Org. Prep. Proc. Int.* **1999**, *31*, 617−680. (c) Liao, C.-C.; Peddinti, R. K. *Acc. Chem. Res.* **2002**, *35*, 856−866.

(6) For Diels−Alder reactions of dimethyl acetylenedicarboxylate with 2,4-cyclohexadienones, see: (a) Alder, K.; Flock, F. H.; Lessenich, H. *Chem. Ber.* **1957**, *90*, 1709−1720. (b) Kalberer, F.; Schmid, H. *Helv. Chim. Acta* **1957**, *40*, 779−786. (c) Wessely, F.; Budzikiewicz, H. *Monatsh. Chem.* **1959**, *90*, 62−67. (d) Schultz, A. G.; Dittami, J. P.; Lavieri, F. P.; Salowey, C.; Sundararaman, P.; Szymula, M. B. *J. Org. Chem.* **1984**, *49*, 4429−4440. (e) Becker, H.-D.; Ruge, B. *J. Org. Chem.* **1980**, *45*, 2189−2195. (f) Yates, P.; Stevens, K. E. *Tetrahedron* **1981**, *37*, 4401−4410. (g) Yates, P.; Gomes, A.; Burnell, J. D.; Cong, D. D.; Sawyer, J. F. *Can. J. Chem.* **1989**, *67*, 37−47.

(7) (a) Hart, H.; Kuzuya, M. *J. Am. Chem. Soc.* **1974**, *96*, 6436−6450. (b) Hart, H.; Kuzuya, M. *J. Am. Chem. Soc.* **1975**, *97*, 2450−2458. (c) Hiller, A.; Yates, P. *Can. J. Chem.* **1981**, *59*, 2510−2517. (d) Luibrand, R. T.; Broline, B. M.; Charles, K. A.; Drues, R. W. *J. Org. Chem.* **1981**, *46*, 1874−1877. (e) Bogachev, A. A.; Bagryanskaya, I. Y.; Rybalova, T. V.; Gatilov, Y. V.; Kobrina, L. S. *Russ. J. Gen. Chem.* **1996**, *66*, 1284−1293. (f) Kobrina, L. S. *Russ. Chem. Bul.* **2002**, *51*, 1775−1795.

(8) For reactions of other acetylene derivatives with a 2,4-cyclohexadienone, see: (a) Liao, C.-C.; Lin, H.-S. *J. Chin. Chem. Soc.* **1983**, *30*, 69−83. (b) Liao, C.-C.; Lin, H.-S. *J. Chin. Chem. Soc.* **1986**, *33*, 73−82.

10.1021/jo035429y CCC: $27.50
Published on Web 12/23/2003



1 **2**

FIGURE 1. Structures of bicyclo[2.2.2]octenones and bicyclo-[2.2.2]octadienones.

Alder reaction of 2,4-cyclohexadienones with acetylene derivatives.[6−10] Due to the limited accessibility and high propensity toward dimerization of 2,4-cyclohexadienones,[12] their Diels−Alder reactions with acetylenes have not been studied in detail.[13] Not surprisingly, most of the reported studies focused on reactions of dimethyl acetylenedicarboxylate with a few 2,4-cyclohexadienones bearing bulky substituents.[6−8] Furthermore, most types of 2,4-cyclohexadienones have been generated in situ from the corresponding dimers or prepared using inefficient or lengthy protocols.[6−10] Masked *o*-benzoquinones (MOBs) are the most easily accessible 2,4-cyclohexadienones, and the Diels−Alder chemistry of MOBs has been extensively studied in our laboratory.[5c,12] However, the reactions of acetylenes with MOBs bearing synthetically relevant substituents did not offer much promise.[8,13] Consequently, we focused our attention on 2,6,6-trimethyl-2,4-cyclohexadienone (**12**). Despite its great synthetic potential,[10b,14] **12** has not been widely studied,[15] presumably due to the difficulties involved in its preparation, low yields[16a] or long protocols,[16b] and its facile dimerization.[14c,16a,17] Nevertheless, cyclohexadienone **12** has been used as starting material in the total synthesis of several natural products[14] such as patchouli alcohol[10b,14c,d] and carotenoids[18] (Figure 2). Therefore, we sought to develop nondimerizing and easily accessible 2,4-cyclohexadienones.

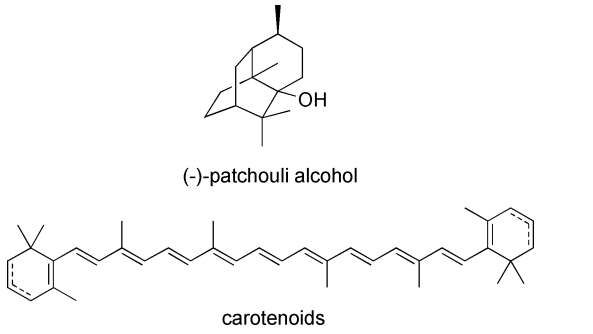
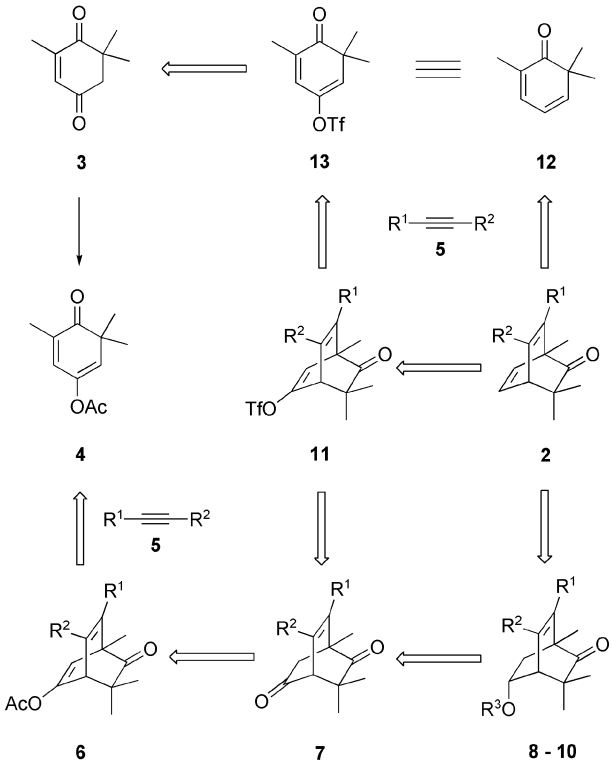


FIGURE 2. Structures of (−)-patchouli alcohol and carotenoids.

SCHEME 1



We envisioned that 4-acetoxy-2,6,6-trimethylcyclohexa-2,4-dienone (**4**), which does not dimerize easily and is accessible in multigram quantities from commercially available 4-ketoisophorone (**3**),[16b] would undergo Diels−Alder reactions with acetylenes **5** to provide adducts **6**. Further, we believed that the adducts **6** could be transformed into the desired bicyclo[2.2.2]octadienones **2** by one of the following two routes: (1) selective reduction of the vinyl acetate moiety in **6** or the less hindered ketone in diones **7** to the alcohols **8** followed by elimination[9a] of the corresponding mesylates **9** or xanthates **10** or, alternatively, (2) the transformation of bicyclo[2.2.2]-octenediones **7** into **2** by Cacchi's procedure[19] for conversion of enolizable ketones into alkenes via vinyl triflates **11** (Scheme 1).

While the first route was found to be inefficient, we were able to prepare bicyclo[2.2.2]octenediones (**7**),[20] a

(9) For indirect methods to prepare bicyclo[2.2.2]octadienones, see: (a) Gompper, R.; Etzbach, K.-H. *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 603−604. (b) Prinzbach, H.; Schal, H.-P.; Hunkler, D. *Tetrahedron Lett.* **1978**, 2195−2198. (c) Yates, P.; Auksi, H. *Can. J. Chem.* **1979**, *57*, 2853−2863. (d) Luibrand, R. T.; Fujinari, E. M. *J. Org. Chem.* **1980**, *45*, 958−960. (e) Yates, P.; Langford, G. E. *Can. J. Chem.* **1981**, *59*, 344−355. (f) Spreitzer, H.; Schiffer, C.; Buchbauer, G. *Liebigs Ann. Chem.* **1986**, 1578−1585. (g) Yamaguchi, M.; Arisawa, M.; Omata, K.; Kabuto, K.; Hirama, M.; Uchimaru, T. *J. Org. Chem.* **1998**, *63*, 7298−7305.

(10) For reactions of phenyl vinyl sulfoxide with 2,4-cyclohexadienones, see: (a) Liao, C.-C.; Hsieh, H.-P.; Lin, S.-Y. *J. Chem. Soc., Chem. Commun.* **1990**, 545−547. (b) Magee, T. V.; Stork, G.; Fludzinski, P. *Tetrahedron Lett.* **1995**, *36*, 7607−7610.

(11) (a) Zimmerman, H. E.; Armesto, D. *Chem. Rev.* **1996**, *96*, 3065−3112. (b) Zimmerman, H. E. *Org. Photochem.* **1991**, *11*, 1−36. (c) Demuth, M. *Org. Photochem.* **1991**, *11*, 37−109. (d) Houk, K. N. *Chem. Rev.* **1976**, *76*, 1−74.

(12) (a) Liao, C.-C.; Chu, C.-S.; Lee, T.-H.; Rao, P. D.; Ko, S.; Song, L.-D.; Shiao, H.-C. *J. Org. Chem.* **1999**, *64*, 4102−4110. (b) Chu, C.-S.; Lee, T.-H.; Rao, P. D.; Song, L.-D.; Liao, C.-C. *J. Org. Chem.* **1999**, *64*, 4111−4118.

(13) Chittimalla, S. K.; Liao, C.-C. *Synlett* **2002**, 565−568.

(14) (a) Näf, F.; Ohloff, G. *Helv. Chim. Acta* **1974**, *57*, 1868−1870. (b) Oppolzer, W.; Briner, P. H.; Snowden, R. L. *Helv. Chim. Acta* **1980**, *63*, 967−969. (c) Bertrand, M.; Teisseire, P.; Pelerin, G. *Tetrahedron Lett.* **1980**, *21*, 2051−2056. (d) Näf, F.; Decorzant, R.; Giersch, W.; Ohloff, G. *Helv. Chim. Acta* **1981**, *64*, 1387−1397.

(15) Curtin, D. Y.; Fraser, R. R. *J. Am. Chem. Soc.* **1958**, *81*, 662−666.

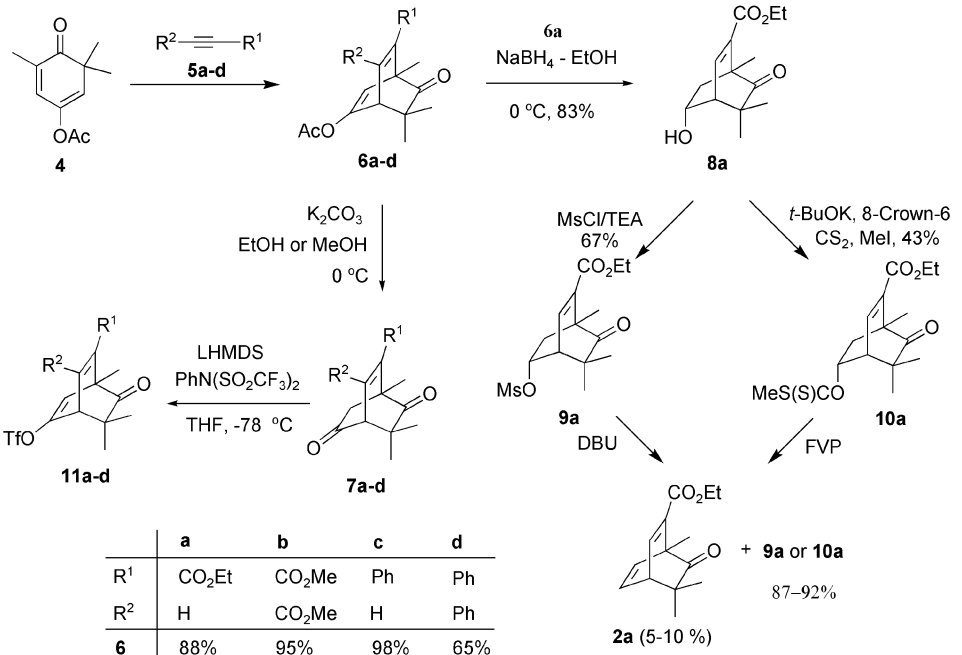
(16) (a) Berge, J. M.; Rey, M.; Dreiding, A. S. *Helv. Chim. Acta* **1982**, *65*, 2230−2241. (b) Soukup, M.; Lukáč, T.; Zell, R.; Roessler, F.; Steiner, K.; Widmer, E. *Helv. Chim. Acta* **1989**, *72*, 365−369.

(17) Brown, T. L.; Curtin, D. Y.; Fraser, R. R. *J. Am. Chem. Soc.* **1958**, *80*, 4339−4341.

(18) Widmer, E. *Pure Appl. Chem.* **1985**, *57*, 741−752.

(19) (a) Cacchi, S.; Morera, E.; Ortar, G. *Tetrahedron Lett.* **1984**, *25*, 4821−4824. (b) Cacchi, S.; Morera, E.; Ortar, G. *Organic Syntheses*; Wiley: New York, 1990; Collect. Vol. VII, pp 126−132.

SCHEME 2



	a	b	c	d
R^1	CO_2Et	CO_2Me	Ph	Ph
R^2	H	CO_2Me	H	Ph
6	88%	95%	98%	65%
7	93%	94%	95%	95%
11	83%	54%	83%	85%

very useful class of compounds with no easy access,[21] and transformed the diones **7** into the desired compounds **2** using $[Pd(PPh_3)_2Cl_2-Bu_3N-HCO_2H]$. The overall result of this four-step route could have been accomplished in one step by the Diels–Alder reaction of an acetylene with 2,6,6-trimethyl-2,4-cyclohexadienone (**12**) except for the problems associated with synthesis and handling of **12**.[10b,14,16a,17,22] Alternatively, we were able to identify and explore the possibility of using 4-triflyloxy-2,6,6-trimethylcyclohexa-2,4-dienone (**13**) instead of **4** and thereby reducing the number of synthetic steps to two.[23] We herein report the details of the attractive utilization of **13** as a nondimerizing alternative to **12** for the first time in the Diels–Alder reactions with acetylenes and a series of olefinic dienophiles resulting in the formation of functionalized bicyclo[2.2.2]octadienones **2** and bicyclo-[2.2.2]octenones **1**, respectively. We also report the Diels–Alder reaction of **13** with phenyl vinyl sulfoxide that led to the preparation of **2f** a key intermediate in Stork's synthesis of patchouli alcohol,[10b] a natural product.

Results and Discussion

(I) Synthesis of Bicyclo[2.2.2]octadienones 2a–f. As mentioned earlier, we envisaged two possible routes by which the vinyl acetates **6** could be transformed into bicyclo[2.2.2]octa-5,7-dien-2-ones **2**. Route 1 requires selective reduction of the vinyl acetate moiety of the adducts **6** or the less hindered keto group of the diones **7** in the presence of a hindered ketone and then elimination of the resultant alcohols **8** or their derivatives **9** and **10**. Route 2 involves conversion of vinyl acetates **6** into bicyclo[2.2.2]octen-2,5-diones **7**, which could then be transformed into the desired compounds **2** by one of the known methods used for conversion of enolizable ketones into alkenes such as Cacchi's method. Apparently, both routes depend on the success of the Diels–Alder reactions of **4** with acetylenes **5** (Scheme 1).

Despite its known stability and availability in multigram quantities, the Diels–Alder chemistry of **4** has not been studied in detail.[24,25] It is important to mention that Yates and co-workers assumed its intermediacy.[21c] We have prepared **4** following a reported procedure as a yellow oil on a 25 g scale. In our hands, too, **4** neither dimerized nor decomposed when stored in a refrigerator for several weeks. Its Diels–Alder reaction with ethyl propiolate (**5a**) at 80 °C under neat conditions furnished the expected adduct **6a** in 88% yield as the sole product (Scheme 2). Similarly, dimethyl acetylenedicarboxylate (**5b**) was reacted with **4** to provide **6b** in 95% yield. Phenylacetylene (**5c**) also underwent highly regioselective cycloaddition with **4** at 120 °C, affording **6c** as the sole product in 98% yield. On the other hand, diphenylacetylene (**5d**) reacted with **4** at 120 °C and afforded the adduct **6d** only in 65% yield. The remarkable regioselectivity observed in the cycloadditions of **5a** and **5c** with cyclohexadienone **4** is noteworthy. Similar regioselectivity was also noticed in the reactions of MOBs bearing a

(20) Yang, M.-S.; Lu, S.-S.; Rao, Ch. P.; Tsai, Y.-F.; Liao, C.-C. *J. Org. Chem.* **2003**, *68*, 6543–6553.

(21) (a) Hill, R. K.; Morton, G. H.; Peterson, J. R.; Walsh, J. A.; Paquette, L. A. *J. Org. Chem.* **1985**, *50*, 5528–5533. Demuth, M.; Ritterskamp, P.; Weigt, E.; Schaffner, K. *J. Am. Chem. Soc.* **1986**, *108*, 4149–4154. (c) Yates, P.; Burnell, J. D.; Freer, V. J.; Sawyer, J. F. *Can. J. Chem.* **1987**, *65*, 69–77.

(22) For methods to prepare **12**, see: (a) Quinkert, G.; Durner, G.; Klein, E.; Adam, F.; Haupt, E.; Leibfritz, R. *Chem. Ber.* **1980**, *113*, 2227–2248. (b) Bertrand, M.; Teisseire.; Pelerin, G. *Tetrahedron Lett.* **1980**, 21, 2055–2056.

(23) Yang, M.-S.; Chang, S.-Y.; Lu, S.-S.; Rao, P. D.; Liao, C.-C. *Synlett* **1999**, 225–227.

(24) (a) Widmer, E.; Zell, R.; Grass, H.; Marbet, R. *Helv. Chim. Acta* **1982**, *65*, 958–967. (b) Hagiwara, H.; Yamada, Y.; Sakai, H.; Suzuki, T.; Ando, M. *Tetrahedron* **1998**, *54*, 10999–11010.

(25) Broger, E. A.; Yvo, C.; Schmid, R.; Siegfried, T. *Chem. Abstr.* **1996**, *124*, 1215.

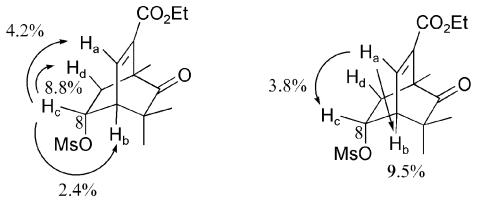


FIGURE 3. ^{1}H NMR studies of NOE for **9a**.

spirolactone moiety as a mask with acetylenes **5a** and **5c**.[8]

It was initially believed that reduction of enol acetates **6a**−**d** or diones **7a**−**d** to the corresponding alcohols followed by dehydration via elimination of the corresponding mesylates or xanthates would provide the desired compounds **2a**−**d**. However, reduction of **6a** with $NaBH_4$ at 0 °C in ethanol provided the alcohol **8a** as a single isomer in 83% yield. Alcohol **8a** was converted into mesylate **9a** (67%) by treatment with methanesulfonyl chloride in the presence of triethylamine. However, attempted elimination of mesylate **9a** with DBU was found to be inefficient under various conditions. The desired product **2a** was produced in <5% yield along with 92% yield of unchanged **9a** (Scheme 2). As an alternative approach, the xanthate **10a** (43%) was prepared from **8a** and subjected to flash vacuum pyrolysis (FVP) at various temperatures without much success. The desired compound **2a** was obtained in about 10% yield along with 87% yield of unchanged **10a** (Scheme 2).

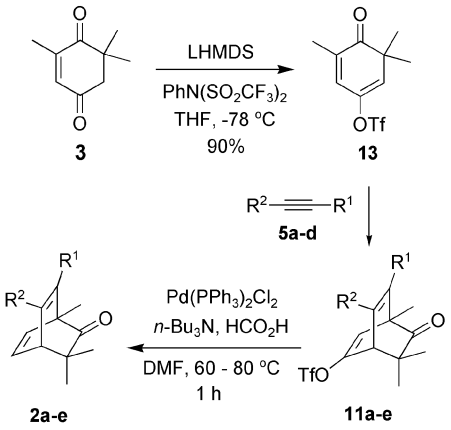
The stereochemistry of compounds **8a**−**10a** was determined from NOE experiments on the mesylate **9a**. Significant NOE enhancements were observed in signals corresponding to H_a, H_b, and H_d when H_c at δ 4.89 was irradiated (Figure 3). Similarly when H_a at δ 7.27 was irradiated, about 3.8% NOE enhancement was observed in the signal corresponding to H_c, indicating the proximity of H_a and H_c. On the basis of these results, the stereochemistry of C-8 of compounds **8a**−**10a** was assigned as shown.

As route 1 proved to be inefficient, we have decided to transform the adducts **6a**−**d** into corresponding bicyclo[2.2.2]octene-2,5-diones **7a**−**d** and then subject the resultant **7a**−**d** to the Cacchi procedure to get the corresponding desired bicyclo[2.2.2]octadienones **2a**−**d**. Accordingly, adduct **6a** was treated with K_2CO_3 in ethanol at 0 °C to afford the desired bicyclo[2.2.2]octene-2,5-dione **7a** in 93% yield. Similarly, **7b**−**d** were obtained in high yields (Scheme 2).

It is important to mention that there are no straightforward general procedures for the preparation of bicyclo[2.2.2]octene-2,5-diones.[21] Prior to these studies, only a few bicyclo[2.2.2]octadienones were known in the literature.[6,7a−e] Parent bicyclo[2.2.2]octene-2,5-dione was prepared from hydroquinone in 16% yield.[21b] Yates and coworkers prepared two bicyclo[2.2.2]octene-2,5-diones by treatment of cyclohex-2-ene-1,4-diones with a large excess of isopropenyl acetate and dimethyl acetylenedicarboxylate followed by methanolysis.[21c]

Cacchi's procedure has been shown to be quite efficient for the conversion of enolizable ketones to alkenes in a regioselective manner under relatively mild conditions.[19] It involves conversion of ketones into vinyl triflates and

SCHEME 3



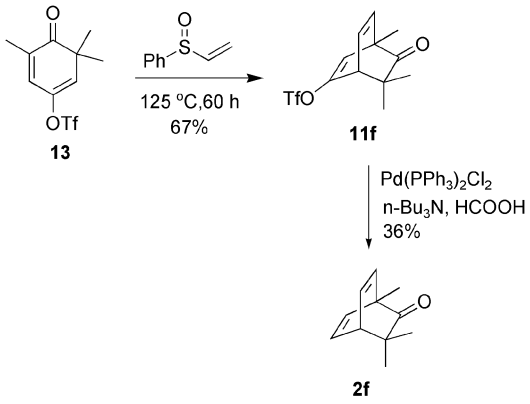
	a	b	c	d	e
R^1	CO_2Et	CO_2Me	Ph	Ph	H
R^2	H	CO_2Me	H	Ph	CO_2Et
11	73%	94%	90%	90%	12%
2	83%	81%	87%	99%	81%

reductive removal of triflates using Pd-tributylammonium formate. We have initially prepared vinyl triflates **11a**−**d** from enediones **7a**−**d**, respectively, in moderate to good yields. Among the various conditions examined, LHMDS as the base and *N*-phenyltriflimide as the triflating agent at −78 °C in THF provided the best results. Thus, treatment of **7a** with LHMDS followed by *N*-phenyltriflimide furnished the desired **11a** in 83% yield. Compound **7b** afforded **11b** only in 54% yield under the same conditions. On the other hand, vinyl triflates **11c**,**d** were obtained in good yields from **7c**,**d**, respectively (Scheme 2).

At this stage, it occurred to us that the compounds **11a**−**d** could possibly be prepared in a more direct and simple manner in two steps from the Diels−Alder reactions of 4-triflyloxy-2,6,6-trimethyl-2,4-cyclohexadienone (**13**) with acetylenes **5a**−**d**. Accordingly, 4-ketoisophorone (**3**) was converted to the cyclohexadienone **13** under the aforementioned conditions employed for the preparation of vinyl triflates **11a**−**d** (Scheme 3). Cyclohexadienone **13** was prepared from **3** in 90% yield as a colorless oil on a 8 g scale. Furthermore, **13** was found to be quite stable and did not dimerize for several weeks when stored in a refrigerator.

The Diels−Alder reactions of **13** with acetylenes **5a**−**d** proceeded smoothly. Reaction of **13** with **5a** at 80 °C under neat conditions for 24 h afforded a separable mixture of regioisomers **11a** (73%) and **11e** (12%). The same reaction when performed in toluene (80 °C, 24 h) provided less attractive results: **11a** (66%) and **11e** (17%) were obtained. On the other hand, the Diels−Alder reactions of **13** with **5b**−**d** furnished single adducts **11b**−**d**, respectively, in good yields. We then subjected **11a** to the $Pd(PPh_3)_2Cl_2$-tributylammonium formate reduction in DMF at 60−80 °C for 1 h for reductive removal of triflate group, which proceeded smoothly to afford the desired bicyclo[2.2.2]octadienone **2a** in 83% yield. Furthermore, no trace of products resulting from possible over-reduction of **11a** was observed. Similarly, the adducts **2b**−**e** were obtained in 81−99% yield from **11b**−**e**, respectively

SCHEME 4

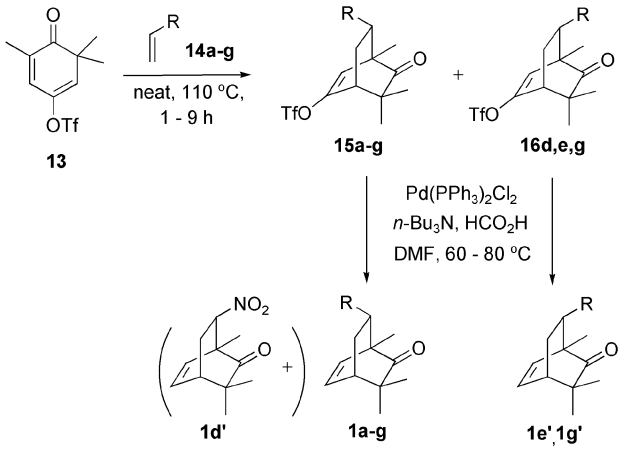


(Scheme 3). It is pertinent to mention that while the dienone **4** provided single regioisomers in the Diels−Alder reactions with ethyl propiolate (**5a**) and phenylacetylene (**5c**), the dienone **13** afforded a single regioisomer in the Diels−Alder reaction with **5a** and a 6:1 regioisomeric mixture with **5c**. This discrepancy may be due the partial electronic mismatching of the 4π and 2π components, as the dienone **13** is more electron deficient in comparison with dienone **4**.

Phenyl vinyl sulfoxide (PVSO) has been employed as an equivalent to acetylene in Diels−Alder reactions.[26] We became interested in its reactions with **13** mainly because these reactions could lead to compounds that are potentially useful in the synthesis of natural products. Accordingly we studied the reaction of **13** with PVSO. As expected, **13** reacted with PVSO at 125 °C for 60 h to furnish **11f** in 67% yield, which in turn upon reduction furnished the bicyclo[2.2.2]octadienone **2f** (36%). Note that **2f** is the key intermediate in Stork's synthesis of patchouli alcohol (Scheme 4).[10b]

(II) Synthesis of Bicyclo[2.2.2]octenones 1a−j. Encouraged by the results obtained from the Diels−Alder reactions of cyclohexa-2,4-dienone **13** with acetylenic dienophiles **5a−d**, we became interested in extending the Diels−Alder protocol to olefinic dienophiles to generate highly functionalized bicyclo[2.2.2]oct-5-en-2-ones **1**. To determine the feasibility of the cycloaddition of **13** with olefinic dienophiles **14a−j**, we have first attempted the reaction with methyl vinyl ketone (**14a**, MVK, 5 equiv). In contrary to the reaction of masked *o*-benzoquinones,[12a] the reaction of **13** with **14a** did not proceed at room temperature even after 2 days. After considerable experimentation, a single isomer **15a** was isolated in 89% yield when the reaction was performed at 110 °C. No other adducts were observed from the ^{1}H NMR spectrum of the crude reaction mixture, indicating that the cycloaddition proceeded in a highly regio- and stereoselective manner. Encouraged by this result, the study of the Diels−Alder reactions of **13** was extended first to other monosubstituted electron-deficient alkenes, viz., methyl acrylate (**14b**), phenyl vinyl sulfone (**14c**), and nitroethylene (**14d**). The *endo*-adducts **15b−d** were obtained in good to excellent yields (Scheme 5). In the reaction of **13** with nitroethylene (**14d**), the minor *exo*-isomer **16d** was

SCHEME 5



	a	b	c	d(d')	e(e')	f	g(g')
R	COMe	CO_2Me	SO_2Ph	NO_2	CN	Ph	$CH=CH_2$
15	89%	85%	92%	88%	67%	80%	72%
16	-	-	-	3%	31%	-	18%
1	90%	95%	98%	59% (34%)	77% (93%)	82%	75% (76%)

isolated in 3% yield. In the case of acrylonitrile (**14e**), the reaction was less selective and furnished a separable 2:1 mixture of *endo*-**15e**/*exo*-**16e** isomers in quantitative yield. The lower selectivity of acrylonitrile was also observed in its Diels−Alder reactions with masked *o*-benzoquinones[27] and other 4π partners.[28] The reactions of **13** with disubstituted electron-deficient alkenes, methyl methacrylate (**14h**), and *N*-phenylmaleimide (**14j**) provided the corresponding *endo*-adducts **15h** and **15j** in very good yield (Scheme 6).

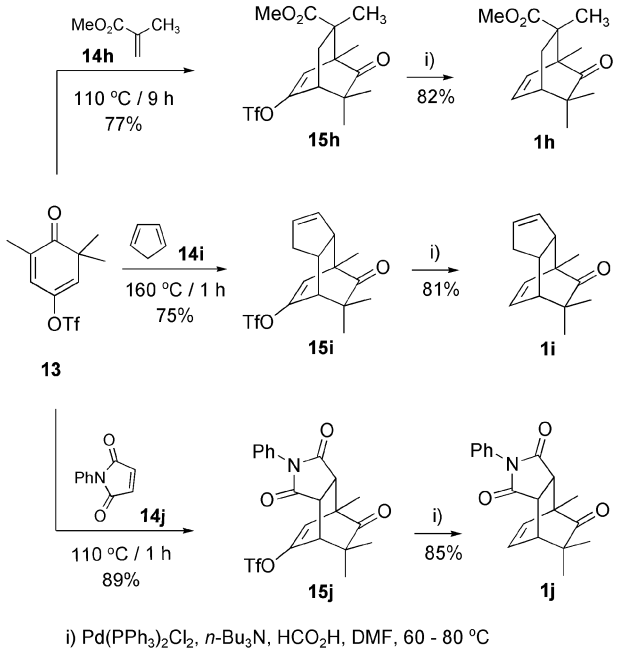
The conjugative dienophiles, viz., styrene (**14f**), 1,3-butadiene (**14g**), and cyclopentadiene (**14i**), were then used as cycloaddition partners with **13**. The reaction of **13** with styrene proceeded in highly selective manner to furnish *endo*-adduct **15f** exclusively. 1,3-Butadiene, generated in situ from 3-sulfolene, cycloadded with **13** to give a mixture of adducts, *endo*-**15g** and *exo*-**16g**; the major isomer *endo*-**15g** was isolated in 72% yield. Cyclopentadiene (**14i**), a well-known diene in Diels−Alder chemistry, was employed as an educt in the cycloaddition reaction with **13** at 160 °C for 1 h to furnish a single cycloadduct **15i** in good yield, wherein cyclopentadiene formally played the role of dienophile. It is worthwhile mentioning that the reaction of dienone **12** with cyclopentadiene at room temperature for 3 days was reported to yield a mixture of cycloadducts.[15] Unlike masked *o*-benzoquinones,[29] the dienone **13** did not participate in the cycloaddition with electron-rich dienophiles such as benzyl vinyl ether and phenyl vinyl sulfide.

(26) (a) Paquette, L. A.; Moerck, R. E.; Harirchian, B.; Magnus, P. D. *J. Am. Chem. Soc.* **1978**, *100*, 1597−1599. (b) Lucchi, O. D.; Modena, G. *Tetrahedron* **1984**, *40*, 2585−2632.

(27) Chittimalla, S. K.; Liao, C.-C. *Tetrahedron* **2003**, *59*, 4039−4046.

(28) (a) Jorgensen, W. L.; Lim, D.; Blake, J. F. *J. Am. Chem. Soc.* **1993**, *115*, 2936−2942. (b) Afarinkia, K.; Posner, G. H. *Tetrahedron Lett.* **1992**, *33*, 7839−7842. (c) Valentin, C. D.; Freccero, M.; Mirko, S.-A.; Zanaletti, R. *Tetrahedron* **2000**, *56*, 2547−2559. (d) Kienzle, V. F. *Helv. Chem. Acta* **1975**, *58*, 1180−1183. (e) Ruiz, N.; Buon, C.; Pujol, M. D.; Guillaumet, G.; Coudert, G. *Synth. Commun.* **1996**, *26*, 2057−2066.

SCHEME 6



i) $Pd(PPh_3)_2Cl_2$, *n*-Bu_3N, HCO_2H, DMF, 60 - 80 °C

The reductive removal of triflate groups of **15** and **16** was achieved under Cacchi's conditions (Bu_3N, HCO_2H, $Pd(PPh_3)_2Cl_2$, DMF, 60−80 °C) to generate bicyclo[2.2.2]-octenones **1** in good to quantitative yields (Schemes 5 and 6). Interestingly, the reduction of *endo*-adduct **15d** afforded 34% yield of *exo*-**1d′** along with 59% yield of *endo*-**1d**.

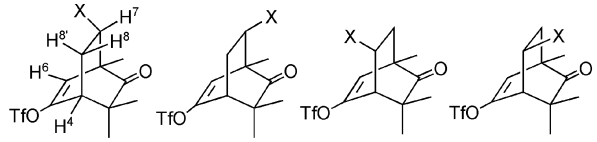


FIGURE 4. Four possible Diels−Alder adducts (shown for monosubstituted olefinic dienophiles).

The existence of H^4-H^8 and $H^4-H^{8'}$ couplings (J = 2.7−3.4 Hz) for the adducts **15** derived from the unsymmetrical olefinic dienophiles clearly indicates their ortho regiochemistry (with respect to the carbonyl function) (Figure 4). Though the W-type long-range couplings $^4J_{6,7}$ could not be measured for Diels−Alder adducts **15**, they were obtained (J = 0.6−1.5 Hz) for the reduction products **1** except for **1h**. Thus, the endo stereochemistry of adducts **15** (except for **15h**) and the exo stereochemistry of adducts **16** were established. The regio- and stereochemical assignments of the cycloadduct **15f** were further corroborated from its single-crystal X-ray structure.[30]

The presence of an electron-withdrawing or conjugative group on the dienophile **14** appears to be necessary for the success of the cycloaddition. Although there are four possible modes of [4 + 2] cycloaddition (Figure 4) for **13** with unsymmetrical dienophiles, the adduct **15** has emerged as the sole adduct in most of the cases, showing that these cycloadditions are highly selective even at elevated temperatures. As in the case of masked *o*-benzoquinones,[5c,11a,29] the overwhelming regioselectivity procured in the present Diels−Alder cycloadditions appears to be the result of regioselecting the directionality of the carbonyl group of the dienone **13**. The observed stereoselectivity clearly indicates that these cycloadditions follow the endo rule. The extremely high selectivities achieved in the reaction of cyclopentadiene may be due to its cisoid conformation, unlike in the transoid 1,3-butadiene, which exhibited less selectivity.

Conclusion

The present studies have succeeded in exploring the attractive possibility of using 2,4-cyclohexadienones **4** and **13** as nondimerizing and easily accessible alternatives for **12**. This methodology overcomes the problems associated with the parent 2,6,6-trimethyl-2,4-cyclohexadienone. It is pertinent to mention that compound **12** has been used as starting material in the total synthesis of natural products despite the fact that **12** dimerizes quite readily and requires a lengthy sequence of reactions to access. On the other hand, **4** and **13** are quite stable and react quite smoothly with acetylenes **5a**−**d**, phenyl vinyl sulfoxide, and olefins **14a**−**j** and hence hold considerable potential as dienes for Diels−Alder reactions in general. The vinyl triflate moiety in cyclohexadienone **13**, as well as bicyclo[2.2.2]octadien-2-ones **11a**−**f** and bicyclo[2.2.2]-oct-5-en-2-ones **15a**−**j**, could be a useful handle for further elaboration using organometallic coupling reactions such as Stille coupling, Suzuki coupling, and the Heck reaction. Finally, the present methodology provides easy access to relatively less common bicyclo[2.2.2]octene-2,5-diones and bicyclo[2.2.2]octa-5,7-dien-2-ones.

Experimental Section

(1*S,4*R**)-1,3,3-Trimethyl-5-acetoxy-7-ethoxycarbonylbicyclo[2.2.2]octa-5,7-dien-2-one (6a).** A mixture of **4** (1.94 g, 10.0 mM) and ethyl propiolate (**5a**, 1.96 g, 20.0 mM) was heated at 80 °C for 24 h. Removal of excess **5a** under reduced pressure followed by column chromatography on silica gel using 15% ethyl acetate in hexanes as an eluent furnished **5a** (2.56 g, 88%) as a pale yellow solid: mp 86−87 °C (from hexanes); IR (film) 3080, 1775, 1765, 1721, 1645, 1450 cm^{-1}; ^1H NMR (400 MHz) δ 7.42 (d, J = 7.0 Hz, 1H), 5.70 (d, J = 2.8 Hz, 1H), 4.14 (q, J = 7.2 Hz, 2H), 3.38 (dd, J = 7.0, 2.8 Hz, 1H), 2.14 (s, 3H), 1.62 (s, 3H), 1.25 (t, J = 7.2 Hz, 3H), 1.16 (s, 3H), 1.03 (s, 3H); ^{13}C NMR (100 MHz) δ 208.4, 167.8, 164.0, 156.0, 146.0, 137.4, 115.2, 60.6, 56.1, 52.0, 40.1, 27.5, 26.1, 21.0, 15.0, 14.0; MS (EI, 70 eV) *m*/*z* (rel intensity) 292 (M^+, weak), 251 (11), 223 (13), 180 (14), 177 (13), 135 (28), 70 (100); HRMS (EI) calcd for $C_{16}H_{20}O_5$ (M^+) 292.1311, found 292.1310. Anal. Calcd for $C_{16}H_{20}O_5$: C, 65.74; H, 6.96. Found: C, 65.84; H, 6.93.

(1*S,4*R**)-1,3,3-Trimethyl-5-acetoxy-7,8-bis(methoxycarbonyl)bicyclo[2.2.2]octa-5,7-dien-2-one (6b).** Compound **6b** (3.19 g, 95%) was prepared as a pale yellow solid by heating **4** (1.94 g, 10.0 mM) with dimethyl acetylenedicarboxylate (**5b**, 2.84 g, 20.0 mM) at 80 °C for 24 h followed by column chromatography (silica gel, 15% ethyl acetate in hexanes): mp 78−79 °C (from hexanes); IR (film) 1770, 1740, 1725, 1645,1441 cm^{-1}; ^1H NMR (400 MHz) δ 5.80 (d, J = 2.8 Hz, 1H), 3.88 (d, J = 2.8 Hz, 1H), 3.79 (s, 3H), 3.77 (s, 3H), 2.16 (s, 3H), 1.42 (s, 3H), 1.19 (s, 3H), 1.04 (s, 3H); ^{13}C NMR (100 MHz) δ 206.5, 167.4, 165.9, 163.0, 156.8, 147.4, 136.0,

(29) (a) Arjona, O.; Medel, R.; Plumet, J. *Tetrahedron Lett.* **1999**, *40*, 8431−8433. (b) Gao, S.-Y.; Lin, Y.-L.; Rao, P. D.; Liao, C.-C. *Synlett* **2000**, 421−423. (c) Gao, S.-Y.; Ko, S.; Lin, Y,-L.; Peddinti, R. K.; Liao, C.-C. *Tetrahedron* **2001**, *57*, 297−308.

(30) CCDC depositon no. 182120.

112.7, 57.1, 52.5, 52.3, 51.7, 39.5, 26.4, 26.1, 21.0, 13.1; MS (EI, 70 eV) *m/z* (rel intensity) 336 (M^+, weak), 236 (21), 235 (91), 193 (100), 192 (41), 70 (48); HRMS (EI) calcd for $C_{17}H_{20}O_7$ (M^+) 336.1209, found 336.1210. Anal. Calcd for $C_{17}H_{20}O_7$: C, 60.71; H, 5.94. Found: C, 60.72; H, 5.96.

(1*S,4*R**)-1,3,3-Trimethyl-5-acetoxy-7-phenylbicyclo-[2.2.2]octa-5,7-dien-2-one (6c).** Compound **6c** (2.91 g, 98%) was prepared as an oil by heating **4** (1.94 g, 10.0 mM) with phenylacetylene (**5c**, 2.11 g, 20.9 mM) at 125 °C for 10 h followed by column chromatography (silica gel, 15% ethyl acetate in hexanes): IR (film) 3070, 1766, 1718, 1655, 1600,-1450 cm^{-1}; ^1H NMR (400 MHz) δ 7.26−7.30 (m, 3H), 7.04−7.06 (m, 2H), 6.45 (d, J = 6.1 Hz, 1H), 5.83 (d, J = 2.9 Hz, 1H), 3.35 (dd, J = 6.1, 2.9 Hz, 1H), 2.20 (s, 3H), 1.30 (s, 3H), 1.22 (s, 3H), 1.19 (s, 3H); ^{13}C NMR (100 MHz) δ 209.9, 167.8, 157.2, 146.9, 137.1, 133.7, 128.1, 127.8, 127.2, 114.5, 57.8, 51.9, 41.2, 28.0, 26.6, 21.1, 15.4; MS (70 eV) *m/z* (rel intensity) 297 ($M^+ + 1$, weak), 226 (85), 185 (62), 184 (100), 167 (17); HRMS (EI) calcd for $C_{19}H_{20}O_3$ (M^+) 297.1491, found 297.1484.

(1*S,4*R**)-1,3,3-Trimethyl-5-acetoxy-7,8-diphenylbicyclo-[2.2.2]octa-5,7-dien-2-one (6d).** Compound **6d** (2.41 g, 65%) was prepared as a pale yellow solid by heating **4** (1.94 g, 10.0 mM) with diphenylacetylene (**5d**, 3.56 g, 20.0 mM) at 125 °C for 2 days followed by column chromatography (silica gel, 15% ethyl acetate in hexanes): mp 108−109 °C (from EtOAc−hexanes); IR (neat) 3050, 1766, 1717, 1688, 1600, 1500, 1445 cm^{-1}; ^1H NMR (400 MHz) δ 7.25−7.20 (m, 3H), 7.09−7.14 (m, 5H), 6.92−6.90 (m, 2H), 5.93 (d, J = 3.0 Hz, 1H), 3.71 (d, J = 3.0 Hz, 1H), 2.23 (s, 3H), 1.26 (s, 6H), 1.21 (s, 3H); ^{13}C NMR (100 MHz) δ 209.9, 167.9, 156.9, 143.7, 140.5, 138.4, 136.5, 129.4, 128.3, 128.1, 127.8, 126.9, 126.8, 115.1, 58.4, 57.6, 41.5, 26.9, 26.6, 21.2, 15.9; MS (EI, 70 eV) *m/z* (rel intensity) 372 (M^+, weak), 302 (55), 261 (44), 260 (100), 245 (17); HRMS (EI) calcd for $C_{25}H_{24}O_3$ (M^+) 372.1725, found 372.1740. Anal. Calcd for $C_{25}H_{24}O_3$: C, 80.62; H, 6.49. Found: C, 80.51; H, 6.55.

General procedure for the synthesis[23] and spectral analysis of 1,3,3-trimethylbicyclo[2.2.2]oct-7-ene-2,5-diones (**7a**,[23] **7b**,[21c] **7c**,[20] **7d**[20]) were reported earlier.

(1*S,4*R**,5*R**)-8-Hydroxy-1,3,3-trimethyl-6-ethoxycarbonylbicyclo[2.2.2]oct-5-en-2-one (8a).** To a solution of **6a** (507 mg, 1.74 mM) in ethanol (10 mL) at 0 °C was added $NaBH_4$ (33 mg, 0.88 mM) with stirring. The resulting mixture was stirred for 3 h at 0 °C. Then, water was added and extracted with methylene chloride. The organic layer was dried (Na_2SO_4) and concentrated. The residue was purified by column chromatography on silica gel using 30% ethyl acetate in hexanes as an eluent to afford **8a** (366 mg, 83%) as a colorless oil: IR (film) 3460, 1715, 1608, 1458 cm^{-1}; ^1H NMR (300 MHz) δ 7.30 (d, J = 7.1 Hz, 1H), 4.17 (q, J = 7.1 Hz, 2H), 4.14 (ddd, J = 10.0, 5.8, 2.4 Hz, 1H), 2.84 (dd, J = 7.1, 2.4 Hz, 1H), 2.18 (dd, J = 14.0, 10.0 Hz, 1H), 1.54 (dd, J = 14.0, 5.8 Hz, 1H), 1.41 (s, 3H), 1.40 (s, 3H), 1.29 (t, J = 7.1 Hz, 3H), 1.09 (s, 3H); ^{13}C NMR (75 MHz) δ 215.2, 164.6, 146.1, 133.3, 69.0, 60.6, 51.1, 49.5, 42.7, 38.4, 29.4, 26.4, 16.2, 14.0; MS (EI, 70 eV) m/z (rel intensity) 252 (M^+, 1), 206 (12), 165 (100), 137 (35), 93 (77); HRMS (EI) calcd for $C_{14}H_{20}O_4$ (M^+) 252.1362, found 252.1366.

(1*S,4*R**,5*R**)-8-(Methylsulfonyl)oxy-1,3,3-trimethyl-6-ethoxycarbonylbicyclo[2.2.2]oct-5-en-2-one (9a).** To a solution of **8a** (50 mg, 0.02 mM) in CH_2Cl_2 (12 mL) was added triethylamine (2.5 mL) with stirring followed by methanesulfonyl chloride (0.05 mL, 0.64 mM) under a nitrogen atmosphere. After 1 h of stirring, a 2% HCl (10 mL) solution was added, and the mixture was extracted with CH_2Cl_2 (3 × 15 mL). The separated organic layer was washed with saturated $NaHCO_3$ solution and brine, dried ($MgSO_4$), and concentrated. The residue was purified by column chromatography on silica gel using 30% ethyl acetate in hexanes as an eluent to afford **9a** (144 mg, 67%) as a white solid: mp 105−106 °C (from hexanes); IR (film) 1721, 1459, 1349, 1253, 1065 cm^{-1}; ^1H NMR (300 MHz) δ 7.27 (d, J = 7.2 Hz, 1H), 4.89 (ddd, J = 10.3, 5.7, 2.6 Hz, 1H), 4.18 (q, J = 7.1 Hz, 2H), 3.21 (dd, J = 7.2, 2.6 Hz, 1H), 3.04 (s, 3H), 2.34 (dd, J = 14.5, 10.3 Hz, 1H), 1.81 (dd, J = 14.5, 5.7 Hz, 1H), 1.43 (s, 3H), 1.35 (s, 3H), 1.29 (t, J = 7.1 Hz, 3H), 1.13 (s, 3H); ^{13}C NMR (75 MHz) δ 212.8, 163.9, 143.4, 134.9, 76.0, 60.9, 49.3, 48.6, 42.4, 38.5, 36.0, 28.9, 26.1, 15.8, 14.0; MS (EI, 70 eV) m/z (rel intensity) 330 (M^+, 3), 207 (25), 133 (30), 93 (42), 70 (100); HRMS (EI) calcd for $C_{15}H_{22}O_6S$ (M^+) 330.1138, found 330.1140. Anal. Calcd for $C_{15}H_{22}O_6S$: C, 54.54; H, 6.72. Found: C, 54.46; H, 6.74.

(1*S,4*R**,5*R**)-8-[(Methylthio)thiocarbonyl]oxy-1,3,3-trimethyl-6-ethoxycarbonylbicyclo[2.2.2]oct-5-en-2-one (10a).** To a solution of **8a** (93 mg, 0.37 mM) in CH_2Cl_2 (10 mL) was added 1 drop of 18-crown-6 followed by CS_2 (0.6 mL, 1 mM) under a nitrogen atmosphere. The reaction mixture was stirred for 5 min at room temperature, and potassium *tert*-butoxide (53 mg, 0.47 mM) was added. After 2 h of stirring, methyl iodide (0.25 mL, 4.0 mmol) was added, and the stirring was continued for an additional 2 h. Then, water (20 mL) was added and extracted with CH_2Cl_2 (3 × 15 mL). The separated organic layer was washed with saturated $NaHCO_3$ solution and brine, dried ($MgSO_4$), and concentrated. The residue was purified by column chromatography on silica gel using 10% ethyl acetate in hexanes as an eluent to afford **10a** (56 mg, 43%) as a white solid: mp 85−86 °C (from hexanes); IR (film) 1722, 1457, 1374, 1235, 1056 cm^{-1}; ^1H NMR (300 MHz) δ 7.32 (d, J = 7.2 Hz, 1H), 5.62 (ddd, J = 10.2, 5.6, 2.5 Hz, 1H), 4.19 (q, J = 7.1 Hz, 2H), 3.30 (dd, J = 7.2, 2.5 Hz, 1H), 2.57 (s, 3H), 2.42 (dd, J = 14.5, 10.2 Hz, 1H), 1.73 (dd, J = 14.5, 5.6 Hz, 1H), 1.45 (s, 3H), 1.32 (s, 3H), 1.30 (t, J = 7.1 Hz, 3H), 1.12 (s, 3H); ^{13}C NMR (75 MHz) δ 214.9, 213.5, 164.1, 143.9, 134.8, 79.1, 60.7, 49.5, 47.2, 42.2, 35.5, 28.9, 26.1, 19.0, 15.9, 14.0; MS (EI, 70 eV) m/z (rel intensity) 342 (M^+, 2), 251 (13), 207 (100), 161 (75), 93 (88); HRMS (EI) calcd for $C_{16}H_{22}O_4S_2$ (M^+) 342.0961, found 342.0969. Anal. Calcd for $C_{16}H_{22}O_4S_2$: C, 56.11; H, 6.47. Found: C, 56.04; H, 6.45.

(1*R,4*S**)-5-Trifluoromethanesulfonyloxy-1,3,3-trimethyl-7-ethoxycarbonylbicyclo[2.2.2]octa-5,7-dien-2-one (11a).** To a solution of **7a** (980 mg, 3.92 mM) in THF (2 mL) at −78 °C was added LHMDS (8.6 mL, 4.3 mM, 0.5M in THF) over 15 min with stirring under a nitrogen atmosphere. Then, *N*-phenyltrifluoromethanesulfonimide (1.5 g, 4.2 mM) in THF (19 mL) was added to the reaction mixture and the stirring continued for 2 h at −78 °C. The reaction mixture was brought to room temperature. Then, 1 M HCL (15 mL) and water (15 mL) were added sequentially, and the mixture was extracted with ethyl acetate (2 × 20 mL). The separated organic layer was washed with saturated NaCl solution, dried ($MgSO_4$), and concentrated. The residue was purified by column chromatography on silica gel using 15% ethyl acetate in hexanes as an eluent to afford **11a** (1250 mg, 83%) as a colorless liquid: IR (film) 1727, 1653, 1602, 1426, 1225, 1068 cm^{-1}; ^1H NMR (300 MHz) δ 7.44 (d, J = 6.6 Hz, 1H), 5.87 (d, J = 3.1 Hz, 1H), 4.20 (q, J = 7.2 Hz, 2H), 3.57 (dd, J = 6.6, 3.1 Hz, 1H), 1.70 (s, 3H), 1.30 (t, J = 7.2 Hz, 3H), 1.25 (s, 3H), 1.12 (s, 3H); ^{13}C NMR (100 MHz) δ 206.7, 163.5, 154.7, 144.9, 137.5, 119.8, 118.4 (q, CF_3), 61.0, 57.2, 51.9, 39.9, 27.5, 26.6, 15.0, 14.0; MS (FAB) m/z (rel intensity) 383 ($M^+ + 1$, 61), 337 (49), 267 (32), 159 (19), 137 (21), 91 (22), 70 (100); HRMS (FAB) calcd for $C_{15}H_{18}O_6F_3S$ ($M^+ + 1$) 383.0776, found 383.0775.

(1*S,4*R**)-5-Trifluoromethanesulfonyloxy-1,3,3-trimethyl-7,8-bis(methoxycarbonyl)bicyclo[2.2.2]octa-5,7-dien-2-one (11b).** Compound **7b** (1.00 g, 3.4 mM) was treated at −78 °C with LHMDS (3.8 mL, 3.8 mM, 1 M in THF) followed by *N*-phenyltriflimide (1.40 g, 3.9 mM) following the procedure described for the preparation of **11a**. Column chromatography of the crude product on silica gel using 15% ethyl acetate in hexanes as an eluent afforded a white solid (782 mg, 54%): mp 87 °C (from hexanes); IR (film) 1732, 1656, 1627, 1429, 1219, 1067 cm^{-1}; ^1H NMR (300 MHz) δ 5.88 (d, J = 3.0 Hz, 1H), 4.07 (d, J = 3.0 Hz, 1H), 3.83 (s, 3H), 3.82 (s, 3H), 1.49 (s, 3H), 1.27 (s, 3H), 1.11 (s, 3H); ^{13}C NMR (75 MHz) δ 204.9, 165.1, 162.4, 155.5, 146.9, 135.8, 118.3 (q, CF_3), 117.6, 57.9, 52.8, 52.5, 51.7, 39.4, 26.2, 26.1, 13.0; MS (FAB) m/z (rel

intensity) 427 ($M^+ + 1$, 21), 325 (100), 154 (14), 136 (17), 70 (53); HRMS (EI) calcd for $C_{16}H_{17}O_8F_3S$ (M^+) 426.0596, found 426.0582. Anal. Calcd for $C_{16}H_{17}O_8F_3S$: C, 45.07; H, 4.02. Found: C, 45.10; H, 4.05.

(1*S,4*R**)-5-Trifluoromethanesulfonyloxy-1,3,3-trimethyl-7-phenylbicyclo[2.2.2]octa-5,7-dien-2-one (11c).** Compound **7c** (1.01 g, 3.98 mM) was treated at −78 °C with LHMDS (4.4 mL, 4.4 mM, 1 M in THF) followed by *N*-phenyltriflimide (1.57 g, 4.39 mM) following the procedure described for the preparation of **11a**. Column chromatography of the crude product on silica gel using 5% ethyl acetate in hexanes as an eluent afforded a white solid (1.27 g, 83%): mp 93−94 °C (from hexanes); IR (film) 1725, 1656, 1425, 1216, 1067 cm^{-1}; ^1H NMR (300 MHz) δ 7.35−7.30 (m, 3H), 7.05−7.00 (m, 2H), 6.48 (d, J = 6.4 Hz, 1H), 5.93 (d, J = 3.2 Hz, 1H), 3.52 (dd, J = 6.4, 3.2 Hz, 1H), 1.32 (s, 3H), 1.26 (s, 3H), 1.23 (s, 3H); ^{13}C NMR (75 MHz) δ 208.1, 156.1, 147.1, 136.0, 133.0, 128.2, 128.1, 127.7, 119.4, 118.5 (q, CF_3), 58.8, 51.8, 41.0, 27.9, 26.5, 15.3; MS (FAB) m/z (rel intensity) 387 ($M^+ + 1$, 70), 316 (15), 95 (34), 69 (65), 55 (100); HRMS (EI) calcd for $C_{18}H_{17}O_4F_3S$ (M^+) 386.0800, found 386.0804. Anal. Calcd for $C_{18}H_{17}O_4F_3S$: C, 55.95; H, 4.43. Found: C, 55.93; H, 4.43.

(1*S,4*R**)-5-Trifluoromethanesulfonyloxy-1,3,3-trimethyl-7,8-diphenylbicyclo[2.2.2]octa-5,7-dien-2-one (11d).** Compound **7d** (2.00 g, 6.06 mM) was treated at −78 °C with LHMDS (6.5 mL, 6.5 mM, 1 M in THF) followed by *N*-phenyltriflimide (2.36 g, 6.6 mM) following the procedure described for the preparation of **11a**. Column chromatography of the crude product on silica gel using 5% ethyl acetate in hexanes as eluent afforded a white solid (2.37 g, 85%). mp 101 °C (from CH_2Cl_2-hexanes); IR (film) 3064, 1724, 1655, 1425, 1241, 1071 cm^{-1}, ^1H NMR (300 MHz) δ 7.22−7.25 (m, 3H), 7.05−7.14 (m, 5H), 6.88−7.04 (m, 2H), 6.01 (d, J = 3.2 Hz, 1H), 3.86 (d, J = 3.2 Hz, 1H), 1.30 (s, 6H), 1.24 (s, 3H); ^{13}C NMR (75 MHz) δ 207.9, 155.5, 143.4, 140.2, 137.2, 135.6, 129.3, 128.3, 128.1, 128.0, 127.4, 127.3, 119.4, 118.5 (q, CF_3), 59.2, 57.2, 41.2, 26.6, 26.3, 15.7; MS (FAB) m/z (rel intensity) 463 ($M^+ + 1$, 51), 392 (100), 215 (17), 70 (22); HRMS (EI) calcd for $C_{24}H_{21}O_4F_3S$ (M^+) 462.1113, found 462.1144. Anal. Calcd for $C_{24}H_{21}O_4F_3S$: C, 62.33; H, 4.58. Found: C, 62.34; H, 4.56.

4-Trifluoromethanesulfonyloxy-2,6,6-trimethylcyclohexa-2,4-dienone (13). To a solution of **3** (5.00 g, 32.85 mM) in THF (20 mL) at −78 °C was added LHMDS (34 mL, 34.0 mM, 1M in THF) with stirring under a nitrogen atmosphere. After 15 min, *N*-phenyltrifluoromethanesulfonimide (12.23 g, 34.22 mM) in THF (60 mL) was added and the stirring continued for 2 h at −78 °C. The reaction mixture was brought to room temperature. Then, 1 M HCl (15 mL) followed by water (30 mL) was added and extracted with ethyl acetate (3 × 30 mL). The separated organic layer was washed with brine, dried ($MgSO_4$), and concentrated. The residue was purified by column chromatography on silica gel using 15% ethyl acetate in hexanes as an eluent to afford **13** (8.42 g, 90%) as a yellowish oil: IR (film) 1673, 1425, 1365, 1215, 1141 cm^{-1}; ^1H NMR (300 MHz) δ 6.75 (qd, J = 3.1, 1.6 Hz, 1H), 6.12 (d, J = 3.1 Hz, 1H), 1.95 (d, J = 1.6 Hz, 3H), 1.29 (s, 6H); ^{13}C NMR (75 MHz) δ 202.3, 141.5, 136.5, 133.0, 132.6, 118.5 (q, CF_3), 46.5, 25.7,15.3; MS (EI, 70 eV) m/z (rel intensity) 284 (M^+, 2), 281 (61), 151 (16), 83 (38), 70 (100); HRMS (EI) calcd for $C_{10}H_{11}O_4F_3S$ (M^+) 284.0330, found 284.0321.

Diels−Alder Reaction of 13 with Ethyl Propiolate (5a). A mixture of **13** (1.30 g, 4.58 mM) and **5a** (1.10 g, 11.7 mM) was heated for 24 h at 80 °C. Then, excess ethyl propiolate was distilled out and the crude product was separated by column chromatography on silica gel using 10% ethyl acetate in hexanes as an eluent to obtain **11a** (1.28 g, 73%) and **11e** (0.22 g, 12%) as colorless liquids.

(1*R,4*S**)-5-Trifluoromethanesulfonyloxy-1,3,3-trimethyl-8-ethoxycarbonylbicyclo[2.2.2]octa-5,7-dien-2-one (11e):** IR (film) 1722, 1651, 1616, 1427, 1233, 1067 cm^{-1}; ^1H NMR (300 MHz) δ 7.00 (d, J = 2.1 Hz, 1H), 5.84 (d, J = 3.1 Hz, 1H), 4.27 (q, J = 7.1 Hz, 2H), 4.03 (apparent t, 1H), 1.57 (s, 3H), 1.32 (t, J = 7.1 Hz, 3H), 1.24 (s, 3H), 1.05 (s, 3H); ^{13}C NMR (100 MHz) δ 206.7, 163.0, 155.7, 144.2, 139.9, 118.2, 118.3 (q, CF_3), 61.2, 57.5, 51.8, 39.5, 26.2, 15.4, 14.0; MS (FAB) m/z (rel intensity) 383 ($M^+ + 1$, 61), 337 (49), 267 (32), 137 (21), 70 (100); HRMS (EI) calcd for $C_{15}H_{17}O_6F_3S$ (M^+) 382.0698, found 382.0683.

Diels−Alder Reaction of 13 with Dimethyl Acetylenedicarboxylate (5b). A mixture of **13** (3.27 g, 11.5 mM) and **5b** (3.40 g, 23.9 mM) was heated for 10 h at 80 °C. Purification by column chromatography on silica gel using 15% ethyl acetate in hexanes as an eluent furnished **11b** (4.61 g, 94%) as a colorless solid.

Diels−Alder Reaction of 13 with Phenylacetylene (5c). A mixture of **13** (203 mg, 0.7 mM) and **5c** (163 mg, 1.6 mM) was heated for 5 h at 120 °C. Purification by column chromatography on silica gel using 4% ethyl acetate in hexanes as an eluent afforded **11c** (247 mg, 90%) as a colorless solid.

Diels−Alder Reaction of 13 with Diphenylacetylene (5d). A mixture of **13** (3.25 g, 11.4 mM) and **5d** (6.33 g, 35.5 mM) was heated for 48 h at 120 °C. Purification by column chromatography on silica gel using 5% ethyl acetate in hexanes as an eluent afforded **11d** (4.75 g, 90%) as a colorless solid.

(1*R,4*R**)-5-Trifluoromethanesulfonyloxy-1,3,3-trimethylbicyclo[2.2.2]octa-5,7-dien-2-one (11f).** A mixture of **13** (2.0 g, 7.04 mM) and phenyl vinyl sulfoxide (3.25 g, 21.3 mmol) was heated at 125 °C for 60 h. Column chromatography of the reaction mixture on silica gel using 5% ethyl acetate in hexanes as an eluent afforded a yellow oil (1.45 g, 67%): IR (film) 3077, 1728, 1651, 1425, 1215, 1066 cm^{-1}; ^1H NMR (300 MHz) δ 6.62 (dd, J = 7.0, 6.1 Hz, 1H), 6.10 (dd, J = 7.0, 1.7 Hz, 1H), 5.84 (d, J = 3.1 Hz, 1H), 3.48 (ddd, J = 6.1, 3.1, 1.7 Hz, 1H), 1.51 (s, 3H), 1.19 (s, 3H), 1.11 (s, 3H); ^{13}C NMR (75 MHz) δ 207.7, 155.5, 135.5, 135.4, 118.5, 118.4 (q, CF_3), 56.6, 52.4, 40.5, 27.5, 26.3, 15.5; MS (FAB) m/z (rel intensity) 311 ($M^+ + 1$, 59), 267 (11), 177 (9), 149 (26), 70 (100); HRMS (EI) calcd for $C_{12}H_{14}O_4F_3S$ ($M^+ + 1$) 311.0565, found 311.0577.

(1*S,4*R**)-1,3,3-Trimethyl-6-ethoxycarbonylbicyclo[2.2.2]-octa-5,7-dien-2-one (2a).** A mixture of **11a** (1.25 g, 3.3 mM), tri-*n*-butylamine (1.82 g, 9.8 mM), formic acid (300 mg, 6.5 mM), and $Pd(PPh_3)_2Cl_2$ (69 mg, 0.098 mM) in DMF (2 mL) was stirred at 60−80 °C for 1 h. The mixture was cooled, and water was added. The reaction mixture was extracted with ether, and the combined organic layer was dried (Na_2SO_4) and concentrated. The residue was purified by column chromatography on silica gel using 15% ethyl acetate in hexanes as an eluent to give a colorless oil (632 mg, 83%): IR (film) 1720, 1586, 1455, 1236, 1063 cm^{-1}; ^1H NMR (300 MHz) δ 7.41 (d, J = 6.5 Hz, 1H), 6.51 (dd, J = 7.0, 6.1 Hz, 1H), 6.05 (dd, J = 7.0, 1.9 Hz, 1H), 4.18 (q, J = 7.1 Hz, 2H), 3.62 (ddd, J = 6.5, 6.1, 1.9 Hz, 1H), 1.70 (s, 3H), 1.29 (t, J = 7.1 Hz, 3H), 1.12 (s, 3H), 1.07 (s, 3H); ^{13}C NMR (75 MHz, CD_3OD) δ 210.8, 165.9, 148.9, 137.5, 136.9, 136.0, 61.5, 59.4, 50.2, 41.5, 28.9, 28.6, 15.1, 14.5; MS (FAB) m/z (rel intensity) 235 ($M^+ + 1$, 100), 189 (78), 161 (27), 119 (43), 70 (84); HRMS (EI) calcd for $C_{14}H_{18}O_3$ (M^+) 234.1256, found 234.1260.

(1*S,4*R**)-1,3,3-Trimethyl-5,6-bis(methoxycarbonyl)-bicyclo[2.2.2]octa-5,7-dien-2-one (2b).** Following the procedure described for the preparation of **2a**, a mixture of **11b** (600 mg, 1.04 mM), tri-*n*-butylamine (780 mg, 4.2 mM), formic acid (130 mg, 2.8 mM), and $Pd(PPh_3)_2Cl_2$ (30 mg, 0.043 mM) in DMF (2 mL) was used, and the residue was purified by column chromatography on silica gel using 25% ethyl acetate in hexanes as an eluent to afford a colorless oil (314 mg, 81%): IR (film) 1726, 1642, 1440, 1265, 1055 cm^{-1}; ^1H NMR (300 MHz) δ 6.65 (dd, J = 6.9, 6.2 Hz, 1H), 6.05 (dd, J = 6.9, 1.8 Hz, 1H), 4.13 (dd, J = 6.2, 1.8 Hz, 1H), 3.82 (s, 3H), 3.78 (s, 3H), 1.48 (s, 3H), 1.14 (s, 3H), 1.07 (s, 3H); ^{13}C NMR (75 MHz) δ 207.0, 166.3, 163.5, 145.8, 137.3, 136.7, 133.2, 59.2, 52.4, 52.2, 48.7, 39.7, 28.3, 26.8, 12.6; MS (FAB) m/z (rel intensity) 279 ($M^+ + 1$, 10), 186 (40), 177 (100), 70 (21); HRMS (EI) calcd for $C_{15}H_{18}O_5$ (M^+) 278.1155; found 278.1140.

(1*S,4*R**)-1,3,3-trimethyl-6-phenylbicyclo[2.2.2]octa-5,7-dien-2-one (2c).** Following the procedure described for the preparation of **2a**, a mixture of **11c** (121 mg, 0.31 mM), tri-*n*-butylamine (175 mg, 0.94 mM), formic acid (30 mg, 0.65 mM), and $Pd(PPh_3)_2Cl_2$ (5 mg, 0.007 mM) in DMF (0.7 mL) was used, and the residue was purified by column chromatography on silica gel using 4% ethyl acetate in hexanes as an eluent to afford a colorless oil (64 mg, 87%): IR (film) 3053, 1714, 1602, 1490, 1446, 1380, 1018 cm^{-1}; ^1H NMR (300 MHz) δ 7.30−7.26 (m, 3H), 7.05−7.02 (m, 2H), 6.63 (dd, J = 6.9, 6.3 Hz, 1H), 6.40 (d, J = 6.2 Hz, 1H), 6.10 (dd, J = 6.9, 1.9 Hz, 1H), 3.56 (dt, J = 8.2, 2.5 Hz, 1H), 1.33 (s, 3H), 1.19 (s, 3H), 1.13 (s, 3H); ^{13}C NMR (75 MHz) δ 210.5, 145.3, 137.7, 137.2, 134.8, 134.7, 128.3, 127.8, 127.0, 60.1, 49.0, 41.5, 28.8, 28.6, 14.9; MS (FAB) m/*z* (rel intensity) 239 (M^+ + 1, 100), 195 (21), 168 (59), 165 (17); HRMS (EI) calcd for $C_{17}H_{18}O$ (M^+) 238.1358, found 238.1367.

(1*S,4*R**)-1,3,3-Trimethyl-5,6-diphenylbicyclo[2.2.2]octa-5,7-dien-2-one (2d).** Following the procedure described for the preparation of **2a**, a mixture of **11d** (2.45 g, 5.3 mM), tri-*n*-butylamine (2.95 g, 15.9 mM), formic acid (490 mg, 10.65 mM), and $Pd(PPh_3)_2Cl_2$ (112 mg, 0.16 mM) in DMF (5 mL) was used, and the residue was purified by column chromatography on silica gel using 5% ethyl acetate in hexanes as an eluent to afford a white solid (1.65 mg, 99%): mp 111−112 °C (from EtOAc−hexanes); IR (film) 3053, 1713, 1599, 1447, 1379, 1019 cm^{-1}; ^1H NMR (300 MHz) δ 7.26−7.10 (m, 3H), 7.10−7.04 (m, 5H), 6.89−6.86 (m, 2H), 6.78 (dd, J = 7.0, 6.3 Hz, 1H), 6.19 (dd, J = 7.0, 1.9 Hz, 1H), 3.92 (dd, J = 6.3, 1.9 Hz, 1H), 1.29 (s, 3H), 1.24 (s, 3H), 1.18 (s, 3H); ^{13}C NMR (75 MHz) δ 210.4, 144.4, 139.0, 137.1, 136.9, 135.5, 129.5, 128.0, 127.8, 127.7, 126.8, 126.6, 60.7, 55.0, 41.6, 28.5, 27.6, 15.3; MS (FAB) *m*/*z* (rel intensity) 315 (M^+ + 1, 53), 244 (100), 154 (54), 136 (37); HRMS (EI) calcd for $C_{23}H_{22}O$ (M^+) 314.1671, found 314.1669. Anal. Calcd for $C_{23}H_{22}O$: C, 87.86; H, 7.05. Found: C, 87.97; H, 7.07.

(1*S,4*R**)-1,3,3-Trimethyl-5-ethoxycarbonylbicyclo[2.2.2]-octa-5,7-dien-2-one (2e).** Following the procedure described for the preparation of **2a**, a mixture of **11e** (206 mg, 0.54 mM), tri-*n*-butylamine (313 mg, 1.69 mM), formic acid (52 mg, 1.13 mM), and $Pd(PPh_3)_2Cl_2$ (12 mg, 0.017 mM) in DMF (0.7 mL) was used, and the residue was purified by column chromatography on silica gel using 10% ethyl acetate in hexanes as an eluent to afford a colorless oil (103 mg, 81%): IR (film) 1714, 1632, 1588, 1456 cm^{-1}; ^1H NMR (300 MHz) δ 6.97 (d, J = 2.4 Hz, 1H), 6.61 (dd, J = 6.8, 6.4 Hz, 1H), 6.01 (dd, J = 6.8, 2.0 Hz, 1H), 4.23 (dq, J = 9.5, 3.6 Hz, 2H), 4.09 (ddd, J = 6.4, 2.4, 2.0 Hz, 1H), 1.55 (s, 3H), 1.31 (t, J = 7.1 Hz, 3H), 1.12 (s, 3H), 1.01 (s, 3H); ^{13}C NMR (100 MHz) δ 209.2, 164.3, 143.5, 140.5, 137.3, 133.2, 60.8, 59.2, 48.7, 40.1, 28.3, 27.0, 15.2, 14.2; MS (FAB) *m*/*z* (rel intensity) 235 (M^+ + 1, 100), 205 (17), 189 (78), 119 (43); HRMS (EI) calcd for $C_{14}H_{18}O_3$ (M^+) 234.1256, found 234.1262.

1,3,3-Trimethylbicyclo[2.2.2]octa-5,7-dien-2-one (2f). Following the procedure described for the preparation of **2a**, a mixture of **11f** (255 mg, 0.82 mM), tri-*n*-butylamine (456 mg, 2.46 mM), formic acid (75 mg, 1.64 mM), and $Pd(PPh_3)_2Cl_2$ (17 mg, 0.024 mM) in DMF (1.0 mL) was used, and the residue was purified by column chromatography on silica gel using 5% ethyl acetate in hexanes as an eluent to afford a colorless oil (49 mg, 36%): IR (film) 3055, 1717, 1458, cm^{-1}; ^1H NMR (300 MHz) δ 6.63 (dd, J = 6.9, 6.1 Hz, 1H), 6.03 (dd, J = 6.9, 1.9 Hz, 2H), 3.53 (tt, J = 6.7, 1.9 Hz, 1H), 1.49 (s, 3H), 1.07 (s, 6H); ^{13}C NMR (75 MHz) δ 210.3, 136.8, 133.9, 58.0, 49.7, 41.1, 28.5, 15.4; GC-MS (70 eV) *m*/*z* (rel intensity) 163 (M^+ + 1, 1), 162 (M^+, 5), 119 (10), 91 (16), 70 (100); HRMS (EI) calcd for $C_{11}H_{14}O$ (M^+) 162.1045, found 162.1031.

(1*S,4*R**,7*S**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-acetylbicyclo[2.2.2]oct-5-en-2-one (15a).** A mixture of **13** (100 mg, 0.35 mM) and methyl vinyl ketone (**14a,** 123 mg, 1.76 mM) was heated at 110 °C for 4 h under nitrogen. The excess **14a** was removed under reduced pressure followed by column chromatography on silica gel using a 1:7 mixture of ethyl acetate and hexanes as an eluent to furnish **15a** (70 mg, 89%) as a yellowish liquid: IR (neat) 2885, 1720, 1651, 1420, 1215 cm^{-1}; ^1H NMR (400 MHz) δ 5.67 (d, J = 2.8 Hz, 1H), 2.76−2.72 (m, 2H), 2.45 (ddd, J = 13.2, 7, 2.6 Hz, 1H), 2.09 (s, 3H), 1.88 (ddd, J = 13.2, 10.0, 3.1 Hz, 1H), 1.27 (s, 3H), 1.14 (s, 3H), 1.13 (s, 3H); ^{13}C NMR (100 MHz) δ 211.7, 205.9, 152.4, 118.4 (q, CF_3), 116.6, 52.0, 51.1, 47.5, 43.3, 30.4, 28.3, 25.9, 23.8, 15.7; MS (EI, 70 eV) *m*/*z* (rel intensity) 354 (M^+, 6), 241 (79), 240 (55), 221 (89), 125 (100), 107 (23), 91 (44), 69 (40), 43 (94); HRMS (EI) calcd for $C_{14}H_{17}F_3O_5S$ (M^+) 354.0749, found 354.0748.

(1*S,4*S**,7*S**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-methoxycarbonylbicyclo[2.2.2]oct-5-en-2-one (15b).** Compound **15b** (69 mg, 85%) was obtained as a yellowish oil when **13** (63 mg, 0.22 mM) was heated with methyl acrylate (**14b**, 380 mg, 4.41 mM) at 110 °C for 2 h under nitrogen followed by column chromatography (silica gel, EtOAc/hexanes 1:10): IR (neat) 2982, 1731, 1654, 1422, 1212, 1139 cm^{-1}; ^1H NMR (400 MHz) δ 5.58 (d, J = 2.8 Hz, 1H), 3.66 (s, 3H), 2.72 (ddd, J = 3.1, 2.8, 2.7 Hz, 1H), 2.61 (dd, J = 9.8, 6.7 Hz, 1H), 2.43 (ddd, J = 13.4, 9.8, 3.1 Hz, 1H), 2.05 (ddd, J = 13.4, 6.7, 2.7 Hz, 1H), 1.25 (s, 3H), 1.14 (s, 3H), 1.11 (s, 3H); ^{13}C NMR (100 MHz) δ 211.4, 172.7, 153.2, 118.5 (q, CF_3), 115.6, 52.1, 52.0, 47.5, 44.5, 43.3, 28.9, 26.1, 23.8, 15.9; MS (EI) *m*/*z* (rel intensity) 370 (M^+, 1), 241 (43), 237 (92), 209 (72), 167 (100), 141 (93), 135 (24), 123 (26), 107 (24), 91 (40), 69 (73), 69 (27), 41 (23); HRMS (EI) calcd for $C_{14}H_{17}F_3O_6S$ (M^+) 370.0698, found 370.0698.

(1*S,4*R**,7*S**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-phenylsulfonylbicyclo[2.2.2]oct-5-en-2-one (15c).** Compound **15c** (145 mg, 92%) was obtained as a white solid when **13** (100 mg, 0.35 mM) was heated with phenyl vinyl sulfone (**14c**, 300 mg, 1.78 mM) at 110 °C for 2 h under nitrogen followed by column chromatography (silica gel, EtOAc/hexanes 1:7): mp 151−152 °C; IR (neat) 2978, 1731, 1656, 1422, 1217 cm^{-1}; ^1H NMR (400 MHz) δ 7.84 (d, J = 6.0 Hz, 2H), 7.66−7.24 (m, 3H), 5.67 (d, J = 2.8 Hz, 1H), 3.31 (dd, J = 9.2, 8.0 Hz, 1H), 2.66 (ddd, J = 3.0, 3.0, 2.8 Hz, 1H), 2.16−2.04 (m, 2H), 1.60 (s, 3H), 1.14 (s, 3H), 1.04 (s, 3H); ^{13}C NMR (100 MHz) δ 209.5, 152.6, 139.0, 134.0, 129.4, 128.4, 118.8 (q, CF_3), 116.0, 62.3, 52.2, 46.4, 42.9, 28.3, 26.0, 23.7, 16.7; MS (EI) *m*/*z* (rel intensity) 452 (M^+, 1), 319 (51), 311 (89), 241 (98), 177 (55), 148 (62), 143 (93), 125 (86), 107 (76), 91 (100), 43 (100); HRMS (EI) calcd for $C_{18}H_{19}F_3O_6S_2$ (M^+) 452.0575, found 452.0572. Anal. Calcd for $C_{18}H_{19}F_3O_6S_2$: C, 47.78; H, 4.23. Found: C, 47.90; H, 4.26.

(1*S,4*R**,7*S**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-nitrobicyclo[2.2.2]oct-5-en-2-one (15d).** Compound **15d** (333 mg, 88%) was obtained as a white solid along with yellowish liquid **16d** (13 mg, 3%) when **13** (300 mg, 1.06 mM) was heated with nitroethylene (**14d**, 573 mg, 7.80 mM) at 110 °C for 1 h under nitrogen followed by column chromatography (silica gel, EtOAc/hexanes 1:10): mp 86−87 °C; IR (neat) 2923, 2853, 1732, 1651, 1557, 1422, 1362, 1211 cm^{-1}; ^1H NMR (400 MHz) δ 5.58 (d, J = 2.6 Hz, 1H), 4.66 (dd, J = 9.3, 5.8 Hz, 1H), 2.85 (ddd, J = 2.9, 2.9, 2.6 Hz, 1H), 2.78 (ddd, J = 14.5, 9.3, 2.9 Hz, 1H), 2.47 (ddd, J = 14.5, 5.8, 2.9 Hz, 1H), 1.34 (s, 3H), 1.21 (s, 3H), 1.10 (s, 3H); ^{13}C NMR (100 MHz) δ 208.1, 153.5, 118.6 (q, CF_3), 113.7, 84.9, 54.6, 46.7, 43.2, 30.8, 26.2, 23.4, 14.8; MS (FAB) *m*/*z* (rel intensity) 358 (M^+ + 1, 13), 311 (100), 241 (79), 154 (49), 107 (33), 91 (65), 43(66), 41 (36); HRMS (EI) calcd for $C_{12}H_{14}F_3NO_6S$ (M^+) 357.0494, found 357.0570. Anal. Calcd for $C_{12}H_{14}F_3NO_6S$: C, 40.34; H, 3.95; N, 3.92. Found: C, 40.41; H, 3.96; N, 4.10.

(1*S,4*R**,7*R**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-nitrobicyclo[2.2.2]oct-5-en-2-one (16d):** IR (neat) 2924, 2856, 1732, 1650, 1555, 1422, 1366, 1248, 1209 cm^{-1}; ^1H NMR (400 MHz) δ 5.58 (d, J = 3.3 Hz, 1H), 4.71 (dd, J = 10.7, 4.6 Hz, 1H), 2.74 (ddd, J = 3.3, 3.2, 2.7 Hz, 1H), 2.63 (ddd, J = 14.5, 10.7, 3.2 Hz, 1H), 2.48 (ddd, J = 14.5, 4.6, 2.7 Hz, 1H), 1.35 (s, 3H), 1.30 (s, 3H), 1.24 (s, 3H); ^{13}C NMR (100

MHz) δ 208.4, 155.8, 118.5 (q, *C*F$_3$), 115.4, 89.3, 53.0, 47.3, 44.8, 28.2, 27.2, 22.4, 15.0; MS (FAB) *m/z* (rel intensity) 358 (M$^+$ + 1, 48) 357 (M$^+$, 2), 327 (49), 311 (72), 241 (77), 178 (52), 107 (43), 91(94), 43 (100), 41 (48); HRMS (EI) calcd for $C_{12}H_{14}F_3NO_6S$ (M$^+$) 357.0494, Found: 357.0567.

(1*S,4*R**,7*S**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-cyanobicyclo[2.2.2]oct-5-en-2-one (15e).** Compound **15e** (239 mg, 67%) was obtained as a yellowish oil along with a white solid **16e** (110 mg, 31%) when **13** (300 mg, 1.06 mM) was heated with acrylonitrile (**14e**, 900 mg, 16.05 mM) at 110 °C for 6 h under nitrogen followed by column chromatography (silica gel, EtOAc/hexanes 1:7): IR (neat) 2923, 2360, 1733, 1653, 1217 cm^{-1}; ^{1}H NMR (400 MHz) δ 5.70 (d, *J* = 2.8 Hz, 1H), 2.77−2.73 (m, 2H), 2.58 (ddd, *J* = 13.6, 10.2, 2.8 Hz, 1H), 2.16 (ddd, *J* = 13.6, 5.1, 3.1 Hz, 1H), 1.46 (s, 3H), 1.16 (s, 3H), 1.08 (s, 3H); ^{13}C NMR (100 MHz) δ 210.0, 154.9, 118.9, 118.5 (q, *C*F$_3$), 115.5, 51.3, 47.0, 43.6, 32.2, 28.8, 26.2, 23.4, 16.5; MS (EI) *m/z* (rel intensity) 337 (M$^+$, 0.3), 204 (34), 176 (35), 108 (49), 107 (21), 70 (100), 69(75), 41 (49); HRMS (EI) calcd for $C_{13}H_{14}F_3NO_4S$ (M$^+$) 337.0596, found 337.0596. **(1*S**,4*R**,7*R**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-cyanobicyclo[2.2.2]oct-5-en-2-one (16e):** mp 83−84 °C (from ethyl acetate−hexanes); IR (neat) 2982, 2360, 1731, 1652, 1426, 1216 cm^{-1}; ^{1}H NMR (400 MHz) δ 5.63 (d, *J* = 2.8 Hz, 1H), 2.80 (dd, *J* = 11.2, 4.8 Hz, 1H), 2.73 (ddd, *J* = 5.6, 2.8, 2.8 Hz, 1H), 2.45−2.32 (m, 2H), 1.44 (s, 3H), 1.24 (s, 3H), 1.20 (s, 3H); ^{13}C NMR (100 MHz) δ 209.2, 155.2, 118.8, 118.4 (q, *C*F$_3$), 116.4, 51.7, 47.5, 44.1, 32.7, 27.7, 26.5, 23.1, 16.7; MS (EI) *m/z* (rel intensity) 337 (M$^+$, 9), 176 (29), 108 (40), 107 (24), 70 (91), 69(100), 49 (23), 41 (43), 39 (23); HRMS (EI) calcd for $C_{13}H_{14}F_3NO_4S$ (M$^+$) 337.0596, found 337.0599.

(1*S,4*R**,7*R**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-phenylbicyclo[2.2.2] oct-5-en-2-one (15f).** Compound **15f** (171 mg, 80%) was obtained as a white solid when **13** (150 mg, 0.53 mM) was heated with styrene (**14f**, 550 mg, 5.28 mM) at 110 °C for 4 h under nitrogen followed by column chromatography (silica gel, EtOAc/hexanes 1:5): mp 100−101 °C; IR (neat) 2929, 1726, 1650, 1422, 1215 cm^{-1}; ^{1}H NMR (400 MHz) δ 7.27−7.24 (m, 3H), 7.13 (d, *J* = 5.0 Hz, 2H), 5.55 (d, *J* = 3.0 Hz, 1H), 2.79 (dd, *J* = 9.5, 7.0 Hz, 1H), 2.74 (ddd, *J* = 3.4, 3.0, 2.7 Hz, 1H), 2.68 (ddd, *J* = 13.7, 9.5, 3.4 Hz, 1H), 2.10 (ddd, *J* = 13.7, 7.0, 2.7 Hz, 1H), 1.22 (s, 3H), 1.19 (s, 3H), 0.88 (s, 3H); ^{13}C NMR (100 MHz) δ 213.1, 154.1, 141.4, 128.5, 128.4, 127.2, 118.5 (q, *C*F$_3$), 116.0, 54.7, 48.0, 45.5, 43.0, 33.5, 26.2, 24.2, 16.5; MS (EI) *m/z* (rel intensity) 388 (M$^+$, 15), 317 (26), 255 (46), 185 (85), 105 (45), 104 (45), 69 (20), 28 (32); HRMS (EI) calcd for $C_{18}H_{19}F_3O_4S$ (M$^+$) 388.0956, found 388.0954. Anal. Calcd for $C_{18}H_{19}F_3O_4S$: C, 55.66; H, 4.93. Found: C, 55.70; H, 4.98.

(1*R,4*R**,7*R**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-ethenylbicyclo[2.2.2]oct-5-en-2-one (15g).** Compound **15g** (239 mg, 72%) was obtained as a yellowish oil along with compound **16g** (110 mg, 18%) when **13** (300 mg, 1.06 mM) was heated with 3-sulfolene (**14g**, 600 mg, 5.71 mM) at 160 °C for 2 h under nitrogen followed by column chromatography (silica gel, EtOAc/hexanes 1:50): IR (neat) 2978, 1727, 1650, 1425, 1215 cm^{-1}; ^{1}H NMR (400 MHz) δ 5.50 (d, *J* = 2.8 Hz, 1H), 5.40 (ddd, *J* = 16.8, 9.9, 9.6 Hz, 1H), 5.03 (dd, *J* = 9.9, 1.5 Hz, 1H), 4.98 (ddd, *J* = 16.8, 1.5, 0.6 Hz, 1H), 2.61 (ddd, *J* = 3.0, 2.8, 2.8 Hz, 1H), 2.38 (ddd, *J* = 13.6, 9.4, 3.0 Hz, 1H), 2.24 (ddd, *J* = 9.6, 9.4, 5.7 Hz, 1H), 1.61 (ddd, *J* = 13.6, 5.7, 2.8 Hz, 1H), 1.15 (s, 3H), 1.13 (s, 3H), 1.12 (s, 3H); ^{13}C NMR (100 MHz) δ 213.6, 153.8, 138.1, 118.6 (q, *C*F$_3$), 116.8, 116.1, 53.1, 47.6, 45.2, 43.5, 30.3, 26.1, 23.7, 16.4; MS (EI) *m/z* (rel intensity) 338 (M$^+$, 53), 268 (79), 205 (78), 150 (100), 135 (34), 107 (40), 69(42), 41 (82); HRMS (EI) calcd for $C_{14}H_{17}F_3O_4S$ (M$^+$) 338.0800, found 338.0798. **(1*R**,4*R**,7*S**)-1,3,3-Trimethyl-5-trifluoromethanesulfonyloxy-7-ethenylbicyclo[2.2.2]-oct-5-en-2-one (16g):** IR (neat) 2977, 1724, 1655, 1424, 1214, 1069 cm^{-1}; ^{1}H NMR (400 MHz) δ 5.67 (d, *J* = 2.8 Hz, 1H), 5.31 (ddd, *J* = 16.3, 10.4, 10.3 Hz, 1H), 5.06 (ddd, *J* = 10.3, 1.6, 0.4 Hz, 1H), 5.02 (ddd, *J* = 16.3, 1.6, 0.4 Hz, 1H), 2.59 (ddd, *J* = 3.0, 2.8, 2.7 Hz, 1H), 2.38 (ddd, *J* = 11.0, 10.4, 4.5 Hz, 1H), 2.21 (ddd, *J* = 13.9, 11.0, 3.0 Hz, 1H), 1.82 (ddd, *J* = 13.9, 4.5, 2.7 Hz, 1H), 1.15 (s, 3H), 1.13 (s, 3H), 1.12 (s, 3H); ^{13}C NMR (100 MHz) δ 214.1, 154.2, 137.1, 119.0, 118.6 (q, *C*F$_3$), 118.2, 53.3, 48.4, 48.0, 44.8, 29.1, 26.6, 22.3, 16.7; MS (EI) *m/z* (rel intensity) 338 (M$^+$, 15), 268 (41), 205 (86), 156 (100), 135 (49), 107 (69), 69(45), 41 (30); HRMS (EI) calcd for $C_{14}H_{17}F_3O_4S$ (M$^+$) 338.0800, found 338.0797.

(1*S,4*R**,7*S**)-1,3,3,7-Tetramethyl-5-trifluoromethanesulfonyloxy-7-methoxycarbonylbicyclo[2.2.2]oct-5-en-2-one (15h).** Compound **15h** (157 mg, 77%) was obtained as a yellowish oil when **13** (150 mg, 0.53 mM) was heated with methyl methacrylate (**14h**, 530 mg, 5.29 mM) at 110 °C for 9 h under nitrogen followed by column chromatography (silica gel, EtOAc/hexanes 1:13): IR (neat) 2983, 1737, 1659, 1423, 1216 cm^{-1}; ^{1}H NMR (400 MHz) δ 5.64 (d, *J* = 2.8 Hz, 1H), 3.61 (s, 3H), 2.59 (ddd, *J* = 3.3, 2.8, 2.7 Hz, 1H), 2.48 (dd, *J* = 14.1, 3.3 Hz, 1H), 1.97 (dd, *J* = 14.1, 2.7 Hz, 1H), 1.21 (s, 3H), 1.13 (s, 3H), 1.08 (s, 6H); ^{13}C NMR (100 MHz) δ 213.1, 174.6, 152.5, 119.0, 118.4 (q, *C*F$_3$), 56.3, 52.1, 49.3, 47.4, 44.2, 36.1, 27.3, 22.9, 22.0, 14.1; MS (EI) *m/z* (rel intensity) 384 (M$^+$, 4), 255 (91), 251 (95), 223 (88), 181 (98), 155 (99), 151 (84), 149 (94), 105 (100), 85 (100), 83 (100), 69 (89), 51 (100), 49 (100); HRMS (EI) calcd for $C_{15}H_{19}F_3O_6S$ (M$^+$) 384.08545, found 384.08549.

(1*S,2*S**,6*R**,7*R**)-1,11,11-Trimethyl-10-oxotricyclo-[5.2.2.0^{2,6}]undeca-3,8-dien-8-yltrifluoromethanesulfonate (15i).** Compound **15i** (275 mg, 75%) was obtained as a yellowish liquid when **13** (297 mg, 1.04 mM) was heated with a dimer of cyclopentadiene (1.295 g, 19.60 mM) at 160 °C for 1 h under nitrogen followed by column chromatography (silica gel, EtOAc/hexanes 1:20): IR (neat) 2975, 2935, 1725, 1650, 1453, 1423, 1248, 1214 cm^{-1}; ^{1}H NMR (400 MHz) δ 5.78 (dddd, *J* = 8.2, 4.4, 2.0, 2.0 Hz, 1H), 5.54−5.51 (m, 1H), 5.38 (d, *J* = 3.2 Hz, 1H), 3.10−3.03 (m, 1H), 2.77−2.75 (m, 1H), 2.65 (t, *J* = 3.2 Hz, 1H), 2.63−2.60 (m, 1H), 2.13−2.05 (m, 1H), 1.26 (s, 3H), 1.14 (s, 3H), 1.12 (s, 3H); ^{13}C NMR (100 MHz) δ 214.1, 152.3, 134.4, 127.9, 118.3 (q, *C*F$_3$), 113.7, 53.8, 53.7, 52.4, 43.8, 38.3, 37.3, 26.1, 23.6, 16.0; MS (EI) *m/z* (rel intensity) 350 (M$^+$, 22), 286 (11), 285 (96), 280 (33), 151 (19), 147 (36), 66 (100), 28 (26), 18 (49); HRMS (EI) calcd for $C_{15}H_{17}F_3O_4S$ (M$^+$) 350.0800, found 350.0802.

(1*S,2*S**,6*S**,7*R**)-1,11,11-Trimethyl-3,5,10-trioxo-4-phenyl-4-azatricyclo[5.2.2.0^{2,6}]undec-8-en-8-yltrifluoromethanesulfonate (15j).** Compound **15j** (545 mg, 89%) was obtained as a white solid when **13** (300 mg, 1.06 mM) was heated with *N*-phenylmaleimide (**14j**, 365 mg, 2.11 mM) at 110 °C for 1 h under nitrogen followed by column chromatography (silica gel, EtOAc/hexanes 1:5): mp 127−128 °C; IR (neat) 2979, 1785, 1716, 1642, 1424, 1216 cm^{-1}; ^{1}H NMR (400 MHz) δ 7.44−7.36 (m, 3H), 7.18 (d, *J* = 5.0 Hz, 2H), 5.63 (d, *J* = 3.1 Hz, 1H), 3.56 (dd, *J* = 8.3, 3.4 Hz, 1H), 3.25 (dd, *J* = 3.4, 3.1 Hz, 1H), 2.84 (d, *J* = 8.3 Hz, 1H), 1.56 (s, 3H), 1.20 (s, 3H), 1.14 (s, 3H); ^{13}C NMR (100 MHz) δ 209.9, 174.9, 173.3, 150.9, 131.4, 129.1, 128.9, 126.3, 118.1 (q, *C*F$_3$), 113.6, 51.8, 48.2, 44.7, 42.7, 42.6, 25.7, 23.2, 15.5; MS (EI) *m/z* (rel intensity) 457 (M$^+$, 10), 324 (78), 297 (13), 296 (64), 240 (15), 149 (25), 119 (38), 91 (11), 69 (100), 28 (11); HRMS (EI) Calcd for $C_{20}H_{18}F_3NO_6S$ (M$^+$) 457.0807, found 457.0807. Anal. Calcd for $C_{20}H_{18}F_3NO_6S$: C, 52.51; H, 3.97; N, 3.06. Found: C, 52.44; H, 3.96; N, 3.12.

(1*S,4*S**,7*S**)-1,3,3-Trimethyl-7-acetylbicyclo[2.2.2]oct-5-en-2-one (1a).** A mixture of **15a** (160 mg, 0.45 mM), tri-*n*-butylamine (250 mg, 1.35 mM), formic acid (42 mg, 0.91 mM), and Pd(PPh$_3$)$_2$Cl$_2$ (10 mg, 0.014 mM) in DMF (1 mL) was stirred at 60−80 °C for 1 h. The mixture was cooled, and water was added. The reaction mixture was extracted with ethyl acetate (3 × 15 mL), and the combined organic layer was dried (MgSO$_4$) and concentrated. The residue was purified by column chromatography on silica gel using 10% ethyl acetate in hexanes as an eluent to give a yellowish oil **1a** (84 mg, 90%); IR (neat) 2957, 1712, 1449, 1364 cm^{-1}; ^{1}H NMR (400 MHz) δ 6.49 (dd, *J* = 8.1, 6.6 Hz, 1H), 5.72 (ddd, *J* = 8.1, 1.3, 1.3 Hz,

1H), 2.70 (dd, J = 9,6, 7.3 Hz, 1H), 2.61−2.57 (m, 1H), 2.28 (ddd, J = 13.0, 9.6, 3.4 Hz, 1H), 2.05 (s, 3H), 1.46 (ddd, J = 13.0, 7.3, 2.5 Hz, 1H), 1.16 (s, 3H), 1.06 (s, 3H), 1.00 (s, 3H); ^{13}C NMR (100 MHz) δ 214.5, 208.1, 137.5, 129.4, 50.9, 50.6, 43.5, 43.1, 30.6, 28.4, 27.6, 24.7, 15.5; MS (EI) *m/z* (rel intensity) 206 (M^+, 26), 136 (59), 135 (24), 121 (26), 93 (100), 92 (57), 43 (24), 18 (34); HRMS (EI) calcd for $C_{13}H_{18}O_2$ (M^+) 206.1307, found 206.1308.

(1*S,4*S**,7*S**)-1,3,3-Trimethyl-7-methoxycarbonylbicyclo[2.2.2]oct-5-en-2-one (1b).** Following the procedure described for the preparation of **1a**, a mixture of **15b** (100 mg, 0.27 mM), tri-*n*-butylamine (150 mg, 0.81 mM), formic acid (25 mg, 0.54 mM), and $Pd(PPh_3)_2Cl_2$ (10 mg, 0.014 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 5% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1b** (57 mg, 95%); IR (neat) 2973, 1722, 1207, 1172 cm^{-1}; ^{1}H NMR (400 MHz) δ 6.57 (dd, J = 8.0, 6.6 Hz, 1H), 5.71 (ddd, J = 8.0, 1.3, 1.3 Hz, 1H), 3.64 (s, 3H), 2.64−2.59 (m, 2H), 2.32 (ddd, J = 13.0, 9.7, 3.1 Hz, 1H), 1.66 (ddd, J = 13.0, 7, 2.6 Hz, 1H), 1.20 (s, 3H), 1.08 (s, 3H), 1.05 (s, 3H); ^{13}C NMR (100 MHz) δ 214.5, 174.1, 138.1, 129.0, 51.7, 51.0, 43.6, 43.5, 43.1, 28.8, 27.8, 24.6, 15.6; MS (EI) *m/z* (rel intensity) 222 (M^+, 12), 152 (74), 93 (100), 92 (30), 28 (44), 18 (99); HRMS (EI) calcd for $C_{13}H_{18}O_3$ (M^+) 222.1256, found 222.1257.

(1*S,4*S**,7*S**)-1,3,3-Trimethyl-7-phenylsulfonylbicyclo-[2.2.2]oct-5-en-2-one (1c).** Following the procedure described for the preparation of **1a**, a mixture of **15c** (101 mg, 0.22 mM), tri-*n*-butylamine (135 mg, 0.72 mM), formic acid (30 mg, 0.65 mM), and $Pd(PPh_3)_2Cl_2$ (10 mg, 0.014 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 25% ethyl acetate in hexanes as an eluent to obtain a white solid **1c** (64 mg, 98%): mp 169−170 °C; IR (neat) 2941, 1720, 1308, 1147 cm^{-1}; ^{1}H NMR (400 MHz) δ 7.83 (J = 5.8 Hz, 2H), 7.62−7.51 (m, 3H), 6.50 (dd, J = 8.0, 6.8 Hz, 1H), 5.77 (ddd, J = 8.0, 1.2, 0.9 Hz, 1H), 3.35 (ddd, J = 9.5, 7.6, 0.9 Hz, 1H), 2.58−2.54 (m, 1H), 2.05 (ddd, J = 13.8, 9.5, 3.5 Hz, 1H), 1.78 (ddd, J = 13.8, 7.6, 2.7 Hz, 1H), 1.50 (s, 3H), 1.04 (s, 3H), 1.02 (s, 3H); ^{13}C NMR (100 MHz) δ 212.4, 139.9, 137.4, 133.6, 129.2, 128.3, 62.2, 51.2, 42.8, 42.2, 28.3, 27.8, 24.6, 16.5; MS (EI) *m/z* (rel intensity) 304 (M^+, 10), 163 (96), 146 (67), 134 (85), 93 (100), 92 (79), 91 (46), 76(47), 43 (50); HRMS (EI) calcd for $C_{17}H_{20}O_3S$ (M^+) 304.1133, found 304.1131. Anal. Calcd for $C_{17}H_{20}O_3S$: C, 67.08; H, 6.62. Found: C, 67.12; H, 6.63.

(1*S,4*S**,7*S**)-1,3,3-Trimethyl-7-nitrobicyclo[2.2.2]oct-5-en-2-one (1d).** Following the procedure described for the preparation of **1a**, a mixture of **15d** (74 mg, 0.21 mM), tri-*n*-butylamine (174 mg, 0.64 mM), formic acid (30 mg, 0.65 mM), and $Pd(PPh_3)_2Cl_2$ (10 mg, 0.014 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 10% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1d** (26 mg, 59%) along with compound **1d′** (15 mg, 34%): IR (neat) 2976, 2929, 1726, 1553, 1384, 1367, 1034 cm^{-1}; ^{1}H NMR (400 MHz) δ 6.62 (dd, J = 8.0, 6.6 Hz, 1H), 5.74 (dd, J = 8.0, 1.6 Hz, 1H), 4.57 (dd, J = 11.1, 4.8 Hz, 1H), 2.70−2.65 (m, 1H), 2.39 (ddd, J = 14.5, 4.8, 2.2 Hz, 1H), 2.28 (ddd, J = 14.5, 11.1, 3.4 Hz, 1H), 1.30 (s, 3H), 1.25 (s, 3H), 1.15 (s, 3H); ^{13}C NMR (100 MHz) δ 211.7, 140.9, 129.8, 90.1, 52.4, 44.8, 43.1, 29.1, 28.7, 23.1, 14.7; MS (FAB) *m/z* (rel intensity) 210 (M^+, 64), 137 (30), 130 (28), 128 (52), 93 (100), 91 (35), 55 (30), 43 (35), 41 (29); HRMS (EI) calcd for $C_{11}H_{15}NO_3$ (M^+) 209.1052, found 209.1038.

(1*S,4*S**,7*R**)-1,3,3-Trimethyl-7-nitrobicyclo[2.2.2]oct-5-en-2-one (1d′):** IR (neat) 2975, 2935, 1726, 1553, 1366, 1352, 1035 cm^{-1}; ^{1}H NMR (400 MHz) δ 6.70 (dd, J = 8.0, 7.4 Hz, 1H), 5.69 (d, J = 8.0, 1H), 4.70 (dd, J = 9.3, 5.8 Hz, 1H), 2.75−2.71 (m, 1H), 2.66 (ddd, J = 13.8, 9.3, 3.6 Hz, 1H), 2.07 (ddd, J = 13.8, 5.8, 2.6 Hz, 1H), 1.27 (s, 3H), 1.10 (s, 3H), 1.06 (s, 3H); ^{13}C NMR (100 MHz) δ 210.9, 138.4, 127.3, 85.3, 53.6, 43.1, 42.6, 30.8, 28.0, 24.3, 14.4; MS (FAB) *m/z* (rel intensity) 210 (M^+, 20), 154 (43), 137 (29), 136 (46), 130 (100), 128 (76), 91 (26), 77 (25); HRMS (EI) calcd for $C_{11}H_{15}NO_3$ (M^+) 209.1052, found 209.1034.

(1*S,4*S**,7*S**)-1,3,3-Trimethyl-7-cyanobicyclo[2.2.2]oct-5-en-2-one (1e).** Following the procedure described for the preparation of **1a**, a mixture of **15e** (135 mg, 0.40 mM), tri-*n*-butylamine (229 mg, 1.24 mM), formic acid (51 mg, 1.10 mM), and $Pd(PPh_3)_2Cl_2$ (15 mg, 0.02 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 10% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1e** (58 mg, 77%): IR (neat) 2975, 2238, 1726, 1384, 1034 cm^{-1}; ^{1}H NMR (400 MHz) δ 6.69 (dd, J = 8.0, 6.8 Hz, 1H), 5.85 (ddd, J = 8.0, 1.4, 0.6 Hz, 1H), 2.71 (dd, J = 10, 5.7 Hz, 1H), 2.70−2.60 (m, 1H), 2.51 (ddd, J = 14.3, 10.0, 3.1 Hz, 1H), 1.77 (ddd, J = 14.3, 5.7, 2.7 Hz, 1H), 1.41 (s, 3H), 1.07 (s, 3H), 1.06 (s, 3H); ^{13}C NMR (100 MHz) δ 213.0, 140.0, 129.5, 120.3, 50.1, 43.3, 42.8, 31.4, 29.0, 27.9, 24.1, 16.1; MS (EI) *m/z* (rel intensity) 189 (M^+, 10), 161 (60), 146 (74), 119 (72), 104 (51), 91 (78), 77 (57), 70(100), 41 (56), 39 (62); HRMS (EI) calcd for $C_{12}H_{15}NO$ (M^+) 189.1154, found 189.1152.

(1*S,4*S**,7*R**)-1,3,3-Trimethyl-7-cyanobicyclo[2.2.2]oct-5-en-2-one (1e′).** Following the procedure described for the preparation of **1a**, a mixture of **16e** (112 mg, 0.33 mM), tri-*n*-butylamine (183 mg, 0.99 mM), formic acid (46 mg, 0.98 mM), and $Pd(PPh_3)_2Cl_2$ (12 mg, 0.017 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 15% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1e′** (58 mg, 93%): IR (neat) 2975, 2236, 1721, 1614, 1461, 1384 cm^{-1}; ^{1}H NMR (400 MHz) δ 6.60 (dd, J = 8.0, 6.6 Hz, 1H), 5.78 (dd, J = 8.0, 1.6 Hz, 1H), 2.67−2.63 (m, 1H), 2.60 (dd, J = 12.0, 4.2 Hz, 1H), 2.35 (ddd, J = 13.6, 4.2, 3.1 Hz, 1H), 1.98 (ddd, J = 13.6, 12, 2.8 Hz, 1H), 1.38 (s, 3H), 1.22 (s, 3H), 1.10 (s, 3H); ^{13}C NMR (100 MHz) δ 212.4, 140.3, 130.6, 120.1, 50.6, 43.9, 43.2, 32.1, 28.2, 27.7, 23.7, 16.4; MS (EI) *m/z* (rel intensity) 189 (M^+, 78), 161 (41), 145 (65), 119 (96), 118 (25), 104 (22), 91 (23), 70 (28), 69 (100), 42 (29); HRMS (EI) calcd for $C_{12}H_{15}NO$ (M^+) 189.1154, found 189.1154.

(1*S,4*S**,7*S**)-1,3,3-Trimethyl-7-phenylbicyclo[2.2.2]-oct-5-en-2-one (1f).** Following the procedure described for the preparation of **1a**, a mixture of **15f** (125 mg, 0.33 mM), tri-*n*-butylamine (180 mg, 0.97 mM), formic acid (45 mg, 0.98 mM), and $Pd(PPh_3)_2Cl_2$ (12 mg, 0.017 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 10% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1f** (63 mg, 82%): IR (neat) 2970, 1715, 1601, 1493, 1453, 1380, 1031 cm^{-1}; ^{1}H NMR (400 MHz) δ 7.25−7.14 (m, 5H), 6.70 (dd, J = 8.0, 6.6 Hz, 1H), 5.74 (ddd, J = 8.0, 1.3, 1.3 Hz, 1H), 2.81 (dd, J = 9.4, 7.3 Hz, 1H), 2.70−2.66 (m, 1H), 2.62 (ddd, J = 13.3, 9.4, 3.4 Hz, 1H), 1.71 (ddd, J = 13.3, 7.3, 2.4 Hz, 1H), 1.22 (s, 3H), 1.11 (s, 3H), 0.85 (s, 3H); ^{13}C NMR (100 MHz) δ 216.4, 143.4, 138.7, 129.8, 128.6, 128.1, 126.6, 53.6, 44.8, 44.1, 43.1, 34.0, 27.9, 25.1, 16.2; HRMS (EI) calcd for $C_{17}H_{20}O$ (M^+) 240.1514, found 240.1529.

(1*S,4*S**,7*R**)-1,3,3-Trimethyl-7-ethenylbicyclo[2.2.2]-oct-5-en-2-one (1g).** Following the procedure described for the preparation of **1a**, a mixture of **15g** (374 mg, 1.11 mM), tri-*n*-butylamine (615 mg, 3.32 mM), formic acid (155 mg, 3.37 mM), and $Pd(PPh_3)_2Cl_2$ (60 mg, 0.085 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 2.5% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1g** (159 mg, 75%); IR (neat) 2974, 1716, 1380, 1031, 997, 910 cm^{-1}; ^{1}H NMR (400 MHz) δ 6.51 (dd, J = 8.0, 6.4 Hz, 1H), 5.61 (ddd, J = 8.0, 1.4, 1.4 Hz, 1H), 5.37 (ddd, J = 17.0, 9.9, 9.1 Hz, 1H), 4.92 (dd, J = 9.9, 1.6 Hz, 1H), 4.91 (ddd, J = 17.0, 1.6, 0.8 Hz, 1H), 2.52−2.48 (m, 1H), 2.29 (ddd, J = 12.5, 9.3, 3.0 Hz, 1H), 2.23 (ddd, J = 9.3, 9.1, 5.2 Hz, 1H), 1.20 (ddd, J = 12.5, 5.2, 2.7 Hz, 1H), 1.09 (s, 3H), 1.09 (s, 3H), 1.03 (s, 3H); ^{13}C NMR (100 MHz) δ 217.0, 139.9, 138.4, 129.6, 115.2, 52.1, 44.4, 43.6, 43.3, 30.7, 27.7, 24.6, 16.1; MS (EI) *m/z* (rel intensity) 190 (M^+, 29), 136 (35), 120 (100), 119 (40), 105 (44), 28 (20); HRMS (EI) calcd for $C_{13}H_{18}O$ (M^+) 190.1358, found 190.1356.

(1*S,4*S**,7*S**)-1,3,3-Trimethyl-7-ethenylbicyclo[2.2.2]-oct-5-en-2-one (1g′).** Following the procedure described for the preparation of **1a**, a mixture of **16g** (70 mg, 0.21 mM), tri-*n*-butylamine (115 mg, 0.62 mM), formic acid (30 mg, 0.65 mM), and $Pd(PPh_3)_2Cl_2$ (7 mg, 0.01 mM) in DMF (0.2 mL) was used, and the residue was purified by column chromatography on silica gel using 2.5% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1g′** (30 mg, 76%): IR (neat) 2974, 1724, 1654, 1560, 1541, 1508 cm^{-1}; ^1H NMR (400 MHz) δ 6.48 (dd, J = 8.0, 6.8 Hz, 1H), 5.81 (dd, J = 8.0, 1.6 Hz, 1H), 5.40 (ddd, J = 16.4, 10.4, 10.3 Hz, 1H), 4.98 (dd, J = 10.3, 2.0 Hz, 1H), 4.95 (ddd, J = 16.4, 2.0, 0.8 Hz, 1H), 2.51−2.47 (m, 1H), 2.20 (ddd, J = 10.4, 10.8, 4.8 Hz, 1H), 1.84 (ddd, J = 13.7, 10.8, 2.7 Hz, 1H), 1.75 (ddd, J = 13.7, 4.8, 2.7 Hz, 1H), 1.09 (s, 3H), 1.08 (s, 3H), 1.05 (s, 3H); ^{13}C NMR (100 MHz) δ 217.8, 139.1, 138.0, 133.4, 116.7, 52.4, 48.3, 44.7, 44.0, 29.5, 28.4, 23.0, 16.5; MS (EI) *m*/*z* (rel intensity) 190 (M^+, 28), 161 (26), 149 (30), 136 (35), 120 (100), 119 (41), 105 (45), 43 (60), 28 (33); HRMS (EI) calcd for $C_{13}H_{18}O$ (M^+) 190.1358, found 190.1355.

(1*S,4*S**,7*S**)-1,3,3,7-Tetramethyl-7-methoxycarbonylbicyclo[2.2.2]oct-5-en-2-one (1h).** Following the procedure described for the preparation of **1a**, a mixture of **15h** (125 mg, 0.33 mM), tri-*n*-butylamine (180 mg, 0.97 mM), formic acid (45 mg, 0.98 mM), and $Pd(PPh_3)_2Cl_2$ (12 mg, 0.017 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 10% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1h** (63 mg, 82%): IR (neat) 2980, 1716, 1435, 1252, 1169, 1085 cm^{-1}; ^1H NMR (400 MHz) δ 6.45 (dd, J = 8.0, 6.4 Hz, 1H), 5.77 (dd, J = 8.0, 1.2 Hz, 1H), 3.61 (s, 3H), 2.55−2.51 (m, 1H), 2.20 (dd, J = 14.0, 3.2 Hz, 1H), 1.92 (dd, J = 14.0, 2.0 Hz, 1H), 1.20 (s, 3H), 1.16 (s, 3H), 1.13 (s, 3H), 1.06 (s, 3H); ^{13}C NMR (100 MHz) δ 216.5, 175.8, 136.8, 132.5, 55.6, 51.8, 48.7, 44.1, 43.5, 36.3, 29.3, 23.8, 22.5, 13.9; MS (EI) *m*/*z* (rel intensity) 236 (M^+, 36), 208 (49), 167 (31), 166 (99), 149 (79), 108 (66), 107 (100), 106 (89), 90 (61), 18 (61); HRMS (EI) calcd for $C_{14}H_{20}O_3$ (M^+) 236.1412, found 236.1414.

(1*R,2*R**,6*S**,7*S**)-7,9,9-Trimethyltricyclo[5.2.2.0^{2,6}]-undec-4,10-dien-8-one (1i).** Following the procedure described for the preparation of **1a**, a mixture of **15i** (200 mg, 0.57 mM), tri-*n*-butylamine (320 mg, 1.73 mM), formic acid (80 mg, 1.74 mM), and $Pd(PPh_3)_2Cl_2$ (21 mg, 0.03 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 20% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1i** (94 mg, 81%): IR (neat) 2970, 1715, 1622, 1449 cm^{-1}; ^1H NMR (400 MHz) δ 6.28 (dd, J = 7.8, 5.9 Hz, 1H), 5.69 (dddd, J = 7.0, 4.4, 2.0, 2.0 Hz, 1H), 5.65 (ddd, J = 7.8, 1.3, 1.3 Hz, 1H), 5.55 (ddddd, J = 7.0, 2.0, 2.0, 1.8, 0.8 Hz, 1H), 2.99 (ddddd, J = 9.2, 8.5, 4.7, 3.0, 0.8 Hz, 1H), 2.74−2.71 (m, 1H), 2.64 (ddd, J = 5.4, 3.0, 1.4 Hz, 1H), 2.48 (ddddd, J = 17.0, 9.2, 2.0, 2.0, 1.8 Hz, 1H), 1.99 (ddddd, J = 17.0, 4.7, 2.4, 2.2, 2.0 Hz, 1H), 1.19 (s, 3H), 1.12 (s, 3H), 1.05 (s, 3H); ^{13}C NMR (100 MHz) δ 217.6, 135.3, 133.7, 132.1, 129.2, 54.4, 52.6, 48.5, 43.9, 39.0, 36.9, 28.0, 24.2, 15.9; MS (EI) *m*/*z* (rel intensity) 202 (M^+, 26), 137 (100), 136 (54), 132 (85), 131 (27), 117 (64), 93 (16), 83 (18), 49 (16); HRMS (EI) calcd for $C_{14}H_{18}O$ (M^+) 202.1358, found 202.1359.

(1*R,2*S**,6*S**,7*S**)-7,9,9-Trimethyl-4-phenyl-4-azatricyclo[5.2.2.0^{2,6}]undec-10-ene-3,5,8-trione (1j).** Following the procedure described for the preparation of **1a**, a mixture of **15j** (300 mg, 0.66 mM), tri-*n*-butylamine (365 mg, 1.97 mM), formic acid (90 mg, 1.95 mM), and $Pd(PPh_3)_2Cl_2$ (25 mg, 0.035 mM) in DMF (1 mL) was used, and the residue was purified by column chromatography on silica gel using 20% ethyl acetate in hexanes as an eluent to obtain a yellowish oil **1j** (173 mg, 85%): IR (neat) 2974, 1776, 1712, 1498, 1383 cm^{-1}; ^1H NMR (400 MHz) δ 7.41 (m, 3H), 7.17 (d, J = 5.5 Hz, 2H), 6.50 (dd, J = 8.1, 6.4 Hz, 1H), 5.89 (dd, J = 8.1, 1.8 Hz, 1H), 3.54 (dd, J = 8.1, 3.4 Hz, 1H), 3.29 (ddd, J = 6.4, 3.4, 1.8 Hz, 1H), 2.88 (d, J = 8.0 Hz, 1H), 1.55 (s, 3H), 1.19 (s, 3H), 1.15 (s, 3H); ^{13}C NMR (100 MHz) δ 212.8, 176.8, 174.3, 135.8, 131.6, 131.3, 128.9, 128.6, 126.2, 51.3, 44.6, 44.5, 42.4, 27.3, 23.8, 15.0; MS (EI) *m*/*z* (rel intensity) 309 (M^+, 72), 239 (100), 119 (48), 92 (78), 28 (44); HRMS (EI) calcd for $C_{19}H_{19}O_3N$ (M^+) 309.1365, found 309.1366.

Acknowledgment. We gratefully acknowledge the financial support from the National Science Council (NSC) of the Republic of China. Ch.P.R. thanks the Ministry of Education for a postdoctoral fellowship under the program for Promoting Academic Excellence of Universities, 89-B-FA-04-1-4. R.K.P. thanks the NSC for a postdoctoral fellowship.

Supporting Information Available: ^1H and ^{13}C NMR and DEPT spectra for compounds **1a**−**d**, **1d′**, **1e**, **1e′**, **1f**, **1g**, **1g′**, **1h**−**j**, **2a**−**f**, **6a**−**d**, **8a**−**10a**, **11a**−**f**, **13**, **15a**−**j**, **16d**, **16e**, and **16g**, NOE spectra for compound **9a**, and an ORTEP plot and CIF file of X-ray crystal data for compound **15f**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO035429Y