Synthesis of Some Polyfunctionalized Bicyclo[3.3.1]nonane-2,9-diones and Bicyclo[4.3.1]decane-2,10-diones

Kenn E. Harding,* Beverly A. Clement, Louis Moreno, and Jasna Peter-Katalinic

Department of Chemistry, Texas A&M University, College Station, Texas 77843

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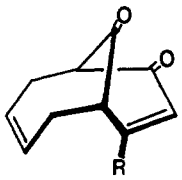
Methods for synthesis of 7,7-disubstituted bicyclo[4.3.1]dec-3-ene-9,10-dione derivatives **2**, synthons for synthesis of elemanolide sesquiterpenes, and related bicyclo[3.3.1]nonanedione systems were developed. It was determined that reaction of electrophilic acrylate and crotonate systems with nucleophilic derivatives of 4-cycloheptenone proceed less readily than the corresponding reactions with saturated cyclic ketones. The 7-substituted bicyclo[4.3.1]dec-3-ene-9,10-dione system was prepared by reaction of the enamine of 4-cycloheptenone with crotonoyl chloride derivatives. Bromination–dehydrobromination gave the enone system **1**, which was converted into a monoketal and treated with a cuprate reagent to give the 7,7-disubstituted system **2**.

In connection with a synthesis of elemanolide sesquiterpenoids, methods for the preparation of functionalized bicyclo[4.3.1]decanedione systems such as **1** and **2** were



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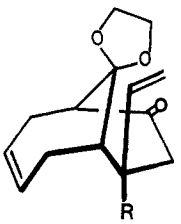


2

R = CH_3, CH_2OR'

required. We now report our results on the synthesis of these compounds and related bicyclo[3.3.1]nonanedione systems which were used as model systems.

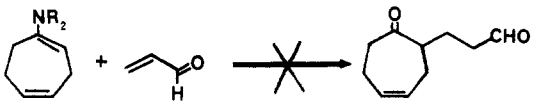
The key element to this approach is the development of procedures for construction of the bridged bicyclic system. The synthesis of unsubstituted bicyclo[3.3.1]nonane-2,9-diones (**3**) has been effected through reaction of

3

a, Y = O
b, Y = H,OH

a cyclohexanone derivative with simple acryloyl derivatives such as acrolein,[1] methyl acrylate,[2] and acryloyl chloride[3] through an addition–condensation sequence. Application of this methodology to synthesis of 4-substituted bicyclo[4.3.1]dec-3-ene-9,10-dione precursors of **1** required reaction of a 4-cycloheptenone derivative with a substituted crotonyl derivative. We have found that both the change from cyclohexanone to 4-cycloheptenone and the change from acryloyl to crotonyl derivatives affect the generality of this method.

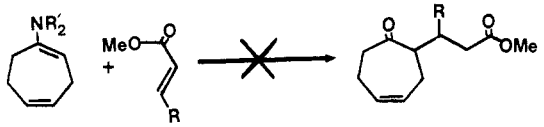
The Michael reaction of the pyrrolidine enamine of cyclohexanone and acrolein is known to proceed in 65% yield, with acid-catalyzed cyclization of the adduct to **3b** proceeding in 90% yield.[1] We were unable to use this approach because we were unable to effect reaction of either the morpholine or the pyrrolidine enamine of 4-cycloheptenone[4] or with even simple α,β-unsaturated aldehydes such as acrolein (eq 1). The reaction of the



(1)

enamine of cycloheptanone with acrolein proceeds normally.[1] Thus, the remote double bond in 4-cycloheptenone affects the nucleophilicity of the enamine in some manner which is not readily rationalized.[5] Related reactions using α-activated 4-cycloheptenone derivatives (α-formyl, α-carboalkoxy) as the nucleophile also failed.

Procedures involving acrylate ester derivatives gave similar results. Although the enamine of cyclohexanone has been reported to react with methyl acrylate in 65% yield and with ethyl crotonate in 56% yield,[2] the pyrrolidine enamine of 4-cycloheptenone failed to react with methyl acrylate even under forcing conditions (eq 2).



(2)

R = CH_3; CH_2OAc

The reaction of the morpholine enamine of cyclohexanone[3] or cycloheptanone[6] with acryloyl chloride gave bicyclo[*n*.3.1]alkanediones in good yields. The same reaction was observed with the enamine of cyclohexanone and crotonoyl chloride.[7] Our initial attempts to apply this reaction to 4-cycloheptenone gave disappointingly low yields. Since this approach was the only one that gave any significant reaction with 4-cycloheptenone, the experimental conditions for this reaction were studied by using both pyrrolidine and morpholine enamines.

It was found that although the pyrrolidine enamine of 4-cycloheptenone was far more reactive than the corresponding morpholine enamine, the yield of the desired bicyclic material was far lower with the pyrrolidine en-

(1) Allan, R. D.; Cordiner, B. G.; Wells, R. J. *Tetrahedron Lett.* **1968**, 6055–6056.
(2) Stork, G.; Brizzolara, A.; Landesman, H.; Szmuszkovicz, J.; Terrell, R. *J. Am. Chem. Soc.* **1963**, *85*, 207–222.
(3) (a) Hickmott, P. W. *Proc. Chem. Soc., London* **1964**, 287. (b) Hargreaves, J. R.; Hickmott, P. W. *Tetrahedron Lett.* **1966**, 4173–4177. (c) Hickmott, P. W.; Hargreaves, J. R. *Tetrahedron* **1967**, *23*, 3151–3159.
(4) Bahurel, Y.; Collonges, F.; Menet, A.; Pautet, F.; Poncet, A.; Descontes, G. *Bull. Soc. Chim. Fr.* **1971**, 2203–2208.
(5) It should be noted that 4-cycloheptenone is recovered in high yield from these reactions. Thus, the problem is not one involving side reactions of the enamine.
(6) Hargreaves, J. R.; Hickmott, P. W.; Hopkins, B. J. *J. Chem. Soc. C* **1969**, 592–595.
(7) Hickmott, P. W.; Miles, G. J.; Sheppard, G.; Urbani, R.; Yoxall, C. T. *J. Chem. Soc., Perkin Trans. 1* **1973**, 1514–1519.

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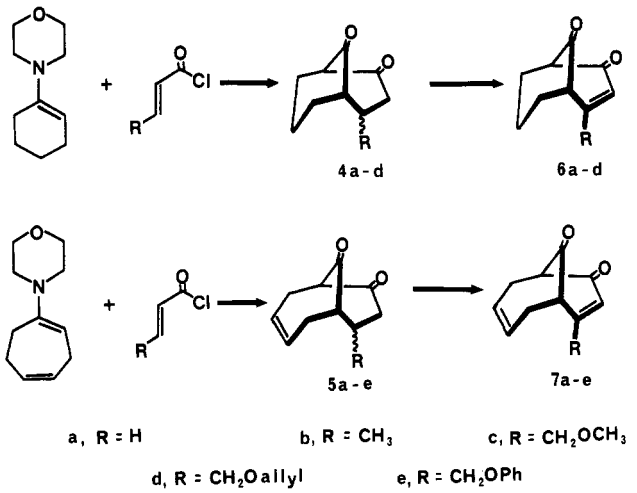
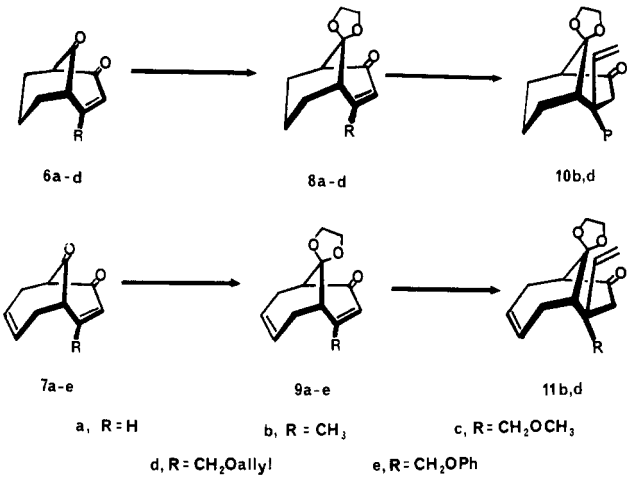
Scheme I



Scheme II



amine owing to the formation of a greater amount of polymeric material. Similarly, α,β-unsaturated acid bromides were found to be far more reactive than the corresponding acid chlorides but gave decidedly lower yields and large amounts of polymeric tars. It was also found that moderate to rapid addition (a few seconds to 30 min) of a benzene solution of the α,β-unsaturated acid chloride to a refluxing solution of the morpholine enamine of 4-cycloheptenone in benzene gave the desired bicyclic material in low yield (5–20%). This material was frequently highly contaminated with byproducts and starting material. However, either very slow addition (2–6 h) of a benzene solution of acid chloride to a refluxing benzene solution of the morpholine enamine in benzene or rapid addition of neat acid chloride to a benzene solution of the morpholine enamine at room temperature gave the desired bicyclic material in good yield (85–100%) with very little, if any, byproducts.[8]

The bicyclo[3.3.1]- and -[4.3.1]alkanediones shown in Scheme I were prepared in good yields by application of the above procedure with several substituted α,β-unsaturated acid chlorides. The 4-substituted crotonyl chlorides used in Scheme I were prepared by treatment with oxalyl chloride of the corresponding acids, which were derived from the methyl esters. Methyl 4-phenoxycrotonate was prepared in 83% yield by treatment of methyl 4-bromocrotonate with phenol and potassium carbonate in acetone.[9] Methyl 4-methoxycrotonate and methyl 4-(allyloxy)crotonate were prepared in 84% and 87% yields, respectively, by simple solvolysis of methyl 4-bromocrotonate in the alcohol.[10]

The conversion of the diones **4** and **5** to the corresponding α,β-unsaturated enones proved to be straightforward. Treatment of the diones with phenyltrimethylammonium tribromide in THF at 0 °C[11,12] gave the corresponding crude α-bromo ketones in quantitative yield. Treatment with lithium carbonate and lithium bromide in DMF at 100 °C[13] for 1–4 h gave the desired enones (**6** and **7**) in high yield.

After several attempts to form ketals of the enones by use of extremely mild conditions had failed, it was found that the conversion could be effected in quantitative yield by refluxing the enone in a benzene solution with an excess of ethylene glycol and a trace of *p*-TsOH for 2–48 h. This produced the diketal. However, the enone carbonyl was easily deprotected by shaking an ether solution of the diketal with an aqueous solution of magnesium sulfate to give ketals **8** and **9** (Scheme II).

The conjugate addition of a vinyl group was first studied with the methyl enones **8b** and **9b**. The initial experiments utilized vinyllithium to generate the cuprate reagent.[14] Methyl enones **8b** and **9b** reacted with the lithium divinylcuprate to give a single product in 90% and 93% yields, respectively. Since vinyllithium is no longer commercially available, further experiments utilized a mixed cuprate. In this case, the vinyl cuprate reagent was generated from the reaction of vinylmagnesium bromide and methylcopper (generated in situ from methyllithium and purified cuprous iodide).[15] The mixed cuprate route resulted in 95% and 98% yields, respectively, of ketals **10b** and **11b**. The vinyl adducts from the two different procedures were identical.

Although the stereochemistry of the addition product has not been defined unequivocally, both steric and stereoelectronic arguments predict the formation of the isomer shown. The vast majority of cyclic enones react with organocopper reagents to form conjugate adducts in which the newly introduced vinyl group is axial.[16] This is typical of kinetically controlled 1,4-additions which are subject to the stereoelectronic requirement that the reagent approach the α,β-unsaturated substrate in a plane perpendicular to the α,β double bond[17–19] and maintain the orbital overlap throughout the transition state. An examination of a model of the enone system in compounds **8** and **9** shows that this stereoelectronic requirement requires approach of the vinyl group on the β face of the system. In addition to the stereoelectronic factor, conjugate addition on the α face would be sterically hindered by eclipsing with

(8) The success observed with acid chlorides is rationalized in terms of a mechanism involving initial N-acylation followed by C–C bond formation by a intramolecular [3,3] sigmatropic rearrangement[3,7] rather than by Michael addition as required with crotonaldehyde or ethyl crotonate.

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(10) Sultanbawa, M. U. S.; Veeravagu, P.; Padmanathan, T. *J. Chem. Soc.* **1960**, 1262–1268. Padmanathan, T.; Sultanbawa, M. U. S. *Ibid.* **1963**, 4210–4218. Zimmerman, M. P. *Synth. Commun.* **1977**, *7*, 189–193.

(11) Marquet, A.; Jacques, J. *Bull. Soc. Chim. Fr.* **1962**, 90–96.

(12) Johnson, W. S.; Bass, J. D.; Williamson, K. L. *Tetrahedron* **1963**, *19*, 861–867.

(13) Corey, E. J.; Hortmann, A. G. *J. Am. Chem. Soc.* **1965**, *87*, 5736–5742.

(14) Corey, E. J.; Carney, R. L. *J. Am. Chem. Soc.* **1971**, *93*, 7318–7319.

(15) Bergbreiter, D. E.; Killough, J. M. *J. Org. Chem.* **1976**, *41*, 2750–2752.

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(18) Allinger, N.; Riew, C. K. *Tetrahedon Lett.* **1966**, 1269–1272.

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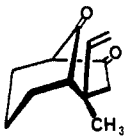
the axial substituent at the γ position.[20] Thus, the necessary stereochemical result is predicted.

Support for the stereochemistry of adducts **10** and **11** has been obtained from NMR spectroscopic studies of the adducts in comparison with the corresponding ketones (**12** and **13**) resulting from hydrolysis of the ketal. In particular, the ^1H signals for the methyl group and the C-2 vinyl proton and the ^{13}C signals for the corresponding carbons are diagnostic. In each case hydrolysis to the ketone led to a significant upfield shift ($\Delta\delta$ = −0.54 and −0.61) for the C-2 vinyl proton and only a small downfield shift ($\Delta\delta$ = 0.06 and 0.04) for the methyl protons. Similarly, the ^{13}C NMR spectra showed a significant upfield shift for the vinyl carbon ($\Delta\delta$ = −5.1 and −5.5) and a much smaller shift for the methyl group ($\Delta\delta$ = −2.0 and −0.9) upon conversion from the ketal to the ketone. These results are only consistent with the vinyl group being axial and near the bridging carbon.



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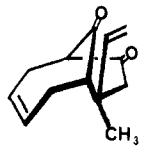

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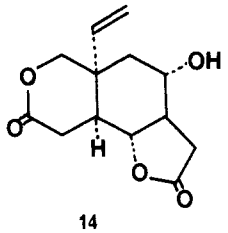
The extension of the cuprate addition reaction to the γ-substituted enone system required further modification of procedures. Reaction of enone **8d** with the mixed cuprate reagent (CH_2=CHMgBr plus MeCu) led to quantitative conversion to **8b**. Reductive removal of γ-acyloxy and alkoxy groups has been reported previously, but some divinylcuprate addition reactions of γ-alkoxycyclohexenones proceed in quite high yield.[22] Thus, we returned to the use of a divinylcuprate but generated the cuprate from vinylmagnesium bromide and cuprous iodide according to the procedure of Heathcock.[22] This reagent converted enone **8d** into the adduct **10d** with no measurable reduction. Similarly, enone **9d** was converted into adduct **11d**.

It may be noted that adducts **11d** and **11e** are synthons requiring only a series of functional group transformations to be converted into prevernolepin (**14**). Studies on these transformations are in progress.



14

Experimental Section

General Procedures. Infrared spectra were determined on a Perkin-Elmer grating infrared spectrophotometer, Model IR8. High-resolution mass spectra were determined on a CEC Model 23-110B spectrometer under the supervision of Dr. R. Grigsby. Other mass spectra were obtained on a CEC Model 21-104 single-focusing mass spectrometer.

Nuclear magnetic resonance (NMR) spectra were determined on a Varian Associates Model HA-100 or T-60 spectrometer. Carbon-13 NMR spectra were determined in $CDCl_3$ solution on a JEOL PFT-100 spectrometer system operating at 25.034 MHz (proton resonance frequency 99.539 MHz) and equipped with a Nicolet 1085 data system. Tetramethylsilane (Me_4Si) was used as the internal reference for all spectra except where stated otherwise. All chemical shifts (^1H and ^{13}C) are reported in parts per million (ppm) downfield from Me_4Si (δ_{Me_4Si} 0.0).

Vapor-phase chromatographic (VPC) analyses were performed on a Hewlett-Packard instrument, Model 700, equipped with a flame-ionization detector with nitrogen as the carrier gas. Columns used were as follows: 6 ft × $^3/_{16}$ in., 10% SE-30 on 60–80-mesh Chromosorb W which was acid washed and treated with dimethyldichlorosilane (DMCS); 6 ft × $^3/_{16}$ in., 10% Carbowax 20M on 60–80 mesh Chromosorb W which was acid washed and treated with DMCS; 5 ft × $^1/_8$ in., 1.5% OV-101 on Chromosorb G. A flow rate of 60 mL/min was normally used. All compounds which were sufficiently volatile were checked for purity on at least one of the columns.

Thin-layer chromatography (TLC) was performed by using either glass plates or plastic sheets which were precoated with a 0.25-mm layer of silica gel 60-F-254 (EM Reagents). Preparative TLC was carried out by using 20 cm × 20 cm glass plates coated with a 1.5-mm layer of silica gel (EM Reagents silica gel PF-254). Column chromatography was performed by using EM Reagents silica gel 60 (finer than 230 mesh).

Tetrahydrofuran was distilled from lithium aluminum hydride or the sodium benzophenone dianion prior to use. Anhydrous ether was stored over sodium ribbon and used as needed. Hexane, pentane, and benzene were stored over sodium ribbon. Ether used for extractions was solvent grade and not purified before use. Methylene chloride was fractionally distilled before use. Other solvents used were not purified except as noted.

Bicarbonate refers to a saturated aqueous solution of sodium bicarbonate unless otherwise noted. Brine refers to a saturated aqueous solution of sodium chloride. Saturated potassium chloride solutions were made with Fisher reagent grade potassium chloride. Ammonium chloride–ammonium hydroxide buffer refers to a saturated aqueous solution of ammonium chloride and sufficient concentrated ammonium hydroxide to raise the pH to 8.

All reactions were run under an argon atmosphere except where stated otherwise. Evaporative distillation refers to bulb to bulb (Kugelrohr), short-path distillation in which the bulb was heated in an oven. The temperatures cited for these distillations refer to the maximum temperatures attained by the air chamber during the distillation. Melting points were determined on a Thomas-Hoover capillary melting point apparatus. All melting points and boiling points are uncorrected. Microanalyses were performed by Chemalytics, Inc.

Methyl 4-Methoxycrotonate. By use of a variation of Sultanbawa's method,[10] 75.00 g (0.42 mol) of methyl 4-bromocrotonate, 40.0 g (0.40 mol) of calcium carbonate, and 250 mL of anhydrous methanol, freshly distilled from magnesium turnings, were heated at reflux for 5 days. At this time, the methanol was removed, and the residue was dissolved with ether and water (containing a trace of HCl). The aqueous solution was extracted twice with 200-mL portions of ether. The ether washes were combined, washed with water and brine, dried over magnesium sulfate, filtered, concentrated, and distilled [bp 120 °C (44 mm)] to yield 45.79 g (84%) of ester: ^1H NMR ($CDCl_3$, 100 MHz) δ 3.34 (s, 3 H, CH_3OCH_2), 3.69 (s, 3 H, CH_3O_2C), 4.05 (dd, J = 4 and 2 Hz, 2 H, OCH_2), 6.04 (dt, J = 16 and 2 Hz, 1 H, =CHCO), 6.93 (dt, J = 16 and 4 Hz, 1 H, CH_2CH=); ^{13}C NMR δ 51.4 (ester OCH_3), 58.5 (ether OCH_3), 71.2 (C-4), 120.9 (C-2), 144.6 (C-3), 166.5 (C-1); IR (film) 1724 (C=O), 1667 cm^{-1}.

4-Methoxycrotonic Acid. By use of a variation of Sultanbawa's method,[10] 45.00 g (0.35 mol) of the above ester and 250 mL of 1 N NaOH were stirred at room temperature for 3 min, during which time the clear, two-phase mixture became a bright yellow, homogeneous solution. The aqueous solution was washed with ether (to remove unreacted ester) and then acidified with 4 N sulfuric acid to a Congo Red endpoint. The acidified solution was extracted twice with 200-mL portions of ether. The organic extracts were combined, washed with brine, dried over magnesium sulfate, filtered, and concentrated to yield 36.94 g (92%) of crystalline acid: mp 62.5–63 °C; ^1H NMR ($CDCl_3$, 100 MHz) δ 3.38 (s, 3 H, OCH_3), 4.11 (dd, J = 4 and 2 Hz, 2 H, OCH_2), 6.06

(20) Marshall, J. A.; Roebke, H. *J. Org. Chem.* **1968**, *33*, 840–843.
(21) Molecular models show a 1,3-diaxial relationship between C-2 of the vinyl group and one of the ketal oxygens which is not present in the corresponding diketone.
(22) Wege, P. M.; Clark, R. D.; Heathcock, C. H. *J. Org. Chem.* **1976**, *41*, 3144–3148.

(dt, J = 16 and 2 Hz, 1 H, =CHCO), 7.06 (dt, J = 16 and 4 Hz, 1 H, CH_2CH=), 11.47 (s, 1 H, COOH); ^{13}C NMR δ 58.6 (OCH_3), 71.0 (C-4), 120.6 (C-2), 146.8 (C-3), 171.4 (C-1); IR (CCl_4) 3800–2500 (br, COOH), 1706 (C=O), 1661 cm^{-1}.

4-Methoxycrotonoyl Chloride. A solution of 40.00 g (0.24 mol) of 4-methoxycrotonic acid in 200 mL of benzene was cooled to 0 °C, and 45.85 g (0.36 mol) of oxalyl chloride was added. The solution was warmed to room temperature until the evolution of gas had ceased (approximately 6 h). At this time, the solution was concentrated and distilled to yield 23.3 g (72% yield) of acid chloride: bp 120 °C (1.0 mm); ^1H NMR ($CDCl_3$, 100 MHz) δ 3.40 (s, 3 H, OCH_3), 4.18 (dd, J = 4 and 2 Hz, 2 H, OCH_2), 6.30 (dt, J = 15 and 2 Hz, 1 H, =CHCO), 7.20 (dt, J = 15 and 4 Hz, 1 H, CH_2CH=); IR (film) no stretch above 3050 cm^{-1}.

Methyl 4-(Allyloxy)crotonate. A mixture of 50.0 g (0.28 mol) of methyl 4-bromocrotonate, 40.0 g of calcium carbonate (0.40 mol), and 200 mL of freshly distilled allyl alcohol was heated at reflux for 3 days, cooled, and filtered into 500 mL of water. The aqueous solution was extracted five times with 150-mL portions of ether. The ether extracts were combined, washed (water, brine, and water), dried over magnesium sulfate, filtered, concentrated, and distilled to yield 37.95 g (87%) of methyl 4-(allyloxy)crotonate [bp 120 °C (44 mm)] as a clear liquid: ^1H NMR ($CDCl_3$, 100 MHz) δ 3.68 (s, 3 H, OCH_3), 4.01 (dt, J = 5.5 and 1 Hz, 2 H, CH_2=$CHCH_2O$), 4.23 (dd, J = 4 and 2 Hz, 2 H, OCH_2CH=CH), 5.16 and 5.34 (m, 2 H, CH_2=$CHCH_2$), 5.68 (m, 1 H, CH_2=$CHCH_2$), 6.05 (dt, J = 16 and 2 Hz, 1 H, CH=CHCO), 6.94 (dt, J = 16 and 4 Hz, 1 H, CH=CHCO); ^{13}C NMR δ 51.5 (OCH_3), 68.6 (allyloxy methylene), 71.7 (C-4), 117.2 (=CH_2), 120.9 (C-2), 134.2 (allyloxy CH=), 144.6 (C-3), 166.6 (C-1); IR (film) 1724 (C=O), 1667, 1439, 1307, 1275, 1172 cm^{-1}.

4-(Allyloxy)crotonic Acid. Hydrolysis of the above methyl ester (20.0 g, 0.13 mol) in the same manner as in the preparation of 4-methoxycrotonic acid yielded 18.15 g (99.7%) of 4-(allyloxy)crotonic acid as a clear oil: ^1H NMR ($CDCl_3$, 100 MHz) δ 4.04 (dt, J = 6 and 1.5 Hz, CH_2=CH_2CH_2O), 4.17 Hz (dd, J = 4 and 2 Hz, 2 H, OCH_2CH=CHCO), 5.20 and 5.37 (m, 2 H, CH_2=$CHCH_2$), 5.94 (m, 1 H, CH_2=$CHCH_2$), 6.10 (dt, J = 16 and 2 Hz, 1 H, CH=CHCO), 7.07 (dt, J = 16 and 4 Hz, 1 H, CH=CHCO); ^{13}C NMR δ 68.4 (OCH_2 of allyloxy), 71.8 (C-4), 117.5 (=CH_2 of allyloxy), 120.6 (C-2), 134.1 (CH= of allyloxy), 147.0 (C-3), 171.4 (C-1); IR (film) 3800–2500 (br, COOH), 1706 (C=O), 1661, 1429, 1311, 1287, 1117, 925 cm^{-1}.

4-(Allyloxy)crotonyl Chloride. Conversion to the acid chloride in the same manner as 4-methoxycrotonyl chloride gave 4-(allyloxy)crotonyl chloride [bp 60–62 °C (0.1 mm)] in 91% yield as a clear liquid: ^1H NMR ($CDCl_3$, 100 MHz) δ 4.04 (dt, J = 5 and 1.5 Hz, 2 H, CH_2=$CHCH_2O$), 4.22 (dd, J = 4 and 2 Hz, 2 H, OCH_2CH=CH), 5.05–5.36 (m, 2 H, CH_2=), 5.67–6.26 (m, 1 H, CH_2=$CHCH_2$), 6.34 (dt, J = 16 and 2 Hz, 1 H, =CHCO), and 7.15 (dt, J = 16 and 4 Hz, 1 H, CH=CHCO); IR (film) no OH stretching above 3000 cm^{-1}.

Methyl 4-Phenoxycrotonate. By use of a variation of Fiecchi's procedure,[9] a mixture of 20 g (112 mmol) of methyl 4-bromocrotonate, 10.5 g (112 mmol) of phenol, and 30.9 g (223 mmol) of K_2CO_3 in 250 mL of acetone was heated at reflux. The reaction mixture was cooled, filtered, and concentrated to give a brown residue which was taken up in diethyl ether. The ethereal layer was washed with 0.1 N NaOH until the aqueous layer remained colorless, with H_2O until the aqueous layer was neutral, and then with brine. The solution was dried over $MgSO_4$, filtered, concentrated, and distilled [bp 118–120 °C (0.25 mm)] to give 18.1 g (83%) of ester: ^1H NMR ($CDCl_3$, 100 MHz) δ 3.76 (s, 3 H, OCH_3), 4.67 (dd, J = 4 and 2 Hz, 2 H, OCH_2), 6.20 (dt, J = 16 and 2 Hz, 1 H, =CHCO), 6.7–7.40 (complex, 6 H, C-3 and phenyl H); ^{13}C NMR δ 51.5 (OCH_3), 66.3 (C-4), 114.7 (C-2′), 121.3 (C-2 or C-4′), 121.4 (C-2 or C-4′), 129.5 (C-3′), 142.9 (C-3), 158.1 (C-1′), 166.3 (C-1); IR (film) 1724 (C=O), 1665, 1600 cm^{-1}.

4-Phenoxycrotonic Acid. A heterogeneous mixture of methyl 4-phenoxycrotonate (10 g, 51.5 mmol) and 1 M NaOH (103 mL, 103 mmol) was stirred at room temperature until it was homogeneous (7–9 h). The solution was washed with 20 mL of ether to remove any neutral material and acidified to pH 1 with 2 N HCl to precipitate the crystalline product. The powdery white crystals were collected by vacuum filtration and were air-dried to give 8.55 g (93%) of 4-phenoxycrotonic acid: mp 130–132 °C; ^1H NMR ($CDCl_3$, 100 MHz) δ 4.75 (dd, J = 2 and 4 Hz, 2 H, OCH_2), 6.23 (dt, J = 16 and 2 Hz, 1 H, =CHCO), 6.84–7.4 (complex, 6 H); ^{13}C NMR δ 66.3 (C-4), 114.7 (C-2′), 121.1 (C-2 or C-4′), 121.5 (C-4′ or C-2), 129.6 (C-3′), 145.3 (C-3), 158.0 (C-1′), 171.2 (C-1). Recrystallization from ethanol–water (9:1) gave material with a melting point of 134–135 °C (lit.[9] mp 136 °C).

4-Phenoxycrotonyl Chloride. To 1 g (5.56 mmol) of 4-phenoxycrotonic acid in 25 mL of benzene was added, rapidly, 2.82 g (22.2 mmol) of oxalyl chloride. The solution was heated to 50–60 °C for 4 h. The benzene was distilled at atmospheric pressure, and the residue was distilled at reduced pressure [bp 119–120 °C (1 mm)] to give 1.03 g (96%) of 4-phenoxycrotonyl chloride.

***N*-(1,4-Cycloheptadien-1-yl)morpholine.** A mixture of 5.00 g (0.05 mol) of 4-cycloheptenone, 23.72 g (0.27 mol) of morpholine, 100 mL of benzene, and a trace of *p*-toluenesulfonic acid monohydrate was refluxed through a Dean–Stark trap until the evolution of water had ceased (~36 h). The solution was concentrated and fractionally distilled to yield 7.36 g (90% yield) of enamine as a clear oil, bp 80 °C (0.1 mm).

Bicyclo[3.3.1]nonane-2,9-dione (4a).[3] To 5.00 g (22.91 mmol) of *N*-(1-cyclohexenyl)morpholine[23] and 20 mL of benzene in a 50-mL, round-bottomed flask was added 2.71 g (22.91 mmol) of acryloyl chloride. Formation of a precipitate was immediate. The suspension was stirred at room temperature for 1 h, and then the benzene was decanted. The white crystalline precipitate was washed with dry hexane and dissolved in 25 mL of ice–water. The aqueous solution was allowed to stand at 0 °C for 1 h and then extracted five times with 25-mL portions of methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [90 °C (0.1 mm)] to yield 4.28 g (94% yield, lit.[3c] yield 45%) of bicyclo[3.3.1]nonane-2,9-dione (**4a**): ^{13}C NMR δ 18.9 (C-7), 22.5 (C-4), 35.1 and 35.8 (C-6 and C-8), 39.3 (C-3), 44.6 (C-5), 64.4 (C-1), 209.7 (C-2), 211.3 (C-9).

Bicyclo[4.3.1]dec-3-ene-9,10-dione (5a). To a solution of 5.00 g (27.89 mmol) of *N*-(1,4-cycloheptadienyl)morpholine in 20 mL of benzene in a 50-mL, round-bottomed flask was added 2.53 g (27.89 mmol) of acryloyl chloride. A precipitate formed immediately. The suspension was stirred at room temperature for 3 h, the benzene was decanted from the precipitate, and the resulting white crystals were washed with dry hexane and then dissolved in 50 mL of ice–water. The aqueous solution was kept at 0 °C for 1 h and then extracted five times with 25-mL portions of methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [110 °C (0.1 mm)] to yield 4.40 g (96% yield) of dione **5a**: ^1H NMR (100 MHz, $CDCl_3$) δ 1.72–3.07 (m, 6 H), 3.27 (m, 3 H), 3.61 (m, 1 H), 5.50–6.20 (m, 2 H); ^{13}C NMR δ 24.2 (C-7), 30.5 and 31.3 (C-2 and C-5), 38.5 (C-8), 46.1 (C-6), 64.6 (C-1), 127.6 and 130.3 (C-3 and C-4), 208.7 (C-9), 210.7 (C-10); IR (film) 1702 cm^{-1} (C=O); mass spectrum, calcd for $C_{10}H_{12}O_2$ m/e 164.083 720, found m/e 164.084 32, m/e (relative intensity) 165 (4), 164 (39), 108 (16), 87 (64), 85 (100), 81 (17), 79 (34), 55 (30), 53 (17), 49 (18), 47 (25), 41 (23), 39 (26).

4-Methylbicyclo[3.3.1]nonane-2,9-dione (4b).[7] To 3.00 g (17.94 mmol) of *N*-(1-cyclohexenyl)morpholine and 100 mL of benzene in a 200-mL, round-bottomed flask was added 1.87 g (17.94 mmol) of crotonoyl chloride. A precipitate formed immediately. The suspension was stirred at room temperature for 3 h, and then the benzene was decanted. The viscous precipitate was first washed with dry hexane and then dissolved in 50 mL of ice–water. The aqueous solution was allowed to stand at 0 °C for 30 min and extracted five times with 50-mL portions of methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [100 °C (0.1 mm)] to yield 2.92 g (98% yield, lit.[7] yield 48%) of dione **4b** as a clear viscous oil: ^1H NMR ($CDCl_3$, 100 MHz) δ 1.045, 1.085 (2 d, J = 7 Hz, 3 H, CH_3),[24] 1.54–2.85 (m, 7 H), 2.99 (m, 3 H, CH_2C=O and CHC=O), 3.64 (m, 1 H, CO-

(23) Stork, G.; Landesman, H. K. *J. Am. Chem. Soc.* **1956**, *78*, 5129–5130.

(24) This is the only bicyclic dione which demonstrated isomerism at C-4. The spectra of the other diones (4 and 5) showed no evidence of two isomers. The stereochemistry of these diones was not determined.

CHCO); ^{13}C NMR (major isomer only)[24] δ 18.6 (C-7), 23.2 (CH_3), 30.0 (C-4), 34.9 and 35.3 (C-6 and C-8), 48.3 (C-2), 53.3 (C-5), 62.7 (C-1), 209.5 (C-2), 211.9 (C-9); IR (film) 1724 cm^{-1} (s, br, C=O); mass spectrum, calcd for $C_{10}H_{18}O_2$ m/e 166.099 370, found m/e 166.099 989.

7-Methylbicyclo[4.3.1]dec-3-ene-9,10-dione (5b). To 500 mg (2.78 mmol) of *N*-(1,4-cycloheptadienyl)morpholine in 20 mL of benzene was added 291 mg (2.78 mmol) of crotonyl chloride, leading to immediate formation of a precipitate. The suspension was stirred at room temperature overnight. The benzene was decanted, and then the oily residue was washed with dry hexane and dissolved in 25 mL of ice–water. The aqueous solution was kept at 0 °C for 1 h and extracted four times with 50-mL portions of methylene chloride. The organic phases were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [120 °C (0.1 mm)] to yield 457 mg (92% yield) of dione **5b** as a clear oil: ^1H NMR ($CDCl_3$, 100 MHz) δ 1.00 (d, J = 8 Hz, 3 H, CH_3), 2.02–3.00 (m, 7 H), 3.26 (m, 2 H), 3.62 (m, 1 H), 5.80 (m, 2 H); ^{13}C NMR δ 21.2 (CH_3), 30.2 and 30.9 (C-2 and C-5), 31.3 (C-7), 46.3 (C-8), 54.1 (C-6), 63.7 (C-1), 127.3 and 129.5 (C-3 and C-4), 208.5 (C-9), 211.1 (C-10); IR (film) 1730 cm^{-1} (C=O). Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.17; H, 7.86. Found: C, 73.97; H, 7.98.

4-(Methoxymethyl)bicyclo[3.3.1]nonane-2,9-dione (4c). To 3.00 g (17.94 mmol) of *N*-(1-cyclohexenyl)morpholine in 100 mL of benzene in a 200-mL round-bottomed flask was added 2.41 g (17.91 mmol) of the 4-methoxycrotonyl chloride. The mixture was allowed to stir for 8 h. At this time the benzene was decanted from the oily precipitate. The precipitate was washed with dry hexane and then dissolved in 100 mL of ice–water. The aqueous solution was kept at 0 °C for 1 h and then extracted five times with 50-mL portions of methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [140 °C (0.1 mm)] to yield 3.16 g (89% yield) of dione **4c**: ^1H NMR ($CDCl_3$, 100 MHz) δ 1.48–2.96 (m, 10 H), 3.02 (m, 1 H, $CH(CO)_2$), 3.26 (s, 3 H, OCH_3), 3.32 (d, J = 6 Hz, 2 H, CH_2O); ^{13}C NMR δ 18.8 (C-7), 35.4 (C-4), 35.7 and 35.9 (C-6 and C-8), 43.3 (C-3), 49.2 (C-5), 58.7 (OCH_3), 63.3 (C-1), 76.7 (CH_2O), 208.7 (C-2), 211.2 (C-9); IR (film), 1730 (C=O), 1100 cm^{-1}; mass spectrum, calcd for $C_{11}H_{16}O_3$ m/e 196.109 930, found m/e 196.110 780, m/e (relative intensity) 197 (4), 196 (34), 164 (26), 122 (23), 99 (100), 96 (22), 95 (29), 84 (22), 55 (59), 45 (49), 41 (27), 39 (20).

7-(Methoxymethyl)bicyclo[4.3.1]dec-3-ene-9,10-dione (5c). To a solution of 1.00 g (5.58 mmol) of *N*-(1,4-cycloheptadienyl)morpholine in 20 mL of benzene in a 50-mL, round-bottomed flask was added 0.75 g (5.58 mmol) of 4-methoxycrotonyl chloride. A precipitate formed immediately. The suspension was stirred at room temperature for 3 h, and the benzene was decanted. The crystalline precipitate was washed with dry hexane and then dissolved in 30 mL of ice–water. The aqueous solution was stirred at 0 °C for 1 h and then extracted five times with methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [140 °C (0.1 mm)] to yield 1.10 g (95% yield) of dione **5c**: ^1H NMR ($CDCl_3$, 100 MHz) δ 2.08–2.98 (m, 9 H), 3.19 (s, 3 H, OCH_3), 3.37 (d, J = 4 Hz, 2 H, OCH_2), 5.78 (m, 2 H, CH=CH); ^{13}C NMR δ 31.1 and 31.4 (C-2 and C-5), 38.7 (C-7), 42.5 (C-8), 50.6 (C-6), 59.0 (CH_3), 64.0 (C-1), 77.6 (CH_2O), 127.4 and 129.6 (C-3 and C-4), 208.6 (C-9), 210.2 (C-10); IR (film) 1700 (C=O), 1090 cm^{-1}; mass spectrum, m/e (relative intensity) 209 (5), 208 (30), 135 (53), 134 (22), 117 (28), 109 (28), 107 (29), 99 (47), 95 (25), 91 (55), 86 (30), 84 (22), 81 (23), 80 (22), 79 (68), 78 (25), 77 (45), 71 (53), 68 (38), 67 (100), 66 (34), 65 (33), 63 (49), 45 (45), 41 (53), 39 (55). Anal. Calcd for $C_{12}H_{16}O_3$: C, 69.21; H, 7.75. Found: C, 68.96; H, 8.02.

4-[(Allyloxy)methyl]bicyclo[3.3.1]nonane-2,9-dione (4d). To 3.00 g (17.94 mmol) of *N*-(1-cyclohexenyl)morpholine and 60 mL of benzene in a 100-mL round-bottomed flask was added 2.88 g (17.9 mmol) of 4-(allyloxy)crotonyl chloride. The solution was stirred at room temperature for 3 h. At this time, the benzene was decanted from the oily precipitate. The residue was first washed with dry hexane and then dissolved in 50 mL of ice–water. The solution was allowed to stand at 0 °C for 1 h and was then extracted five times with 50-mL portions of methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [140 °C (0.2 mm)] to yield 3.72 g (93% yield) of dione **4d** as a clear oil: ^1H NMR (100 MHz, $CDCl_3$) δ 1.49–3.07 (m, 11 H), 3.38 (d, J = 4 Hz, 2 H, OCH_2), 3.92 (dt, J = 6 and 1 Hz, 2 H, CH_2CH=), 5.02–5.31 (m, 2 H, CH_2=), 5.61–6.01 (m, 1 H, CH=CH); ^{13}C NMR δ 18.9 (C-7), 35.5 and 36.0 (C-6 and C-8), 43.6 (C-3), 49.4 (C-5), 63.4 (C-1), 72.0 (OCH_2CH=), 74.2 (CH_2O), 116.9 (CH_2=CH), 134.1 (CH=CH_2), 209.0 (C-2), 211.5 (C-9); IR (film) 1725 (C=O), 1090 cm^{-1}; mass spectrum, calcd for $C_{13}H_{18}O_3$ m/e 222.125 580, found m/e 222.125 197, m/e (relative intensity) 223 (3), 222 (16), 151 (11), 125 (16), 123 (12), 97 (100), 95 (19), 67 (19), 55 (30), 41 (100), 39 (20).

7-[(Allyloxy)methyl]bicyclo[4.3.1]dec-3-ene-9,10-dione (5d). To 5.00 g (27.89 mmol) of *N*-(1,4-cycloheptadienyl)morpholine in 20 mL of benzene was added 4.48 g (27.89 mmol) of 4-(allyloxy)crotonyl chloride. The suspension was stirred at room temperature for 3 h, and then the benzene was decanted. The oily precipitate was washed with dry hexane and dissolved in 30 mL of ice–water. The aqueous solution was kept at 0 °C for 1 h and extracted four times with 50-mL portions of methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [150 °C (0.1 mm)] to yield 5.52 g (95% yield) of bicyclic dione **5d**: ^1H NMR (100 MHz, $CDCl_3$) δ 2.08–3.11 (m, 7 H), 3.31 (m, 2 H), 3.42 (dd, J = 3 and 1 Hz, 2 H, CH_2O), 3.85 (dt, J = 6 and 1 Hz, 2 H, OCH_2CH=), 4.98–5.25 (m, 2 H, =CH_2), 5.53–6.10 (m, 1 H, CH=); ^{13}C NMR δ 31.2 and 31.6 (C-2 and C-5), 38.9 (C-7), 42.6 (C-8), 50.8 (C-6), 64.2 (C-1), 72.3 (OCH_2CH=), 75.0 (CH_2O), 117.2 (H_2C=CH), 127.4 and 129.6 (C-3 and C-4), 133.7 (CH=CH_2), 208.6 (C-9), 210.1 (C-10); IR (film) 1700 (C=O), 1099 cm^{-1}; mass spectrum, calcd for $C_{14}H_{18}O_3$ m/e 234.126 558, found m/e 234.126 542, m/e (relative intensity) 235 (6), 234 (37), 193 (26), 135 (30), 91 (35), 79 (45), 67 (56), 55 (42), 53 (28), 41 (100), 39 (60).

7-(Phenoxymethyl)bicyclo[4.3.1]dec-3-ene-9,10-dione (5e). To 904 mg (5.1 mmol) of *N*-(1,4-cycloheptadienyl)morpholine in 10 mL of refluxing benzene was added 1.0 g (5.1 mmol) of 4-phenoxycrotonyl chloride in 5 mL of benzene via a motor-driven syringe (Sage Instrument syringe pump, Model 355, 12.5% × 1/100). The solution was cooled to 0 °C 3 h and 40 min after the addition of the acid chloride was started and was maintained at 0 °C for 1 h. The benzene layer was decanted, washed with 5 mL of cold $NaHCO_3$ solution and 10 mL of brine, dried over $MgSO_4$, filtered, and concentrated at reduced pressure. Column chromatography (silica gel; ether/methylene chloride, 9:1) gave 550 mg (44%) of light brown crystalline product. The yield of this reaction was variable, ranging from 21% to 47%. Recrystallization from ether gave colorless platelets: mp 126.5–127.5 °C; IR ($CHCl_3$) 1720 (C=O), 1698 (C=O), 1600 cm^{-1} (C=C); ^1H NMR ($CDCl_3$, 100 MHz) δ 2.22–2.80 (m, 5 H), 2.86–3.16 (m, 3 H), 3.56 (br s, 1 H), 4.96 and 4.97 (d, 2 H, CH_2O, two isomers), 5.64–6.08 (m, 2 H), 6.64–7.36 (m, 5 H); ^{13}C NMR δ 31.1 and 31.6 (C-2 and C-5), 37.9 (C-7), 42.6 (C-8), 50.6 (C-6), 64.3 (C-1), 72.2 (CH_2O), 114.2 (ortho aromatic), 121.5 (para aromatic), 127.8 and 129.4 (meta aromatic and C-3 and C-4), 157.8 (C-1 of phenyl), 208.0 (C-10), 209.8 (C-9); mass spectrum, calcd for $C_{17}H_{18}O_3$ m/e 270.1259, found m/e 270.1261, m/e (relative intensity) 271 (20), 270 (90), 135 (25), 131 (25), 107 (25), 95 (30), 94 (70), 91 (40), 79 (55), 77 (60), 67 (25), 65 (35), 55 (45), 53 (25), 51 (25), 41 (100), 39 (100).

Bicyclo[3.3.1]non-3-ene-2,9-dione (6a). A solution of 4.64 g (12.35 mmol) of phenyltrimethylammonium tribromide[11,12] and 100 mL of anhydrous THF in a 125-mL Erlenmeyer flask was cooled to 0 °C, and 1.88 g (12.35 mmol) of dione **4a** was added in 10 mL of anhydrous THF. The orange solution was stirred at 0 °C for 30 min, and the resultant pale yellow suspension was filtered into 50 mL of a 1:1 solution of saturated brine and 0.1 N sodium thiosulfate. The filter cake of phenyltrimethylammonium bromide was washed with ether. The aqueous solution was extracted three times with 150-mL portions of methylene chloride. The organic washes were combined, washed twice with brine, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [130 °C (0.25 mm)] to yield 2.85 g (100%) of bromo ketone as a clear viscous oil: ^1H NMR ($CDCl_3$) δ 1.50–2.90 (m, 10 H), 3.07 (m, 1 H), 4.67 (t, J = 5 Hz, 1 H). This material was used directly in the next reaction.

A mixture of 2.85 g (12.35 mmol) of the above bromo ketone, 3.00 g (40.60 mmol) of lithium carbonate, 5.00 g (57.7 mmol) of lithium bromide, and 40 mL of anhydrous DMF (distilled from barium oxide) was heated, with stirring, at 100 °C in a 100-mL, round-bottomed flask for 2 h, allowed to cool to room temperature, and then poured into 50 mL of saturated brine solution. The aqueous solution was extracted twice with 100-mL portions of ether and three times with 50-mL portions of methylene chloride. The organic phases were combined, washed (brine, water, and brine), dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled to yield 1.86 g (100%) of enone **6a** as a clear oil: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.8–3.0 (m, 6 H), 3.34 (m, 2 H), 6.50 (d, J = 10 Hz, 1 H, =CHC=O), 7.14 (dd, J = 14 and 10 Hz, 1 H, CH=CHCO); ^{13}C NMR δ 16.4 (C-7), 29.9 and 33.4 (C-6 and C-8), 49.1 (C-4), 63.3 (C-1), 132.7 (C-3), 147.9 (C-4), 198.9 (C-2), 207.8 (C-9); IR (film) 1725 and 1665 (C=O), 1640 cm^{-1} (C=C).

4-Methylbicyclo[3.3.1]non-3-ene-2,9-dione (6b). Method A. Bromination–Dehydrobromination. Dione **4b** (1.30 g, 7.77 mmol) was treated with 2.92 g (7.77 mmol) of phenyltrimethylammonium tribromide in the manner described for formation of enone **6a** to yield, after evaporative distillation [100 °C (0.1 mm)], 2.69 g (100%) of crude bromo ketone as a clear oil: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.27, 1.31 (2 d, J = 5 Hz, 3 H, CH_3), 1.54–2.95 (m, 8 H), 3.67 (m, 1 H), and 4.50 (d, J = 3 Hz, 1 H). This material was used directly in the next reaction.

The bromo ketone was heated for 2 h at 80–100 °C with 3.00 g (40.6 mmol) of lithium carbonate and 5.00 g (57.7 mmol) of lithium bromide in 30 mL of anhydrous DMF. A normal workup and evaporative distillation gave 1.27 g (100% yield) of enone **6b**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.48–2.83 (m, 6 H), 2.10 (d, J = 1 Hz, 3 H, CH_3), 3.13 (m, 2 H), 6.33 (m, 1 H, =CHCO); ^{13}C NMR δ 17.1 (C-7), 22.6 (CH_3), 29.7 and 32.8 (C-6 and C-9), 54.6 (C-5), 61.6 (C-1), 130.2 (C-3), 159.8 (C-4), 197.8 (C-2), 208.0 (C-9); IR (film) 1724 and 1667 (C=O), 1639 cm^{-1} (C=C); mass spectrum, calcd for $C_{10}H_{12}O_2$ m/e 164.083 720, found m/e 164.083 719.

Method B. Direct Formation. To 2.62 g (14.63 mmol) of *N*-(1-cyclohexenyl)morpholine and 20 mL of benzene in a 50-mL, round-bottom flask was added 1.50 g (14.63 mmol) of butynoyl chloride.[25] A precipitate formed immediately. The suspension was stirred for 3 h, and then the benzene was decanted. The residue was washed with dry hexane, dissolved in cold water, and extracted four times with 50-mL portions of methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and chromatographed on silica gel (eluting with 50% ether in hexane) to yield 130 mg (5%) of bicyclic enone **6b**. This was identical with material prepared by method A.

4-(Methoxymethyl)bicyclo[3.3.1]non-3-ene-2,9-dione (6c). Dione **4c** (3.16 g, 16.0 mmol) was treated with 6.02 g (16.0 mmol) of phenyltrimethylammonium tribromide in the manner described for preparation of enone **6a** to give, after evaporative distillation [140 °C (0.1 mm)], 4.26 g (100% yield) of crude bromo ketone as a pale yellow oil.

The bromo ketone was heated for 4 h at 100 °C with 2.00 g (27.10 mmol) of lithium carbonate and 5.00 g (57.74 mmol) of lithium bromide in 40 mL of dry DMF. Normal workup and evaporative distillation gave 3.01 g (100% yield) of enone **6c**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.42–3.17 (m, 8 H), 3.41 (s, 3 H, OCH_3), 4.12 (d, J = 3 Hz, CH_2O), 6.52 (m, =CHCO); ^{13}C NMR δ 17.0 (C-7), 30.3 and 32.8 (C-6 and C-8), 50.2 (C-5), 58.9 (OCH_3), 62.3 (C-1), 72.7 (CH_2O), 127.8 (C-3), 158.7 (C-4), 197.8 (C-2), 207.4 (C-9); IR (film) 1724 and 1660 (C=O), 1100 cm^{-1}; mass spectrum, calcd for $C_{11}H_{16}O_3$ m/e 194.093 990, found 194.093 995.

4-[(Allyloxy)methyl]bicyclo[3.3.1]non-3-ene-2,9-dione (6d). Dione **4d** (2.70 g, 12.1 mmol) was treated with 4.55 g (12.1 mmol) of phenyltrimethylammonium tribromide in the manner described for preparation of enone **6a** to give 3.65 g (100% yield) of crude bromo ketone.

The bromo ketone was heated for 4 h at 100 °C with 3.00 g (40.6 mmol) of lithium carbonate and 5.00 g (57.74 mmol) of lithium bromide in 30 mL of dry DMF. A normal workup and evaporative distillation [150 °C (0.1 mm)] gave 2.85 g (100% yield) of enone **6d**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.42–2.39 (m, 6 H), 3.11–3.42 (m, 2 H), 4.06 (dt, J = 6 and 1 Hz, 2 H, CH_2=$CHCH_2$), 4.11 (d, J = 2 Hz, 2 H, CH_2O), 5.20, 5.30, 5.39 (m, 2 H, CH_2=CH), 5.74–6.12 (m, 1 H, =CH), 6.59 (m, 1 H, =CHCO); ^{13}C NMR δ 17.1 (C-7), 30.5 and 32.9 (C-6 and C-8), 50.3 (C-5), 62.3 (C-1), 70.1 (CH_2O), 72.0 (OCH_2CH=), 117.8 (H_2C=CH), 127.9 (C-3), 133.6 (CH=CH_2), 158.8 (C-4), 197.8 (C-2), 207.4 (C-9); IR (film) 1724 and 1667 (C=O), 1637 (C=C), 1090 cm^{-1}; mass spectrum, calcd for $C_{13}H_{16}O_3$ m/e 220.109 930, found m/e 220.108 996, m/e (relative intensity) 221 (5), 220 (42), 162 (48), 134 (49), 95 (26), 91 (23), 79 (31), 67 (25), 55 (52), 41 (100), 39 (35).

Bicyclo[4.3.1]deca-3,7-diene-9,10-dione (7a). Dione **5a** (500 mg, 3.05 mmol) was treated with 1.26 g (3.35 mmol) of phenyltrimethylammonium tribromide in the manner described for preparation of enone **6a** to give, after evaporative distillation [120 °C (0.2 mm)], 740 mg (100% yield) of bromo ketone: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.75–3.80 (m, 7 H), 3.67 (m, 1 H), 4.67 (t, J = 5 Hz, 1 H), 5.82 (m, 2 H).

A mixture of 2.24 g (0.14 mmol) of bromo ketone prepared as above, 3.37 g (47.7 mmol) of lithium carbonate, 7.91 g (90.35 mmol) of lithium bromide, and 40 mL of anhydrous DMF was heated at 100 °C for 1.5 h, cooled to room temperature, and poured into 100 mL of brine. The aqueous solution was extracted five times with ether. The ethereal extracts were combined, washed several times with brine, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [110 °C (0.1 mm)] to yield 1.47 g (99% yield) of enone **7a**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.82–3.08 (m, 4 H), 3.33–3.55 (m, 2 H), 5.73 (m, 2 H), 6.27 (d, J = 10 Hz, 1 H, =CHCO), 6.90 (dd, J = 10 and 6 Hz, 1 H, CH=CHCO); ^{13}C NMR δ 30.2 and 31.2 (C-2 and C-5), 49.4 (C-6), 61.7 (C-1), 127.7, 127.8, and 131.5 (C-3, C-4, and C-8), 147.3 (C-7), 198.7 (C-9), 208.5 (C-10); IR (film) 1724 and 1667 (C=O), 1636 (C=C) cm^{-1}; mass spectrum, calcd for $C_{10}H_{10}O_2$ m/e 162.067 680, found 162.067 680, m/e (relative intensity) 163 (8), 162 (64), 128 (45), 111 (35), 108 (100), 77 (25), 65 (25), 53 (27), 41 (29), 39 (32), 27 (25).

7-Methylbicyclo[4.3.1]deca-3,7-diene-9,10-dione (7b). Method A. Bromination–Dehydrobromination. Dione **5b** (2.50 g, 14.0 mmol) was treated with 5.27 g (14.0 mmol) of phenyltrimethylammonium tribromide as described in the preparation of enone **6a** to give, after evaporative distillation [120 °C (0.1 mm)], 3.61 g (100% yield) of bromo ketone: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.19 (d, J = 6 Hz, 3 H, CH_3), 2.08–2.98 (m, 5 H), 3.52 (m, 2 H), 4.49 (d, J = 3 Hz, 1 H, CHBr), 5.76 (m, 2 H).

The above bromo ketone was heated for 1 h at 100 °C with 6.00 g (81.2 mmol) of lithium carbonate and 10.00 g (115 mmol) of lithium bromide in 40 mL of dry DMF. A normal workup and evaporative distillation [120 °C (0.1 mm)] gave 2.47 g (100% yield) of enone **7b**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.89–2.95 (m, 4 H), 2.00 (d, J = 1.5 Hz, 3 H, CH_3), 3.08 (m, 2 H), 5.76 (m, 2 H), 6.11 (m, 1 H, CHCO); ^{13}C NMR δ 22.0 (CH_3), 29.3 and 30.9 (C-2 and C-5), 54.3 (C-6), 59.9 (C-1), 127.5 and 128.6 (C-3 and C-4), 129.0 (C-8), 159.0 (C-7), 197.0 (C-9), 209.1 (C-10); IR (film) 1724 and 1660 (C=O), 1620 cm^{-1} (C=C); mass spectrum, calcd for $C_{11}H_{12}O_2$ m/e 176.083 720, found m/e 176.084 323, m/e (relative intensity) 177 (8), 176 (64), 133 (32), 109 (100), 105 (39), 91 (30), 77 (23), 66 (25), 53 (26), 41 (27), 39 (35).

Method B. To 2.45 g (14.63 mmol) of *N*-(1,4-cycloheptadienyl)morpholine and 20 mL of benzene in a 50-mL, round-bottomed flask was added 1.50 g (14.63 mmol) of butynoyl chloride.[25] There was an immediate formation of a precipitate. The suspension was stirred at room temperature for 4 h and then filtered. The residue was washed with dry hexane, dissolved in 20 mL of water, and extracted three times with 50-mL portions of methylene chloride. The organic washes were combined, dried over magnesium sulfate, filtered, concentrated, and chromatographed (silica gel, eluting with ether) to yield 150 mg (6.00% yield) of bicyclic enone **7b**. This was identical with material prepared by method A.

7-(Methoxymethyl)bicyclo[4.3.1]deca-3,7-diene-9,10-dione (7c). Dione **5a** (800 mg, 3.84 mmol) was treated with 1.90 g (4.23 mmol) of phenyltrimethylammonium tribromide as described in the preparation of enone **6a** to give, after evaporative distillation [140 °C (0.1 mm)], 1.24 g (100% yield) of crude bromo ketone.

The above bromo ketone was heated for 4 h at 100 °C with 3.00 g (40.6 mmol) of lithium carbonate and 5.00 g (57.7 mmol) of

(25) Prepared by Jones oxidation of 2-butyn-1-ol and treatment of the resulting acid with oxalyl chloride.

lithium bromide in 30 mL of dry DMF. A normal workup and evaporative distillation [140 °C (0.08 mm)] gave 738 mg (94% yield) of enone **7c**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 2.06–3.10 (m, 6 H), 3.24–3.54 (m, 2 H), 3.61 (d, J = 1 Hz, 2 H, CH_2O), 3.18 (s, 3 H, OCH_3), 5.54–6.10 (m, 2 H), 6.18 (m, 1 H, =CHCO); ^{13}C NMR δ 29.9 and 31.0 (C-2 and C-5), 50.2 (C-6), 58.9 (OCH_3), 60.6 (C-1), 72.6 (CH_2O), 127.2, 127.9, and 128.6 (C-3, C-4, and C-8), 158.0 (C-7), 197.8 (C-9), 208.4 (C-10); IR (film) 1720 and 1660 cm^{-1} (C=O). Anal. Calcd for $C_{13}H_{14}O_3$: C, 69.89; H, 6.84. Found: C, 69.9; H, 7.09.

7-[(Allyloxy)methyl]bicyclo[4.3.1]deca-3,7-diene-9,10-dione (7d). Dione **5d** (1.7 g, 7.26 mmol) was treated with 2.73 g (7.26 mmol) of phenyltrimethylammonium tribromide in the manner described for preparation of enone **6a** to give, after normal workup and concentration, 2.27 g (100% yield) of crude bromo ketone.

This bromo ketone was heated for 4 h at 100 °C with 2.00 g (27.1 mmol) of lithium carbonate and 5.00 g (57.7 mmol) of lithium bromide in 40 mL of dry DMF. A normal workup and evaporative distillation [150 °C (0.1 mm)] gave 1.68 g (100% yield) of enone **7d**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 2.08–2.96 (m, 4 H), 3.25–3.50 (m, 2 H), 4.03 (dt, J = 6 and 1 Hz, 2 H, OCH_2CH=), 4.15 (d, J = 1.5 Hz, 2 H, CH_2O), 5.14–5.42 (m, 2 H, =CH_2), 5.68–6.12 (m, 3 H, CH=), 6.32 (m, 1 H, =CHCO); ^{13}C NMR δ 30.0 and 31.0 (C-2 and C-5), 50.3 (C-6), 60.6 (C-1), 70.0 (CH_2O), 71.9 (OCH_2-CH=), 117.7 (H_2C=), 127.1, 127.9, and 128.6 (C-3, C-4, and C-8), 133.7 (CH=CH_2), 158.3 (C-7), 197.8 (C-9), 208.5 (C-10); IR (film) 1720 and 1660 (C=O), 1098 cm^{-1}; mass spectrum, calcd for $C_{14}H_{16}O_3$ m/e 232.109 930, found m/e 232.111 193, m/e (relative intensity) 232 (6), 174 (19), 116 (17), 91 (37), 78 (25), 76 (23), 67 (17), 55 (37), 53 (16), 51 (16), 41 (100), 39 (58).

7-(Phenoxymethyl)bicyclo[4.3.1]deca-3,7-diene-9,10-dione (7e). Dione **5e** (800 mg, 3.27 mmol) was treated with 1.35 g (3.59 mmol) of phenyltrimethylammonium tribromide in the manner described for preparation of enone **6a**, except that the reaction was conducted at room temperature, to give a crude bromo ketone, which was dehydrohalogenated without prior purification. A mixture of the bromo ketone, 2.84 g (32.7 mmol) of LiBr, and 1.21 g (16.4 mmol) of Li_2CO_3 in 20 mL of anhydrous DMF was heated at 120 °C for 4 h, cooled to room temperature, and poured into 100 mL of brine. The solution was extracted five times with methylene chloride. The organic extracts were combined, washed several times with brine, dried over magnesium sulfate, filtered, concentrated, and chromatographed (alumina; ether–methylene chloride, 9:1) to give 630 mg (78.8%) of yellow-white crystals. Recrystallization from ether gave a white powder: mp 110–111 °C; IR ($CHCl_3$) 1719 (C=O), 1662 (C=O), 1595 (C=C) cm^{-1}; ^{1}H NMR δ 2.08–2.96 (m, 4 H), 3.35 (m, 1 H), 3.51 (m, 1 H), 4.69 (d, J = 2 Hz, 2 H), 5.79 (m, 2 H), 6.44 (br s, 1 H), 6.80–7.40 (m, 5 H); ^{13}C NMR δ 30.0 and 31.0 (C-2 and C-5), 50.6 (C-6), 60.6 (C-1), 67.9 (CH_2O), 114.6 (ortho aromatic), 121.8 (para aromatic), 127.7, 127.8, and 128.8 (C-3, C-4, and C-8), 129.7 (meta aromatic), 156.4 (C-7), 157.7 (C-1 of phenyl), 197.6 (C-9), 208.0 (C-10); mass spectrum, calcd for $C_{17}H_{16}O_3$ m/e 268.1099, found m/e 268.1087, m/e (relative intensity) 269 (12), 268 (80), 175 (32), 147 (28), 119 (46), 405 (28), 79 (22), 77 (60), 66 (22), 65 (64), 55 (88), 53 (32), 51 (32), 41 (66), 39 (100).

9,9-(Ethylenedioxy)bicyclo[3.3.1]non-3-en-2-one (8a). A mixture of 1.86 g (12.35 mmol) of bicyclic enone **6a**, 2.00 g of ethylene glycol, 50 mL of benzene, and a crystal of p-toluenesulfonic acid monohydrate was refluxed through a Dean–Stark trap for 48 h (water removed via trap), concentrated, poured into water, and extracted with ether. The ethereal extracts were combined, washed (twice with water, twice with aqueous magnesium sulfate solution and once with brine), dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled to yield 2.40 g (100% yield) of monoketal as a clear viscous oil: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.13–3.42 (m, 8 H), 3.94 (m, 4 H, OCH_2CH_2O), 6.88 (d, J = 10 Hz, 1 H, =CHCO), 6.88 (dd, J = 10 and 6 Hz); ^{13}C NMR δ 15.4 (C-7), 23.7 and 26.3 (C-6 and C-8), 41.0 (C-5), 52.9 (C-1), 64.3 and 64.7 (ketal methylenes), 110.0 (C-9), 131.8 (C-3), 149.2 (C-4), 201.4 (C-2); IR (film) 1701 (C=O), 1110 cm^{-1}; mass spectrum, calcd for $C_{11}H_{14}O_3$ m/e 194.094 280, found m/e 194.095 205, m/e (relative intensity) 195 (5), 194 (36), 88 (33), 84 (100), 49 (34), 47 (60).

9,9-(Ethylenedioxy)-4-methylbicyclo[3.3.1]non-3-en-2-one (8b). Ketalization of enone **6b** in the same manner as that described for enone **6a** gave ketal **8b** [120 °C (0.1 mm)] in 100% yield: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.10–2.20 (m, 6 H), 1.98 (d, J = 1.5 Hz, 3 H, CH_3), 2.45 (m, 2 H), 3.94 (m, 4 H, OCH_2CH_2O), 6.12 (m, 1 H, =CHCO); ^{13}C NMR δ 16.0 (C-7), 23.1 (CH_3), 23.6 and 25.8 (C-6 and C-8), 46.5 (C-1), 51.5 (C-5), 64.3 and 64.7 (ketal methylenes), 110.3 (C-9), 128.7 (C-3), 161.1 (C-4), 200.9 (C-2); IR (film) 1698 (C=O), 1111 cm^{-1}; mass spectrum, calcd for $C_{12}H_{10}O_3$ m/e 208.109 930, found m/e 208.109 140, m/e (relative intensity) 209 (15), 208 (86), 180 (22), 165 (34), 151 (27), 149 (29), 139 (33), 135 (29), 125 (30), 120 (35), 113 (25), 112 (96), 108 (38), 99 (100), 86 (65), 84 (99), 79 (23), 73 (37), 69 (57), 55 (46), 45 (30), 41 (75), 39 (33).

10,10-(Ethylenedioxy)bicyclo[4.3.1]deca-3,7-dien-9-one (9a). Ketalization of 1.47 g of bicyclic enone **7a** in the manner described for enone **6a** gave, after evaporative distillation [120 °C (0.1 mm)], 1.87 g (100% yield) of bicyclic ketal **9a**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.80–2.87 (m, 6 H), 3.97 (m, 4 H, OCH_2CH_2O), 5.49 (m, 2 H, CH=CH), 6.02 (d, J = 10 Hz, 1 H, =CHCO), 6.72 (dd, J = 10 and 6 Hz, 1 H, CH=CHCO); ^{13}C NMR δ 27.2 and 27.6 (C-2 and C-5), 43.0 (C-1), 53.3 (C-6), 64.4 and 65.0 (ketal methylenes), 111.1 (C-10), 127.5, 127.8, and 130.5 (C-3, C-4, and C-8), 149.1 (C-7), 200.9 (C-9); IR (film) 1701 (C=O), 1105 cm^{-1}; mass spectrum, calcd for $C_{12}H_{14}O_3$ m/e 206.095 125, found m/e 206.094 280, m/e (relative intensity) 207 (6), 206 (41), 113 (100), 99 (51), 91 (29), 86 (26), 55 (29), 39 (29).

10,10-(Ethylenedioxy)-7-methylbicyclo[4.3.1]deca-3,7-dien-9-one (9b). Method A. Direct Formation from Enone 7b. Ketalizaton of 2.47 g (14.03 mmol) of bicyclic enone **7b** in the manner described for enone **6a** gave, after evaporative distillation [120 °C (0.1 mm)], 3.09 g (100% yield) of ketal **9b**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.91 (d, J = 1.5 Hz, 3 H, CH_3), 2.10–2.80 (m, 6 H), 3.96 (m, 4 H, OCH_2CH_2O), 5.50 (m, 2 H, CH=CH), 5.86 (m, 1 H, =CHCO); ^{13}C NMR δ 22.7 (CH_3), 26.4 and 27.2 (C-2 and C-5), 47.8 (C-1), 57.8 (C-6), 64.3 and 64.9 (ketal methylenes), 111.4 (C-10), 127.7, 127.9, and 128.1 (C-3, C-4, and C-8), 160.2 (C-7), 199.8 (C-9); IR (film) 1701 (C=O), 1106 cm^{-1}; mass spectrum, calcd for $C_{13}H_{16}O_3$ m/e 220.109 930, found m/e 220.109 930.

Method B. Formation from Ketal 9a. A solution of 1.03 g (5.00 mmol) of ketal **9a** in 50 mL of anhydrous ether was treated with 27.78 mL (50 mmol) of methyllithium (1.8 M in ether) at room temperature for 1 h. The reaction was quenched by careful addition of 10 mL of water. The layers were separated and the aqueous layer was washed with 10 mL of methylene chloride. The organic phases were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [120 °C (0.1 mm)] to yield 1.10 g (99% yield) of tertiary allylic carbinol: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.07 and 1.13 (s, 3 H, CH_3), 1.64–2.68 (m, 6 H), 3.95 (m, 4 H, OCH_2CH_2O), 5.26–5.72 (m, 4 H); ^{13}C NMR (major isomer) δ 23.6 (CH_3) 29.2 and 30.0 (C-2 and C-5), 46.1 (C-1), 45.5 (C-6), 53.5 (C-9), 64.3 (ketal methylenes), 112.3 (C-10), 129.1, 129.4, and 130.2 (C-3, C-4, and C-8), 134.9 (C-7); IR (film) 3200–3500 cm^{-1} (OH); mass spectrum, calcd for $C_{13}H_{18}O_3$ m/e 222.125 580, found 222.126 072, m/e (relative intensity) 223 (15), 222 (98), 165 (25), 151 (29), 129 (21), 128 (49), 126 (32), 125 (29), 113 (100), 99 (60), 91 (27), 86 (53), 79 (32), 77 (21), 69 (25), 55 (25), 43 (21), 41 (34), 39 (28).

To a bright orange slurry of 430 mg (2.00 mmol) of pyridinium chlorochromate in 3 mL of methylene chloride was added 222.1 mg (1.00 mmol) of the above carbinol in 1 mL of methylene chloride. The resultant dark red-black mixture was stirred at room temperature for 2 h and diluted with an equal volume of ether. The ethereal solution was decanted from the black resinous polymer. The polymeric residue was washed twice with 5-mL portions of methylene chloride and three times with 5-mL portions of ether. The organic phases were combined, washed (5% aqueous sodium hydroxide, 5% hydrochloric acid, and bicarbonate), dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [110 °C (0.1 mm)] to yield 220.1 mg (100% yield) of ketal **9b**, identical in all ways to previously prepared material.

Cuprous Iodide. Method A.[26a] Cuprous iodide (Fisher) was dissolved in the minimum amount of saturated aqueous potassium iodide. The yellow solution was decolorized with activated carbon

(26) (a) Kauffman, G. B.; Teter, L. A. *Inorg. Synth.* **1963**, *7*, 9–12. (b) Posner, G. H.; Whitten, C. E.; Sterling, J. J. *J. Am. Chem. Soc.* **1973**, *95*, 7788–7800.

(Darco) and filtered. The cuprous iodide was reprecipitated by addition of 5 volumes of water and then isolated by filtration. The filter cake was washed with water and vacuum dried to yield cuprous iodide as a white powder. This was stored in a brown bottle under argon.

Method B.[26b] Cuprous iodide (Fisher) was placed in an argon-purged Soxhlet extractor and continuously extracted with dry THF for 48 h. The contents of the thimble were vacuum dried, and the white powder was stored in a brown bottle under argon.

9,9-(Ethylenedioxy)-*exo*-4-vinyl-*endo*-4-methylbicyclo[3.3.1]nonan-2-one (10b). A. Mixed Cuprate Method.[15] An oven-dried, argon-purged, 50-mL, round-bottomed flask containing 914 mg (4.80 mmol) of recrystallized cuprous iodide and 20 mL of anhydrous THF was cooled to −78 °C (dry ice–acetone), and 2.82 mL (4.80 mmol) of 1.7 M methyllithium–lithium bromide complex in ether was added. The suspension was warmed to room temperature and stirred for 15 min. The resultant bright orange suspension of methylcopper was cooled to −78 °C (dry ice–acetone), and 4.00 mL (4.80 mmol) of 1.2 M vinylmagnesium bromide in ether was added. (The suspension first turned dark green and then became light yellow.) This mixture was stirred for 15 min at −78 °C, and then 100 mg (0.48 mmol) of enone **8a** was added. The pale yellow solution was allowed to warm to room temperature whereupon the solution became black. The mixture was stirred at room temperature for 2 h and then rapidly poured into 100 mL of vigorously stirred saturated ammonium chloride solution. The pH of the solution was adjusted to 8–10 by the addition of concentrated ammonium hydroxide. The hydrolysis mixture was stirred at room temperature until all the copper salts had dissolved (approximately 1.5 h). The bright blue solution was extracted with ether. The extracts were combined, washed with brine, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [140 °C (0.1 mm)] to yield 107 mg (95% yield) of **10b**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.18 (s, CH_3), 1.54–2.31 (m, 7 H), 2.43 (m, 2 H, CH_2CO), 2.66 (m, 1 H), 3.87 (m, 4 H, OCH_2CH_2O), 4.79, 4.91 (d, J = 18 Hz, d, J = 11 Hz, 2 H, CH_2=CH), 6.18 (dd, J = 18 and 11 Hz, 1 H, CH_2=CH); ^{13}C NMR 18.6 (C-7), 25.9 (C-6 or C-8), 26.9 (CH_3), 27.2 (C-6 or C-8), 38.3 (C-4), 45.7 (C-5), 51.3 (C-3), 54.2 (C-1), 63.8 and 64.0 (ketal methylenes), 108.5 (=CH_2), 110.4 (C-9), 150.5 (CH=), 212.0 (C-2); IR (film) 1724 (C=O), 1110 cm^{-1}; mass spectrum, calcd for $C_{14}H_{20}O_3$ m/e 236.141 230, found m/e 236.140 506.

B. Lithium Divinylcuprate Method.[22] A mixture of 181 mg (0.95 mmol) of recrystallized cuprous iodide, 10 drops of hexamethylphosphorous triamide, and 35 mL of anhydrous ether in an over-dried, argon-purged, 50-mL flask was stirred at room temperature for 1 h and then cooled to −78 °C (dry ice–acetone), and 1.06 mL (1.9 mmol) of 1.8 M vinyllithium in THF was added. The mixture was stirred at −78 °C for 30 min (the solution became bright yellow), and then 100 mg (0.48 mmol) of ketal **8a** in 5 mL of anhydrous ether was added. The mixture was stirred for 1 h and then treated with 20 mL of saturated ammonium chloride solution. After the copper salts had dissolved, the solution was extracted five times with 50-mL portions of methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [130 °C (0.15 mm)] to yield 101.6 mg (90% yield) of **10a**, identical in all ways with material prepared by procedure A.

10,10-(Ethylenedioxy)-*exo*-vinyl-*endo*-7-methylbicyclo[4.3.1]dec-3-en-9-one (11b). An oven-dried, argon-purged, 50-mL, round-bottomed flask containing 1.73 g (9.08 mmol) of recrystallized cuprous iodide and 20 mL of anhydrous THF was cooled to −78 °C (dry ice–acetone), and 5.34 mL (9.08 mmol) of 1.7 M methyllithium–lithium bromide complex in ether was added. The pale yellow suspension was warmed to room temperature and stirred at room temperature for 15 min, at which time a bright yellow-orange precipitate of methylcopper appeared. The suspension was again cooled to −78 °C, and 10.9 mL (9.08 mmol) of vinylmagnesium bromide in ether was added. The suspension, which immediately became dark green, was stirred at −78 °C for 15 min, during which time the color changed to a bright canary yellow. Then 200 mg (0.91 mmol) of ketal **9a** in 10 mL of anhydrous THF was added. The solution became bright orange and then faded to pale yellow. The solution was warmed to room temperature and stirred for 2 h. The resultant black solution was poured into 100 mL of vigorously stirred saturated ammonium chloride solution. The mixture, adjusted to pH 8 by addition of concentrated ammonium hydroxide solution, was then stirred at room temperature for 1.5 h during which time the copper salts dissolved. The hydrolysis solution was extracted five times with 100-mL portions of ether. The ether extracts were combined, washed twice with brine, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [150 °C (0.1 mm)] to yield 221 mg (98% yield) of ketal **11b**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.12 (s, 3 H, CH_3), 1.82–2.88 (m, 8 H), 3.92 (m, 4 H, OCH_2CH_2O), 4.79 (d, J = 11 Hz, 1 H), 4.80 (d, J = 18 Hz, 1 H), 5.04–6.06 (m, 2 H), 6.00 (dd, J = 18 and 11 Hz, 1 H); ^{13}C NMR δ 25.9 (CH_3), 27.6 and 27.8 (C-2 and C-5), 40.3 (C-7), 48.8 (C-6), 49.6 (C-8), 57.1 (C-1), 64.0 and 64.4 (ketal methylenes), 108.8 (=CH_2), 112.8 (C-10), 128.9 and 130.1 (C-3 and C-4), 149.0 (CH=), 211.0 (C-9); IR (film) 1724 (C=O), 1110 cm^{-1}; mass spectrum, calcd for $C_{15}H_{20}O_3$ m/e 248.141 230, found m/e 248.140 279.

***exo*-4-Vinyl-*endo*-4-methylbicyclo[3.3.1]nonane-2,9-dione (12). A. Hydrolysis of Ketal 10b.** A mixture of 200 mg (0.85 mmol) of ketal **10b**, 10 mL of ether, and 20 mL of 10% hydrochloric acid in a 50-mL, round-bottomed flask was stirred vigorously for 16 h. The layers were separated, and the organic phase was washed (water and brine), dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [140 °C (0.1 mm)] to yield 163 mg (100% yield) of the diketone **12**: IR (film) 1730 cm^{-1} (C=O); ^{13}C NMR δ 19.7 (C-7), 24.9 (CH_3), 30.1 and 35.0 (C-6 and C-8), 38.6 (C-4), 50.1 (C-3), 55.4 (C-5), 65.4 (C-1), 113.1 (=CH_2), 145.4 (CH=), 208.0 (C-2), 210.8 (C-9); mass spectrum, calcd for $C_{12}H_{16}O_2$ m/e 192.115 020, found 192.113 913, m/e (relative intensity) 193 (3), 192 (16), 164 (44), 96 (21), 95 (100), 84 (25), 83 (32), 79 (25), 69 (23), 68 (73), 67 (45), 55 (30), 41 (43), 39 (35).

B. Direct Preparation from Dione 6b. Into an oven-dried, argon-purged, 50-mL, round-bottomed flask were placed 181 mg (0.95 mmol) of recrystallized cuprous iodide, 30 mL of anhydrous ether, and 10 drops of hexamethylphosphorous triamide. The mixture was stirred at room temperature for 30 min to dissolve the copper salt and then cooled to −78 °C (dry ice–acetone). To this was added 1.06 mL (1.90 mmol) of 1.8 M vinyllithium, and the solution was stirred an additional 30 min at −78 °C. At this time, 79 mg (0.48 mmol) of the dione **6b** was added in 5 mL of anhydrous ether. The solution was stirred for 1 h at −78 °C, allowed to warm to room temperature, and quenched with 20 mL of saturated ammonium chloride solution. After all the copper salts had dissolved, the solution was extracted five times with 50-mL portions of methylene chloride. The organic extracts were combined, dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [130 °C (0.1 mm)] to yield 39 mg (42.1% yield) of diketone **10b**, identical with material prepared by procedure A.

***exo*-7-Vinyl-*endo*-7-methylbicyclo[4.3.1]dec-3-ene-9,10-dione (13).** A mixture of 400 mg (1.96 mmol) of ketal **11b** in 10 mL of ether and 20 mL of 10% hydrochloric acid in a 50-mL, round-bottomed flask was stirred vigorously for 48 h. The layers were separated, and the organic phase was washed (water and brine), dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [140 °C (0.1 mm)] to yield 400 mg (100% yield) of the diketone **13**: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.16 (s, 3 H, CH_3), 1.80–2.98 (m, 7 H), 3.10–3.48 (m, 1 H), 4.80 (d, J = 18 Hz, 1 H), 4.97 (d, J = 11 Hz, 1 H), 5.59 (dd, J = 18 and 11 Hz, 1 H), 5.50–6.20 (m, 2 H); ^{13}C NMR δ 25.0 (CH_3), 26.2 and 31.9 (C-2 and C-5), 38.7 (C-7), 49.0 (C-8), 56.5 (C-6), 63.6 (C-1), 114.0 (=CH_2), 128.3 and 130.3 (C-3 and C-4), 145.5 (CH=), 209.3 (C-9), 210.9 (C-10); IR (film) 1728 cm^{-1} (C=O); mass spectrum, calcd for $C_{13}H_{16}O_2$ m/e 204.115 020, found m/e 204.115 797, m/e (relative intensity) 205 (2), 204 (9), 121 (20), 109 (31), 108 (21), 105 (21), 95 (100), 92 (30), 91 (27), 84 (22), 81 (21), 80 (38), 79 (38), 77 (21), 69 (27), 67 (33), 66 (20), 55 (23), 53 (27), 41 (43), 39 (39).

9,9-(Ethylenedioxy)-4-[(allyloxy)methyl]bicyclo[3.3.1]non-3-en-2-one (8d). A mixture of 450 mg (2.04 mmol) of keto enone **6d**, 1.50 g (24.16 mmol) of ethylene glycol, 60 mL of benzene, and a small crystal of *p*-toluenesulfonic acid monohydrate in a 100-mL, round-bottomed flask equipped with a Dean–Stark trap and a condensor was refluxed for 2 h and then concentrated. The residue was dissolved in 50 mL of water, and the aqueous solution was extracted four times with 50-mL portions of ether and once

with 50 mL of methylene chloride. The organic washes were combined, washed (twice with water, twice with aqueous magnesium sulfate, and once with brine), dried over magnesium sulfate, filtered, concentrated, and evaporatively distilled [150 °C (0.1 mm)] to yield 540 mg (100% yield) of ketal **8d** as a clear oil: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.00–2.29 (m, 6 H), 2.52 (m, 2 H), 3.90–4.14 (m, 8 H, OCH_2CH_2O, CH_2O, and $=CHCH_2$), 6.34 (m, 1 H, =CHCO); ^{13}C NMR δ 16.0 (C-7), 24.2 and 25.9 (C-6 and C-8), 42.0 (C-5), 52.3 (C-1), 64.4 and 64.8 (ketal methylenes), 70.7 (CH_2O), 71.5 ($OCCH_2CH=$), 110.2 (C-9), 117.4 ($=CH_2$), 127.1 (C-3), 134.1 (CH=), 160.0 (C-4), 201.1 (C-2); IR (film) 1701 (C=O), 1090 cm^{-1}; mass spectrum, calcd for $C_{15}H_{20}O_4$ m/e 264.124 990, found m/e 264.125 602, m/e (relative intensity) 265 (5), 264 (28), 206 (32), 195 (25), 178 (23), 112 (44), 99 (75), 91 (22), 79 (32), 77 (24), 73 (72), 67 (22), 55 (69), 53 (20), 45 (20), 41 (100), 39 (54).

10,10-(Ethylenedioxy)-7-[(allyloxy)methyl]bicyclo[4.3.1]deca-3,7-dien-2-one (9d). Ketalization of 300 mg of enone **7d** in the manner described for enone **6d** gave, after chromatography on a column of silica gel (elution of ether), 357 mg (100% yield) of bicyclic ketal **9d** as a clear oil: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 2.05–2.92 (m, 5 H), 3.38 (m, 1 H), 3.70–4.15 (m, 8 H, OCH_2), 5.08–6.04 (m, 5 H), 6.12 (m, 1 H, =CHCO); ^{13}C NMR δ 26.8 and 27.2 (C-2 and C-5), 43.3 (C-1), 52.5 (C-6), 64.4 and 65.0 (ketal methylenes), 70.6 (CH_2O), 71.3 ($OCH_2CH=$), 111.3 (C-10), 117.4 ($=CH_2$), 126.6, 127.9, and 128.4 (C-3, C-4, and C-8), 134.1 (CH=), 159.4 (C-7), 200.5 (C-9); IR (film) 1701 (C=O), 1100 cm^{-1}; mass spectrum, calcd for $C_{16}H_{20}O_4$ m/e 276.136 752, found 276.136 752, m/e (relative intensity) 276 (10), 235 (78), 138 (21), 113 (100), 99 (54), 92 (28), 73 (36), 55 (36), 41 (64), 39 (36).

9,9-(Ethylenedioxy)-*exo*-4-vinyl-*endo*-4-[(allyloxy)methyl]bicyclo[3.3.1]nonan-2-one (10d). A suspension of 2.88 g (15.13 mmol) of purified cuprous iodide and 25 mL of anhydrous THF in an oven-dried, argon-purged, 100-mL, round-bottomed flask was cooled to −5 °C, and 25.22 mL (30.27 mmol) of vinylmagnesium bromide (1.2 M in ether) was added. The black suspension was stirred at −5 °C for 3 min and then rapidly cooled to −70 °C. To this was added 400 mg (1.51 mmol) of ketal **8d**. The suspension was stirred at −70 °C for 1 h, slowly warmed to 0 °C, and rapidly quenched by being poured into 100 mL of saturated aqueous ammonium chloride solution. The aqueous solution was extracted five times with 50-mL portions of ether. The ether extracts were combined, washed (brine, saturated ammonium chloride, and brine), dried over magnesium sulfate, filtered, concentrated, and chromatographed on silica gel (eluting with ether) to yield 440 mg (99% yield) of **10d** as a pale yellow oil: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.18–2.80 (m, 10 H), 3.15 and 3.34 (2 d, J = 9 Hz, 2 H, CH_2O), 3.74–3.99 (m, 6 H), 4.78–5.38 (m, 2 H, allyl $=CH_2$), 4.88 (d, J = 1.5 Hz, 1 H), 5.03 (d, J = 3 Hz, 1 H), 5.38–6.18 (m, 1 H, allyl CH=), 6.06 (dd, J = 17 and 11 Hz, 1 H, vinyl CH=); ^{13}C NMR δ 19.1 (C-7), 25.3 and 27.0 (C-6 and C-8), 42.6 (C-5), 63.9 (ketal methylenes), 72.3 ($OCH_2CH=$), 75.9 (CH_2O), 110.0 ($=CH_2$ of C-4 vinyl), 110.5 (C-9), 116.9 ($=CH_2$ of allyloxy), 134.4 (CH= of allyloxy), 147.1 (CH= of C-4 vinyl), 211.3 (C-2); IR (film) 1720 cm^{-1} (C=O); mass spectrum, calcd for $C_{17}H_{24}O_2$ m/e 292.167 440, found m/e 292.166 379, m/e (relative intensity) 292 (12), 265 (25), 221 (90), 107 (20), 99 (38), 93 (26), 91 (37), 86 (23), 84 (50), 81 (54), 80 (31), 79 (68), 77 (29), 71 (66), 67 (60), 57 (21), 55 (54), 53 (28), 45 (25), 43 (100), 41 (44), 39 (99).

***exo*-4-Vinyl-*endo*-4-[(allyloxy)methyl]bicyclo[3.3.1]nonane-2,9-dione.** A mixture of 200 mg (0.68 mmol) of ketal **10d**, 10 mL of ether, and 20 mL of 10% hydrochloric acid in a 50-mL, round-bottomed flask was stirred vigorously at room temperature for 24 h. The layers were separated, and the organic phase was washed (water and brine), dried over magnesium sulfate, filtered, concentrated, and chromatographed on silica gel (eluting with ether) to yield 170 mg (100% yield) of dione: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.08–2.80 (m, 9 H), 2.08 (m, 1 H), 3.45 and 3.57 (2 d, J = 10 Hz, 2 H, CH_2O), 3.99 (dt, J = 16 and 10 Hz, 2 H, allylic CH_2), 4.80–5.20 (m, 2 H), 4.90 and 5.04 (d, J = 16 Hz, d, J = 10 Hz, 2 H, $CH_2=$), 5.62 (dd, J = 16 and 10 Hz, 1 H, $CH=CH_2$), 5.67–6.08 (m, 1 H); ^{13}C NMR δ 19.9 (C-7), 30.5 and 35.2 (C-6 and C-8), 42.8 (C-4), 45.7 (C-3), 52.5 (C-5), 65.9 (C-1), 72.3 ($OCH_2CH=$), 74.7 (CH_2O), 115.2 ($=CH_2$ of vinyl), 117.0 ($=CH_2$ of allyloxy), 134.1 (CH= of allyloxy), 142.1 (CH= of vinyl), 207.9 (C-2), 210.4 (C-9); IR (film) 1730 cm^{-1} (C=O); mass spectrum, calcd for $C_{15}H_{20}O_3$ m/e 248.141 997, found m/e 248.141 230, m/e (relative intensity) 249 (5), 248 (16), 177 (81), 164 (60), 149 (24), 121 (51), 107 (30), 105 (28), 99 (39), 93 (25), 91 (38), 86 (25), 84 (52), 79 (74), 77 (31), 71 (66), 67 (60), 52 (21), 55 (54), 53 (28), 45 (25), 43 (100), 41 (44), 39 (99).

10,10-(Ethylenedioxy)-*exo*-7-vinyl-*endo*-7-[(allyloxy)methyl]bicyclo[4.3.1]dec-3-en-9-one (11d). A suspension of 1.38 g (7.24 mmol) of purified cuprous iodide and 25 mL of anhydrous THF in an oven-dried, argon-purged, 100-mL round-bottomed flask was cooled to −5 °C, and 13.16 mL (14.48 mmol) of vinyl magnesium bromide (1.1 M in ether) was added. The black suspension was stirred at −5 °C for 3 min and then rapidly cooled to −70 °C. To this was added 200 mg (0.72 mmol) of ketal **9d**. The suspension was stirred at −70 °C for 1 h, slowly warmed to 0 °C, and rapidly quenched by being poured into 100 mL of saturated aqueous ammonium chloride solution. The aqueous solution was extracted five times with 50-mL portions of methylene chloride. The organic extracts were combined, washed (brine, saturated aqueous ammonium chloride, and brine), dried over magnesium sulfate, concentrated, and chromatographed on silica gel (eluting with ether) to yield 220 mg (100% yield) of **11d** as a pale yellow oil: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.53–3.02 (m, 8 H), 3.12 and 3.45 (2 d, J = 9 Hz, 2 H, CH_2O), 3.83–4.16 (m, 6 H), 4.80–5.70 (m, 2 H, allyl $=CH_2$), 4.89 (d, J = 2.5 Hz, 1 H), 5.04 (d, J = 4.5 Hz), 5.75–6.18 (m, 3 H), and 6.15 (dd, J = 17 and 11 Hz, 1 H, vinyl CH=); ^{13}C NMR δ 27.4 and 27.6 (C-2 and C-5), 43.8 (C-6), 44.9 (C-7), 47.6 (C-8), 57.0 (C-1), 63.9 and 64.2 (ketal methylenes), 72.2 ($OCH_2CH=$), 75.5 (CH_2O), 109.8 ($=CH_2$ of vinyl), 112.8 (C-10), 116.9 ($=CH_2$ of allyloxy), 129.0 and 129.2 (C-3 and C-4), 134.4 (CH= of allyloxy), 147.1 (CH= of vinyl), 210.1 (C-9); IR (film) 1720 cm^{-1} (C=O); mass spectrum, calcd for $C_{28}H_{24}O_4$ m/e 304.167 440, found m/e 304.166 625, m/e (relative intensity) 304 (7), 278 (20), 277 (99), 233 (55), 151 (22), 149 (26), 113 (60), 105 (20), 99 (58), 91 (36), 86 (22), 79 (34), 77 (26), 73 (28), 67 (30), 55 (30), 41 (100), 39 (32).

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Registry No. 4a, 668-46-2; **4b** (isomer 1), 75933-33-4; **4b** (isomer 2), 75933-34-5; **4c**, 75933-35-6; **4d**, 75933-36-7; **5a**, 75933-37-8; **5b**, 75933-38-9; **5c**, 75933-39-0; **5d**, 75933-40-3; **5e** (isomer 1), 75933-41-4; **5e** (isomer 2), 75933-42-5; **6a**, 75933-43-6; **6b**, 75933-44-7; **6c**, 75933-45-8; **6d**, 75933-46-9; **7a**, 75933-47-0; **7b**, 75933-48-1; **7c**, 75933-49-2; **7d**, 75933-50-5; **7e**, 75933-51-6; **8a**, 75933-52-7; **8b**, 75933-53-8; **8d**, 75933-54-9; **9a**, 75933-55-0; **9b**, 75933-56-1; **9d**, 75933-55-0; **10a**, 75933-57-2; **10b**, 75933-58-3; **10d**, 75933-59-4; **11a**, 75933-60-7; **11b**, 75933-61-8; **11d**, 75933-62-9; **12**, 75933-63-0; **13**, 75933-64-1; methyl 4-methoxycrotonate, 59424-95-2; methyl 4-bromocrotonate, 1117-71-1; 4-methoxycrotonic acid, 75933-65-2; 4-methoxycrotonoyl chloride, 61882-45-9; methyl 4-(allyloxy)crotonate, 75933-66-3; 4-(allyloxy)crotonic acid, 75933-67-4; 4-(allyloxy)crotonyl chloride, 75933-68-5; methyl 4-phenoxycrotonate, 75933-69-6; phenol, 108-95-2; 4-phenoxycrotonic acid, 75933-70-9; 4-phenoxycrotonyl chloride, 75933-71-0; *N*-(1,4-cycloheptadien-1-yl)morpholine, 75933-72-1; 4-cycloheptenone, 1121-64-8; morpholine, 110-91-8; *N*-(1-cyclohexenyl)morpholine, 670-80-4; acryloyl chloride, 814-68-6; crotonoyl chloride, 10487-71-5; butanoyl chloride, 141-75-3; vinyl bromide, 593-60-2; 3-chlorobicyclo[3.3.1]nonane-2,9-dione, 75933-73-2; 3-chloro-4-methylbicyclo[3.3.1]nonane-2,9-dione, 75948-70-8; 3-chloro-4-(methoxymethyl)bicyclo[3.3.1]nonane-2,9-dione, 75933-74-3; 3-chloro-4-(allyloxymethyl)bicyclo[3.3.1]nonane-2,9-dione, 75933-75-4; 8-chlorobicyclo[4.3.1]dec-3-ene-9,10-dione, 75948-71-9; 7-methyl-8-chlorobicyclo[4.3.1]dec-3-ene-9,10-dione, 75933-76-5; 7-(methoxymethyl)-8-chlorobicyclo[4.3.1]dec-3-ene-9,10-dione, 75948-72-0; 7-(allyloxymethyl)-8-chlorobicyclo[4.3.1]dec-3-ene-9,10-dione, 75933-77-6; *exo*-4-vinyl-*endo*-4-[(allyloxy)methyl]bicyclo[3.3.1]nonane-2,9-dione, 75933-78-7.