Studies on Intramolecular Higher-Order Cycloaddition Reactions

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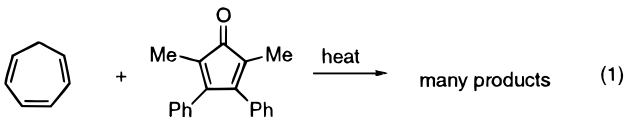
Thermal, metal-free, and metal-promoted intramolecular higher-order cycloadditions are described. Substrates in which the tropone (2,4,6-cycloheptatrien-1-one) nucleus is tethered to various diene moieties undergo exo-selective [6π + 4π] cycloaddition under thermal conditions to afford stereochemically defined tricyclic products. The substrates employed in this study were prepared by addition of the Grignard derivative of the given diene side-chain unit to 2-chlorotropone. In each instance, the requisite 2-substituted tropone was obtained directly from these reaction sequences. A similar study was conducted on the corresponding chromium(0) complexes of related tropone and cycloheptatriene-based substrates. In the cases involving metal mediation both thermal and photochemical activation were effective for delivering cycloadducts. The metal-promoted reactions were shown to proceed exclusively via an endo-selective pathway, which is stereocomplementary to the course of the thermal, metal-free reactions. A tandem Cr(0)-promoted 1,5-H shift-[6π + 2π] cycloaddition protocol is also reported with several systems.

Introduction

Cycloaddition is one of the most powerful methods available for ring construction. Convergency, high levels of stereoselectivity, and the capability of employing functionalized reaction partners are characteristics that have made the Diels−Alder cycloaddition and related processes so central to the modern practice of organic synthesis.[1]

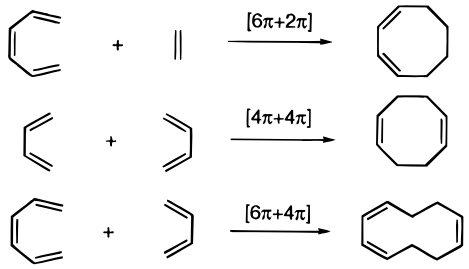
In contrast, the application of so-called higher-order cycloaddition reactions (i.e., those processes involving [6π + 4π], [4π + 4π], [4π + 3π] and [6π + 2π] combinations (Scheme 1)) to problems in organic synthesis has been of relatively limited scope, although most known examples of these transformations exhibit many of the attributes typical of the better known cycloadditions processes.[2] The ability to prepare ring systems that are otherwise difficult or impossible to make is a particularly appealing feature of higher-order cycloadditions. For example, the [6π + 4π] reaction can, in principle, provide direct access to 10-membered carbocycles, which are prominently displayed in a number of interesting and biologically significant natural product families. In spite of the many useful features of these reactions, the inability to control periselectivity during the cycloaddition event has been the principal reason for their relegation to the status of mere laboratory curiosities. A case in point is the thermal cycloaddition between cycloheptatriene and 2,5-dimethyl-3,4-diphenylcyclopentadienone, which led to at least six different cycloadducts arising from multiple, competitive pericyclic reaction channels. The [6 + 4] product was isolated in only minor quantities from this reaction.[3]



(1)

Tropone (2,4,6-cycloheptatrienone) (**1**) and its derivatives, on the other hand, have been found to be among the more effective 6π participants in higher-order cycloadditions.[4] The bicyclo[4.4.1]undecane ring system that emerges from the thermally allowed [6 + 4] cycloaddition between tropone and various simple dienes is a principal substructural feature of several classes of natural products, including the tumor-promoting ingenane diterpenes,[5] the unusual cerorubenate sesterterpenes,[6] and the marine natural product, spiniferin-1[7] (Scheme 2).

Scheme 1



The structural complexity and biological activity of these and related compounds have recently prompted a

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

(2) (a) Rigby, J. H. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, 1991; Vol. 5, pp 617−643. (b) Hosomi, A.; Tominaga, Y. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, 1991; Vol. 5, pp 593−615.

(3) Houk, K. N.; Woodward, R. B. *J. Am. Chem. Soc.* **1970**, *92* , 4143.

(4) (a) Ito, S.; Ohtani, H.; Narita, S.; Honma, H. *Tetrahedron Lett.* **1972**, 2223. (b) Garst, M. E.; Roberts, V. A.; Prussin, C. *Tetrahedron* **1983**, *39*, 581. (c) Garst, M. E.; Roberts, V. A.; Houk, K. N.; Rondan, N. G. *J. Am. Chem. Soc.* **1984**, *106*, 3882. (d) Rigby, J. H.; Cuisiat, S. V. *J. Org. Chem.* **1993**, *58*, 6286. (e) Feldman, K. S.; Wu, M.-J.; Rotella, D. P. *J. Am. Chem. Soc.* **1990**, *112*, 8490. (f) Feldman, K. S.; Come, J. H.; Kosmider, B. J.; Smith, P. M.; Rotella, D. P.; Wu, M.-J. *J. Org. Chem.* **1989**, *54*, 592. (g) Feldman, K. S.; Wu, M.-J.; Rotella, D. P. *J. Am. Chem. Soc.* **1989**, *111*, 6457. (h) Feldman, K. S.; Come, J. H.; Freyer, A. J.; Kosmider, B. J.; Smith, C. M. *Ibid.* **1986**, *108*, 1327.

(5) For an overview of synthetic approaches to the ingenane diterpenes, see: Rigby, J. H. In *Studies in Naural Product Synthesis*; Rahman, A.-U., Ed.; Elsevier: New York, 1993; Vol. 12 (Part H), pp 233−74.

(6) For synthetic studies on the cerorubenate system, see: (a) Paquette, L. A.; Poupart, M.-A. *J. Org. Chem.* **1993**, *58*, 4245. (b) Paquette, L. A.; Deaton, D. N.; Endo, Y.; Poupart, M.-A. *Ibid.* **1993**, *58*, 4262. (c) Paquette, L. A.; Lassalle, G. Y.; Lovely, C. J. *Ibid.* **1993**, *58*, 4254.

(7) For synthetic studies on spiniferin, see: Marshall, J. A.; Conrow, R. E. *J. Am. Chem. Soc.* **1983**, *105*, 5679.

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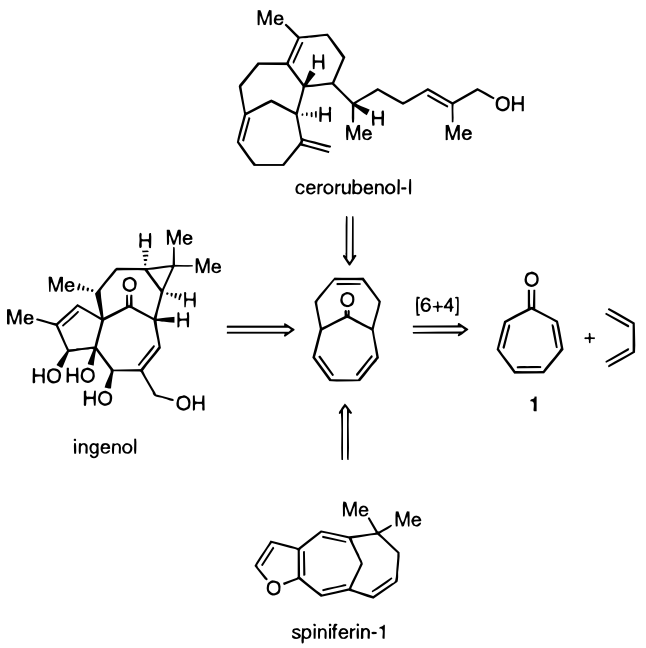
Scheme 2

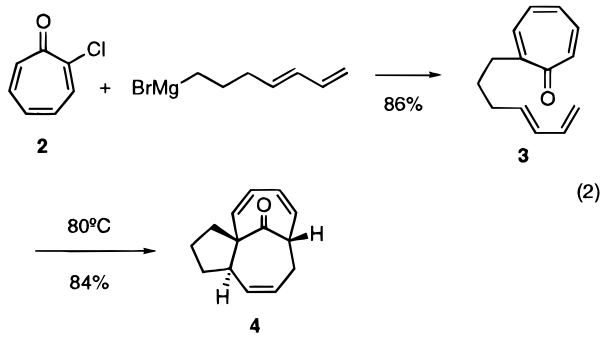


reexamination of higher-order cycloaddition as a synthetic tool. For instance, the successful application of the tropone−diene [6 + 4] cycloaddition to the construction of advanced ingenane intermediates has been reported,[8,9] and in connection with some of these studies, assembly of a very advanced tetracyclic intermediate in the 8-iso-ingenol series has been disclosed, employing this cycloaddition process as the key strategy-level transformation.[4d] It was during the course of this particular study that the periselectivity issue in higher-order cycloadditions became a critical obstacle to synthetic progress, and the intervention of transition metals for controlling these reactions was developed.[10] In this paper, we describe extended studies on intramolecular cycloadditions employing either thermal, metal-free, or metal-mediated conditions.

Intramolecular Thermal, Metal-Free Cycloadditions

Since the intramolecular version of the higher-order cycloaddition process is potentially useful for the rapid assembly of polycyclic systems such as those found in the ingenanes, particular emphasis has been placed on studying substrates in which the 6π and 4π reaction partners are connected by a three-carbon tether.[8,9,11]

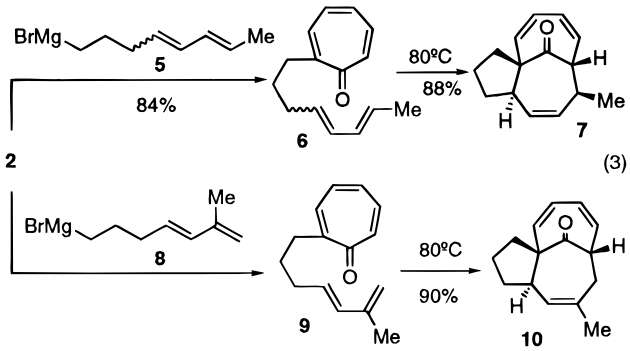
The requisite substrates for cycloaddition studies in the thermal, metal-free tropone series were prepared by addition of the diene-containing side-chain moiety to 2-chlorotropone (**2**)[12a] using a procedure originated by Doering.[12b] Thus, substituted tropone **3** was prepared in good yield by addition of the Grignard reagent derived from 1-bromohepta-4(*E*),6-diene[13] to compound **2** (eq 2).



(2)

This convenient procedure involves an addition−elimination process that regenerates the requisite tropone oxidation level directly. Recently, Funk and co-workers have disclosed another approach into these systems.[9] The desired cycloaddition was achieved by heating a solution of **3** in benzene at reflux for 12 h, affording a single exo-cycloadduct in 84% yield. The exo stereoselectivity exhibited by this reaction is typical of virtually all thermal [6 + 4] cycloadditions of cyclic trienes that have been studied to date.[2a,14]

Tricycles **7** and **10** could also be accessed in diastereomerically homogeneous form and in good yield through intramolecular cycloaddition (eq 3). One of the key



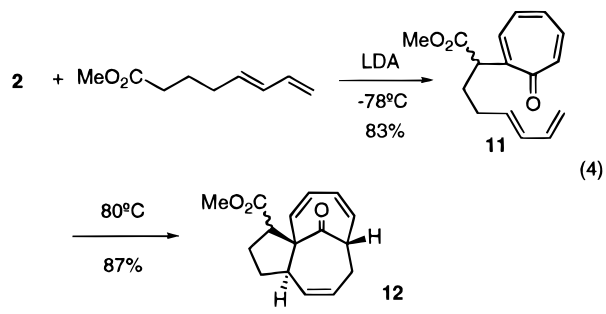
(3)

features of this methodology is that the preparation of all of the cycloaddition precursors is straightforward using well-defined and convenient chemistry. For example, the diene side-chain unit **5** was prepared by treating 4-bromobutanal[15] with the ylide derived from crotyltriphenylphosphonium bromide,[16] which resulted in an inseparable mixture of *E*,*E* and *E*,*Z* isomers. Addition of the corresponding magnesium bromide derivative **5** to compound **2** afforded **6** in good yield as a mixture of diene isomers. Heating this substrate under standard conditions gave the tricycle **7** as a single diastereomer in 88% yield based on recovered starting material. It is noteworthy that virtually all of the unreacted material consisted of the *E*,*Z* isomer. This result is consistent with previous observations from our laboratory in which *Z*-dienes were reluctant to cycloadd to tropone under normal conditions. The stereochemical course of this reaction was consistent with previous reports; however, surprisingly mild conditions were sufficient for effecting this particular transformation in our hands. In a closely related example, cycloaddition of **9** proceeded smoothly under similar conditions to deliver exclusively the exo-

(8) Rigby, J. H.; Moore, T. L.; Rege, S. *J. Org. Chem.* **1986**, *51*, 2398.
(9) Funk, R. L.; Bolton, G. L. *J. Am. Chem. Soc.* **1986**, *108*, 4655.
(10) Rigby, J. H. *Acc. Chem. Res.* **1993**, *26*, 579.
(11) For a more recent entry into this ring system via a [4 + 3] cycloaddition, see: Harmata, M.; Elahmad, S.; Barnes, C. L. *Tetrahedron Lett.* **1995**, *36*, 1397.
(12) (a) Ter Borg, A. P.; Van Helden, R.; Bickel, A. F. *Recl. Trav. Chim., Pays-Bas* **1962**, *81*, 177. (b) Doering, W. v. E.; Hiskey, C. F. *J. Am. Chem. Soc.* **1952**, *74*, 5688.
(13) Roush, W. R.; Gillis, H. R.; Ko, A. I. *J. Am. Chem. Soc.* **1982**, *104*, 2269.
(14) Hoffmann, R.; Woodward, R. B. *J. Am. Chem. Soc.* **1965**, *87*, 4388.
(15) Starr, D.; Hixon, R. M. *Organic Syntheses*; Wiley: New York, 1957; Collect. Vol. II, p 566.
(16) House, H. O.; Cronin, T. H. *J. Org. Chem.* **1965**, *30*, 1061.

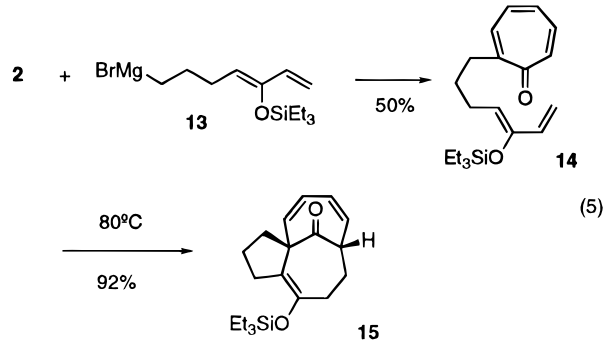
adduct **10** as a single isomer. In this case, the bromo precursor to the Grignard reagent **8** used in the preparation of **9** was easily prepared by adding methallyltriphenylphosphorane[17] to 4-bromobutanal.

More functionalized diene species can also be incorporated into the cycloaddition substrate via this addition−elimination protocol. It is known, for example, that enolates of esters and ketones are excellent participants in these addition reactions,[18] and the lithium enolate of methyl octa-5(*E*),7-dienoate[19] afforded the corresponding tropone **11** in 83% yield by this route (eq 4). Thermal



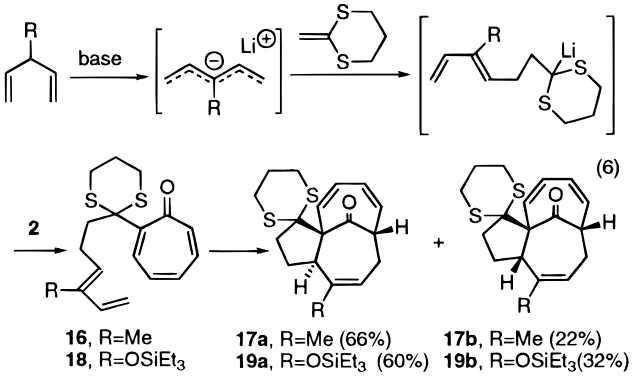
cycloaddition of this species proceeded normally, resulting in the formation of tricycle **12** as a single diastereomer of undetermined stereochemistry at the methoxycarbonyl substituent in good yield. Equilibration to the preferred configuration at this position must have occurred under the conditions of the reaction.

The diene component in these cycloadditions can also accommodate considerable functionalization. For example, treatment of **2** with Grignard reagent **13** gave adduct **14** in 50% yield, and heating this material under standard conditions afforded cycloadduct **15** in excellent yield (eq 5). Interestingly, the enol silyl ether double



bond appears to have equilibrated toward the bridgehead position during this reaction as evidenced by the absence of an appropriate vinyl proton signal in the ^{1}H NMR spectrum. The ^{13}C NMR spectrum, however, clearly revealed the presence of the relocated alkene.

Functionally rich diene units can also be introduced onto the tropone nucleus by employing a novel sequence involving addition of a pentadienyl anion to an appropriate ketene dithioacetal, followed by trapping of the resultant dithioacetal anion with 2-chlorotropone. Thus, metalation of 3-methyl-1,4-pentadiene with *n*-butyllithium afforded the known pentadienyllithium,[20] which underwent smooth addition to 2-methylene-1,3-dithiane (eq 6).[21] Subsequent addition of 2-chlorotropone to this



reaction mixture provided adduct **16**. This somewhat labile material was not purified but was immediately dissolved in benzene and heated to reflux to afford the expected cycloadduct **17a** along with a second product in a ratio of 3:1, respectively. The overall yield for this reaction was a quite respectable 88%. The spectral data for the minor product of this reaction closely resembled the data exhibited by compound **17a**, and extensive ^{1}H-homonuclear decoupling studies revealed that the same connectivity pattern existed in **17b** as in **17a**. On the basis of these observations as well as the presence of a saturated cycloheptanone ($\nu = 1706$ cm^{-1}), the structure of this compound has been assigned as **17b**. It is particularly noteworthy that this product is derived from the very rare endo reaction channel.[2] Molecular models quite clearly indicate the development of some unfavorable steric interactions between the diene system and the 1,3-dithiane moiety in the normally favored exo-transition state, which is presumably sufficient to influence the stereochemical course of the reaction. Recently, a number of reports have described cycloaddition reactions where steric affects appear to be altering normal diastereoselectivity patterns.[22] Other possible pericyclic pathways that are available to the tropone nucleus, such as a [4 + 2] cycloaddition process, have been excluded on the basis of the absence of the requisite α,β-unsaturated cycloheptanone system in the minor product, **17b**. A similar pattern of reactivity was also noted in the cycloaddition of **18**, which was prepared by sequential addition of [3-[(triethylsilyl)oxy]pentadienyl]lithium[23] to 2-methylene-1,3-dithiane followed by reaction with 2-chlorotropone. In this case, a 2:1 mixture of *exo*-**19a** and *endo*-**19b** adducts were produced. The larger percentage of endo product in this case possibly reflects an enhanced destabilizing influence of the large (triethylsilyl)oxy-grouping on the exo-transition state. Further support for the structural assignments made in this series was obtained when hydrolysis of the TES enol ether of **19b**

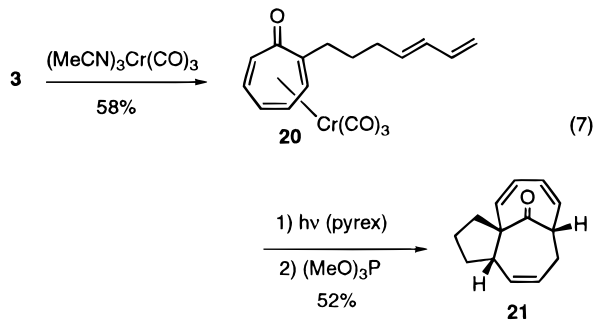
(17) Wolinsky, J.; Chollar, B.; Baird, M. D. *J. Am. Chem. Soc.* **1962**, *84*, 2775.
(18) Rigby, J. H.; Senanayake, C. H.; Rege, S. *J. Org. Chem.* **1988**, *53*, 4596.
(19) Watanabe, Y.; Iida, H.; Kibayashi, C. *J. Org. Chem.* **1989**, *54*, 4088.
(20) (a) Stewart, C. A., Jr. *J. Org. Chem.* **1963**, *28*, 3320. (b) Montgomery, L. K.; Schueller, K.; Bartlett, P. D. *J. Am. Chem. Soc.* **1964**, *86*, 622.
(21) Seebach, D.; Bürstinghaus, R.; Gröbel, B.-T.; Kolb, M. *Liebigs Ann. Chem.* **1977**, 830.
(22) (a) Anderson, B. A.; Wulff, W. D.; Powers, T. S.; Tribbitt, S.; Rheingold, A. L. *J. Am. Chem. Soc.* **1992**, *114*, 10784. (b) Gilbertson, S. R.; Zhao, X.; Dawson, D. P.; Marshall, K. L. *Ibid.* **1993**, *115*, 8517. (c) Wright, M. W.; Smalley, T. L.; Welker, M. E.; Rheingold, A. L. *Ibid.* **1994**, *116*, 6777. (d) Barluenga, J.; Canteli, R.-M.; Florez, J.; Garcia-Granda, S.; Gutierrez-Rodriguez, A. *Ibid.* **1994**, *116*, 6949.
(23) (a) Oppolzer, W.; Snowden, R. L. *Tetrahedron Lett.* **1976**, 4187. (b) Oppolzer, W.; Snowden, R. L. *Ibid.* **1978**, 3505.

revealed the presence of a second saturated cycloheptanone carbonyl group.

It is clear from the examples described above that intramolecular higher-order cycloaddition is a powerful method for the rapid buildup of molecular complexity. Furthermore, tethering the 4π and 6π components together is an effective ploy for controlling periselectivity in these processes. This feature of these reactions becomes evident when the efficiencies of the above transformations are compared with those of the corresponding intermolecular tropone cycloadditions.[4a−d]

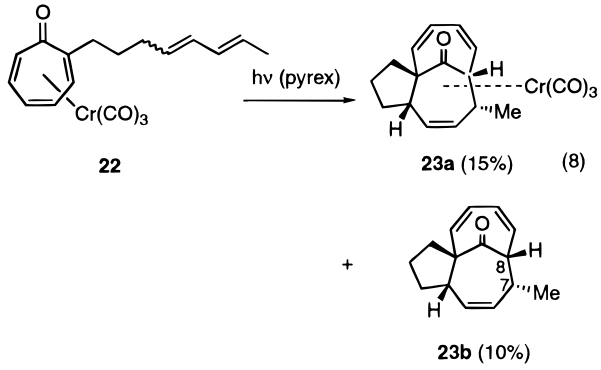
Intramolecular Metal-Promoted Cycloadditions

As alluded to earlier in this paper, transition metal intervention in the higher-order cycloaddition process was pursued as a tactic for enhancing periselectivity in intermolecular cases. For example, group 6 (Cr, Mo) metals have been shown to have a positive influence on the yields of higher-order cycloaddition reactions.[10,24] Extension of this methodology to include intramolecular cycloadditions would be an attractive complement to the thermal, metal-free variants presented above, since access to polycyclic systems with different structural and stereochemical features could be obtained by virtue of the endo nature of the metal-promoted process.[25]



Once again, preparation of the requisite substrates for these cycloadditions is experimentally convenient. Exposure of tropone **3**, prepared previously, to $(MeCN)_3Cr(CO)_3$ provided the somewhat labile η^6 complex **20** in 58% yield. Irradiation (Pyrex) of this material led to the adduct **21** in 52% yield after decomplexation with $(MeO)_3P$. The stereochemical course of this transformation was confirmed by comparison with the known exo-adduct **4**. The relatively modest efficiency of this sequence is probably reflective of the lability of tropone−chromium(0) complexes.[24,26] The stereocomplementarity of the thermal-metal free (exo) and the photochemical, metal-mediated (endo) processes is a particularly significant feature of these reactions.

Photocycloaddition of complex **22** (prepared from **6**) was less effective, affording only low yields of [6 + 4] adducts **23a** and **23b**. The bulk of the reaction mixture in this case consisted of decomplexed tropone **6** and recovered **22** that was enriched in the *Z*-diene isomer. Another unusual feature of this reaction was the direct isolation of decomplexed cycloadduct **23b**. Normally, a separate step is required to demetalate [6 + 4] adducts.[24] The stereochemical course of this reaction was supported by the presence of the characteristic H-7, H-8 coupling constant of 2.1 Hz, which can be contrasted with the 10.5 Hz coupling constant seen in the corresponding exo-isomer **7**. Once again, the low yields are presumably a consequence of the lability of the starting complex, a situation that is exacerbated by the increased steric demands placed on the reaction by the presence of a methyl substituent on the terminal carbon of the diene. In contrast to this observation, it has been noted previously that in most instances steric hindrance at bond-forming sites inhibits thermal, metal-free [6 + 4] cycloaddition to a much greater extent than it influences metal-mediated reactions.[24] Comparing the results depicted in eq 3 with those in eq 8 reveals an interesting exception to this trend.



Extending this intramolecular study to include the cycloheptatriene series involved additional substrate manipulation to set the stage for executing the desired photocycloadditions. However, on the basis of experience gained during the intermolecular studies, it was anticipated that these species would be better behaved than tropone-based ligands under metal promotion.

The initial steps for substrate construction in the hydrocarbon series have some parallels in the tropone work; however, a second operation to isomerize the triene moiety is required prior to the cycloaddition event. Thus, addition of the Grignard reagent of 1-bromohepta-4,6-diene[13] to tricarbonyl(tropylium)chromium(0) tetrafluoroborate (**24**)[27] afforded exo-adduct **25**, which was then rearranged thermally to give the requisite 1-substituted isomer in 50% yield along with lesser quantities of the other triene isomers. While this transformation can be accomplished in the absence of the metal, complexation with Cr(0) is known to facilitate the 1,5-sigmatropy of the 7-endo proton in cycloheptatrienes.[28] With compound **26** now in hand, irradiation under standard conditions followed by decomplexation afforded endo-cycloadduct **27** in 85% yield.

It was known from previous work in our laboratory that thermal activation was also an effective method for executing metal-promoted cycloaddition reactions.[24a] Consequently, a one-pot tandem Cr(0)-promoted 1,5-H-shift-[6 + 4] cycloaddition process could be envisioned as, perhaps, the most efficient means for carrying out these transformations. It was evident from the results with substrate **26** that the addition of the side chain to the

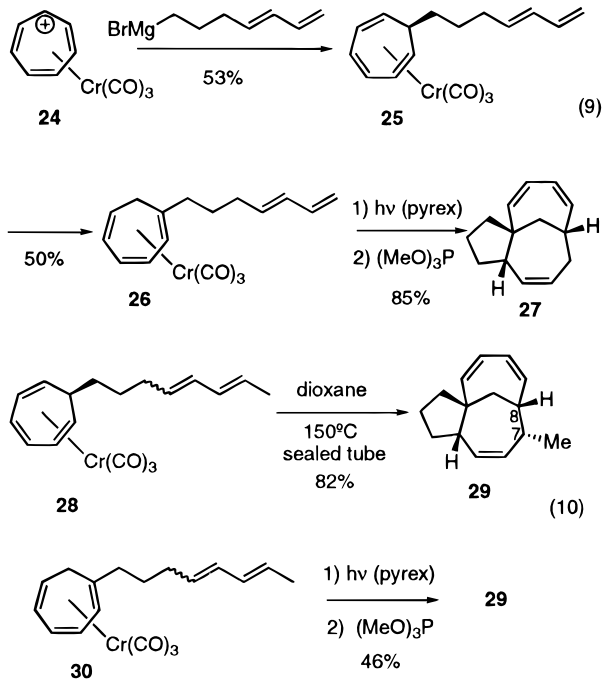
(24) (a) Rigby, J. H.; Ateeq, H. S.; Charles, N. R.; Cuisiat, S. V.; Ferguson, M. D.; Henshilwood, J. A.; Krueger, A. C.; Ogbu, C. O.; Short, K. M.; Heeg, M. J. *J. Am. Chem. Soc.* **1993**, *115*, 1382. (b) Rigby, J. H.; Ateeq, H. S.; Charles, N. R.; Henshilwood, J. A.; Short, K. M.; Sugathapala, P. M. *Tetrahedron* **1993**, *49*, 5495.

(25) For a preliminary account of part of this work, see: Rigby, J. H.; Sandanayaka, V. P. *Tetrahedron Lett.* **1993**, *34*, 935.

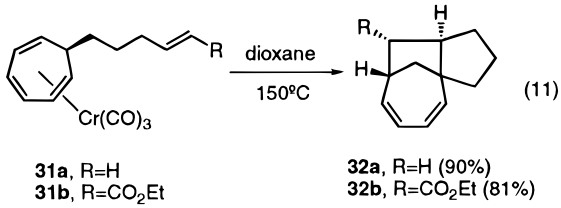
(26) Pauson, P. L.; Todd, K. H. *J. Chem. Soc. C* **1970**, 2315.

(27) Munro, J. D.; Pauson, P. L. *J. Chem. Soc. Z* ***1961***, 3475.

(28) (a) Foreman, M. I.; Knox, G. R.; Pauson, P. L.; Todd, K. H.; Watts, W. E. *J. Chem. Soc., Perkin Trans. 2* **1972**, 1141. (b) Roth, W. R.; Grimme, W. *Tetrahedron Lett.* **1966**, 2347.



tropylium cation complex was a routine operation and that problems arose primarily during the subsequent isomerization step, which was of only modest efficiency. A principal virtue of the tandem reaction concept would be to avoid the isomerization as a separate step in the preparative sequence. In the event, heating readily available exo-complex **28** in dioxane at 150 °C in a sealed tube provided adduct **29** in 82% yield! The H-7, H-8 coupling constant in this compound supported assignment of the endo-stereochemistry. To confirm that the product of thermal activation was indeed identical to the corresponding photocycloadduct, 1-substituted complex **30**, prepared in the same fashion as **26**, was photolyzed under standard conditions to afford **29** in 46% yield. Both products were found to be identical in all regards.



Cycloadditions involving the combination of a 6π partner with a 2π reactant have been reported previously in several contexts,[4f−h,24b] and it was assumed that the intramolecular, metal-promoted cycloaddition protocol could be extended to include these reactions as well.[25] Exo-substituted complex **31a**, prepared as above, when heated for several hours at 150 °C in a sealed tube underwent a smooth tandem 1,5-H-shift-[6+2] cycloaddition to give the anticipated cycloadduct **32a** in 90% yield based on recovered starting material. The structure and stereochemistry of this adduct were confirmed by comparison with a known material prepared in a different fashion.[25] The same procedure can be employed on complexes possessing more functionalized side chains as evidenced by the clean, stereoselective cycloaddition of complex **31b** to give tricycle **32b** in 81% yield. This complex, which proved to be unusually stable, was prepared in good yield by addition of the Zn−Cu derivative[29] of ethyl 6-iodo-2-hexenoate[30] to tricarbonyl(tropylium)chromium(0) tetrafluoroborate. The product of this cycloaddition (**32b**) is being examined as a possible precursor for natural product synthesis.

In summary, the results described above demonstrate that intramolecular higher-order cycloadditions can be controlled so as to effectively deliver structurally elaborate polycyclic systems with attendant high levels of predictable periselectivity and stereoselectivity.

Applications of some of this methodology to natural product synthesis is currently underway in our laboratory.

Experimental Section[31]

2-[Hepta-4(*E*),6-dienyl]-2,4,6-cycloheptatrien-1-one (3). To a suspension of magnesium turnings (558 mg, 23 mmol) in dry THF (20 mL) were added one crystal of iodine, ca. 0.6 mL of 1,2-dibromoethane, and several drops of a solution of 1-bromohepta-4,6-diene (3.63 g, 20.6 mmol) in dry THF (5 mL). The stirred mixture was gently warmed with a heat gun to initiate the reaction. As the reaction proceeded, the solution of the bromo diene was added in small portions. After the addition was complete, the mixture was stirred at room temperature for an additional 2 h. The reaction mixture was then cooled to −20 °C, and a solution of 2-chlorotropone (1.79 g, 1.27 mmol) in dry THF (5 mL) was added dropwise. The reaction was stirred for a few minutes and then quenched with saturated aqueous ammonium chloride solution. The aqueous layer was extracted with methylene chloride, and the organic layer was washed with saturated aqueous sodium bicarbonate solution and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and flash chromatography (silica gel, ether/hexanes, 30:70) of the residue gave 2.2 gm (86%) of the product: IR (CCl_4) ν 2930, 1655, 1629, 1582 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.68 (quin, J = 7.6 Hz, 2H), 2.17 (q, J = 7.2 Hz, 2H), 2.65 (t, J = 7.4 Hz, 2H), 5.00 (dd, J = 16.8, 25.2 Hz, 2H), 5.71 (m, 1H), 6.07 (m, 1H), 6.32 (m, 1H), 6.88−7.23 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 28.3, 32.5, 35.3, 115.0, 131.6, 132.7, 133.9, 134.7, 134.9, 135.4, 137.3, 140.5, 155.8, 187.1; LRMS *m/e* 200 (12); HRMS calcd for $C_{14}H_{16}O$ 200.1201, found 200.1208. Anal. Calcd for $C_{14}H_{16}O$: C, 83.94; H, 8.05. Found: C, 83.95; H, 8.06.

1,2,3,8,9,11a-Hexahydro-3a,8-methano-3a*H*-cyclopentacyclodecen-12-one (4). Compound **3** (200 mg, 1 mmol) was heated under reflux in benzene (4 mL) for 12 h at 80 °C under N_2 atmosphere. The solvent was evaporated under reduced pressure and the residue purified by flash chromatography (silica gel, ether/petroleum ether, 20:80), yielding 168 mg (84%) of **4**: IR (CCl_4) ν 2959, 1704, 1695, 1450, 1171 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.43−1.88 (m, 4H), 1.94 (m, 1H), 2.23−2.46 (m, 2H), 2.67 (m, 1H), 2.88 (m, 1H), 3.49 (q, J = 6.5 Hz, 1H), 5.41−6.05 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 23.8, 28.6, 34.9, 35.0, 47.2, 56.0, 66.2, 123.4, 126.4, 127.7, 130.3, 135.8, 137.9, 204.6; LRMS *m/e* 200 (5), 157 (8), 134 (58), 120 (100); HRMS calcd for $C_{14}H_{16}O$ 200.1201, found 200.1206. Anal. Calcd for $C_{14}H_{16}O$: C, 83.94; H, 8.05. Found: C, 83.97; H, 8.04.

2-(4,6-Octadienyl)-2,4,6-cycloheptatrien-1-one (6). To a suspension of magnesium (144 mg, 6 mmol) in dry THF (10 mL) was added a small amount of a solution of 1-bromo-4,6-octadiene (1.0 g, 5.2 mmol) in dry THF (5 mL). A few drops of dibromoethane were added to this solution to activate the magnesium, and the flask was then warmed to initiate the reaction. The remainder of the bromo diene in THF was added dropwise to the resultant mixture, and the reaction was stirred at room temperature for 2 h. At this time, the reaction was cooled to −20 °C, and a solution of 2-chlorotropone (351 mg, 2.5 mmol) in dry THF (2 mL) was added dropwise. The

(29) Yeh, M.-C. P.; Sheu, B.-A.; Fu, H.-W.; Tau, S.-I.; Chuang, L.-W. *J. Am. Chem. Soc.* **1993**, *115*, 5941.
(30) Cooke, M. P., Jr.; Parlman, R. M. *J. Am. Chem. Soc.* **1977**, *99*, 5222.
(31) For general experimental information, consult ref 24a.

reaction was stirred at −20 °C for a few minutes and was then quenched with saturated aqueous ammonium chloride solution. The organic phase was separated, and the aqueous layer was extracted with methylene chloride (3 × 10 mL). The combined organic layers were washed with saturated aqueous sodium bicarbonate solution and dried over anhydrous sodium sulfate, and the solvent was removed under reduced pressure. The crude material was purified by chromatography (silica gel, petroleum ether/ether, 70:30), affording 450 mg (84%) of adduct isolated as an inseparable *E*/*Z* mixture: IR (CCl_4) ν 2957, 1655, 1630, 1584 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.59−1.85 (m, 5H), 2.18 (q, J = 6.9 Hz, 1H), 2.65 (q, J = 8.1 Hz, 1H), 2.05(q, J = 7 Hz, 1H), 5.28 (m, 1H), 5.52−5.71 (m, 1H), 5.99 (m, 1H), 6.27 (m, 1H), 6.89−7.28 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 17.8, 18.2, 27.4, 28.4, 28.7, 32.3, 35.0, 126.8, 128.9, 129.1, 129.3, 130.7, 131.2, 131.5, 132.4, 133.7, 134.8, 134.9, 135.2, 140.2, 186.8; LRMS *m*/*e* 214 (1), 185 (4), 171 (10); HRMS calcd for $C_{15}H_{18}O$ 214.1357, found 214.1358.

1,2,3,8,9,11a-Hexahydro-3a,8-methano-9*β*-methyl-3a*H*-cyclopentacyclodecen-12-one (7). A solution of compound **6** (155 mg, 0.72 mmol) was heated under reflux in benzene (3 mL) for 24 h. The flask was cooled to room temperature and the solvent removed under vacuum. Flash chromatography (silica gel; petroleum ether/ether, 70:30) afforded 89 mg (88%) of the cycloadduct based on recovery of 54 mg of starting material that was greatly enriched in the *E*,*Z* isomer: IR (CCl_4) ν 3014, 2961, 2872, 1704, 1454, 1375, 1305, 1262 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.10 (d, J = 6.5 Hz, 3H), 1.50−1.58 (m, 1H), 1.60−1.72 (m, 2H), 1.79−1.88 (m, 1H), 1.95−2.06 (m, 1H), 2.54 (dd, J = 3.7, 4.0 Hz, 1H), 2.79 (m, 1H), 3.14 (m, 2H), 5.34−5.47 (m, 2H), 5.49 (d, J = 11 Hz, 1H), 5.73−6.00 (m, 3H); ^{13}C NMR ($CDCl_3$) δ 20.0, 24.8, 31.2, 35.3, 35.4, 49.7, 64.3, 64.8, 121.5, 126.6, 133.1, 136.1, 138.6, 208.2; LRMS *m*/*e* 214 (10), 185 (3), 184 (2), 171 (8); HRMS calcd for $C_{15}H_{18}O$ 214.1357, found 214.1357. Anal. Calcd for $C_{15}H_{18}O$: C, 84.06; H, 8.47. Found: C, 84.06; H, 8.48.

2-[6-Methylhepta-4(*E*),6-dienyl]-2,4,6-cycloheptatrien-1-one (9). To a flame-dried two-necked flask was added Mg foil (12.5 mmol, 300 mg), dry THF (25 mL), and a few drops of 1,2-dibromoethane. A solution of 1-bromo-6-methylhepta-4(*E*),6-diene (1.13 g, 6.3 mmol) in dry THF (5 mL) was added dropwise. The reaction was stirred at room temperature until all of the magnesium had reacted (approximately 2 h). The flask was then cooled to −20 °C, and a solution of 2-chlorotropone (2.7 mmol, 380 mg) in dry THF (3 mL) was added dropwise. The resultant mixture was stirred at −20 °C for a few minutes and then quenched with saturated aqueous ammonium chloride solution. The organic layer was separated, and the aqueous layer was extracted with methylene chloride. The combined organic layers were washed with saturated aqueous sodium bicarbonate solution and dried over anhydrous sodium sulfate and the solvent removed under reduced pressure. The crude material was purified by chromatography (silica gel, hexanes/ether, 70:30), yielding 380 mg (66%) of **9**: IR (CCl_4) ν 2935, 1659, 1629, 1580 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.70 (quin, J = 6.0 Hz, 2H), 1.84 (s, 3H), 2.19 (q, J = 7 Hz, 2H), 2.65 (t, J = 6.2 Hz, 2H), 4.87 (m, 2H), 5.59 (m, 1H), 6.20 (d, J = 15 Hz, 1H), 6.87−7.30 (m, 5H); ^{13}C NMR ($CDCl_3$) 18.7, 28.3, 32.5, 35.3, 114.2, 130.2, 131.6, 132.7, 133.8, 134.8, 135.3, 140.7, 142.2, 155.9, 187.2; LRMS *m*/*e* 214(3), 171 (5), 134 (45); HRMS calcd for $C_{15}H_{18}O$ 214.1357, found 214.1357.

1,2,3,8,9,11a-Hexahydro-3a,8-methano-10-methyl-3a*H*-cyclopentacyclodecen-12-one (10). A solution of compound **9** (125 mg, 0.58 mmol) in benzene (5 mL) was heated at reflux for 12 h. The reaction mixture was cooled and the solvent removed under reduced pressure. Flash chromatography (silica gel, hexanes/ether, 70:30) gave 112 mg (90%) of compound **10**: IR (CCl_4) ν 2958, 2877, 1704, 1589, 1446, 1373, 1264, 1048 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.42−1.59 (m, 1H), 1.60−1.83 (m, 6H), 1.90−2.06 (m, 2H), 2.39−2.51 (m, 1H), 2.78−2.87 (m, 2H), 3.37−3.45 (m, 1H), 5.13 (t, J = 1.4 Hz, 1H), 5.47 (d, J = 11 Hz, 1H), 5.73 (dd, J = 3.1, 7.4 Hz, 1H), 5.87 (dd, J = 6.2, 11.3 Hz, 1H), 5.98 (dd, J = 6.2, 10.6 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 24.2, 24.8, 32.6, 34.6, 35.3, 47.8, 55.1, 65.1, 121.7, 126.1, 129.2, 129.4, 136.5, 137.7, 205.1; LRMS *m*/*e* 214 (12), 171 (8), 134 (44), 178 (100); HRMS calcd for $C_{15}H_{18}O$ 214.1357, found 214.1354. Anal. Calcd for $C_{15}H_{18}O$: C, 84.06; H, 8.47. Found: C, 84.08; H, 8.49.

2-[1-Carbomethoxyhepta-4(*E*),6-dienyl]-2,4,6-cycloheptatrien-1-one (11). A flamed-dried two-necked flask was charged with freshly distilled diisopropylamine (2.5 mmol, 0.35 mL) and dry THF (4 mL). The solution was cooled to 0 °C, and *n*-BuLi (2.5 M, 2.5 mmol, 1 mL) was added dropwise. The reaction was stirred at 0 °C for 10 min, the temperature was lowered to −78 °C, and a solution of methyl octa-5(*E*),7-dienoate (2.2 mmol, 338 mg) in dry THF (1 mL) was added. The reaction mixture was stirred for 45 min at −78 °C, and then a solution of 2-chlorotropone (2.0 mmol, 280 mg) in THF (1 mL) was slowly added. The reaction was stirred at −78 °C for a few additional minutes and then quenched with saturated aqueous ammonium chloride solution. The organic phase was separated, and the aqueous phase was extracted with ether (3 × 10 mL). The combined organic layers were dried over anhydrous sodium sulfate and concentrated under reduced pressure. Flash chromatography (silica gel, hexanes/ether, 70:30) gave 430 mg (83%) of product: IR (CCl_4) ν 1734, 1638, 1588 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.76 (m, 1H), 2.18 (m, 3H), 2.69 (m, 2H), 3.58 (s, 3H), 6.91−7.29 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 25.8, 30.5, 30.9, 31.1, 47.9, 48.1, 115.2, 117.3, 130.1, 131.0, 132.7, 133.0, 133.4, 133.6, 135.1, 135.4, 137.0, 140.4, 151.9, 155.8, 173.7, 185.7; LRMS *m*/*e* 218 (5), 186 (30), 159 (71); HRMS calcd for $C_{16}H_{18}O_3$ 258.1255, found 258.1261.

1,2,3,8,9,11a-Hexahydro-3a,8-methano-3-carbomethoxy-3a*H*-cyclopenta-cyclodecen-12-one (12). A solution of compound **11** (0.47 mmol, 122 mg) was heated under reflux in benzene (5 mL) for 24 h. The flask was cooled to room temperature, and the solvent was removed under reduced pressure. Flash chromatography (silica gel, hexanes/ether, 70:30) afforded 107 mg (87%) of product: IR (CCl_4) 2942, 1732, 1706, 1442, 1370, 1105 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.47 (m, 1H), 2.00−2.16 (m, 4H), 2.74−2.93 (m, 2H), 3.52 (s, 3H), 3.54−3.61 (m, 1H), 3.91 (dd J = 8.1, 9.5 Hz, 1H), 5.42−5.53 (m, 2H), 5.71−5.82 (m, 2H), 5.97-6.04 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 25.1, 27.1, 33.2, 50.1, 50.3, 51.3, 56.9, 66.6, 123.9, 126.8, 127.9, 128.6, 134.5, 134.7, 173.5, 201.9; LRMS *m*/*e* 258 (1), 226 (29), 198 (20), 178 (10); HRMS calcd for $C_{16}H_{18}O_3$ 258.1255; found 258.1250.

2-[5-[(Triethylsilyl)oxy]hepta-4(*E*)-6-dienyl]-2,4,6-cycloheptatrien-1-one (14). A flame-dried two-neck flask was charged with magnesium turnings (7 mmol, 168 mg). To this was added freshly distilled THF (8 mL) along with a few drops of dibromoethane. A solution of 1-bromo-5-(triethylsiloxy)-4,6-heptadiene (5.0 mmol, 1.5 g) in THF (2 mL) was added dropwise over 0.5 h. The reaction was stirred at room temperature for an additional 2 h. After the disappearance of most of the magnesium turnings, the flask was cooled to −20 °C and 2-chlorotropone (2.27 mmol, 318 mg) in THF (1 mL) was added dropwise. The reaction was stirred at −20 °C for a few minutes and quenched with saturated aqueous ammonium chloride solution. The aqueous layer was extracted with methylene chloride, and the combined organic layers were washed with brine and dried over anhydrous sodium sulfate. Solvent was removed under vacuum, and the crude product was purified by flash chromatography (silica gel, petroleum ether/EtOAc, 80:20). This afforded 380 mg (50%) of product: IR (CCl_4) ν 2937, 1629, 1589 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.66 (q, J = 7.7 Hz, 6H), 0.96 (t, J = 7.8 Hz, 9H), 1.64 (q, J = 7.3 Hz, 2H), 2.16 (q, J = 7.5 Hz, 2H), 2.66 (t, J = 7.5 Hz, 2H), 4.78 (t, J = 7.1 Hz, 1H), 4.94 (dd, J = 10.6 Hz, 0.8 Hz, 1H), 6.89−6.97 (m, 2H), 7.02−7.08 (m, 2H), 7.12−7.24 (m, 1H): ^{13}C NMR ($CDCl_3$) δ 5.3, 6.7, 25.7, 28.3, 35.3, 111.5, 115.0, 132.4, 133.7, 134.9, 135.7, 140.3, 149.1, 155.6, 186.9.

1,2,3,8,9,10-Hexahydro-3a,8-methano-11-[(triethylsilyl)oxy]-3a*H*-cyclopentacyclodecen-12-one (15). A solution of **14** (280 mg, 0.84 mmol) in benzene (7 mL) was heated at reflux for 6 h. The flask was cooled, and the solvent was removed under vacuum. Flash chromatography of the residue (silica gel, hexanes/ether, 30:70) gave 258 mg (92%) of product: IR (CCl_4) δ 2957, 2877, 1702, 1669, 1460, 1302 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.64 (q, J = 7.8 Hz, 9H), 0.95 (t, J = 7.8 Hz, 9H), 1.54−1.68 (m, 2H), 1.70−1.80 (m, 2H), 2.09−2.66 (m, 6H),

3.36−3.47 (m, 1H), 5.66−5.89 (m, 2H), 5.91−6.02 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 5.8, 6.6, 20.6, 22.8, 30.6, 32.5, 36.9, 55.5, 62.2, 119.2, 122.5, 127.0, 128.2, 136.4, 146.4, 201.1. Anal. Calcd for $C_{20}H_{30}O_2Si$: C, 72.94; H, 8.81. Found: C, 72.91; H, 8.83.

3a,8-Methano-3,3-(1,3-propylenedithio)-11-methyl-1,2,8,9,11a-pentahydro-3a*H*-cyclopentacyclodeca-4,6,10-trien-12-one (17a). To a solution of 3-methyl-1,4-pentadiene (2 mmol, 164 mg) in dry THF (3 mL) at 0 °C was added *n*-butyllithium (2.5 M, 2.2 mmol, 0.88 mL). The mixture was allowed to warm to room temperature and then stirred at this temperature for 1 h. The reaction mixture was cooled to −25 °C, and a solution of 2-methylene-1,3-dithiane (2 mmol, 264 mg) in THF (1 mL) was added to the reaction. The reaction was stirred at this temperature for 1 h, and then a solution of 2-chlorotropone (1.9 mmol, 267 mg) in THF (1 mL) was added dropwise. After a few minutes, the reaction was quenched with saturated aqueous ammonium chloride solution, extracted with ether, and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure to yield 349 mg (55%) of crude product **16**: ^{1}H NMR ($CDCl_3$) δ 1.69 (s, 3H), 1.88−1.96 (m, 2H), 2.18 (q, J = 7.7 Hz, 2H), 2.53−2.67 (m, 6H), 4.90 (d, J = 10.6 Hz, 1H), 5.05 (d, J = 17.3 Hz, 1H), 5.46 (t, J = 7.2 Hz, 1H), 6.32 (dd, J = 17.34, 10.71 Hz, 1H), 6.78−7.28 (m, 4H), 7.99 (d, J = 10 Hz, 1H), which was then dissolved in benzene without further purification and heated at reflux for 32 h. The reaction flask was then cooled to room temperature, and the solvent was removed under reduced pressure. Flash chromatography (silica gel, ether/hexanes, 70:30) afforded two products.

17a: 230 mg (66%); IR (CCl_4) ν 2959, 2872, 1704, 1651, 1457, 1413, 1353, 1255, 1218 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.71 (s, 3H), 1.98−2.46 (m, 6H), 2.60−3.20 (m, 6H), 3.57 (m, 1H), 3.83 (t, J = 9.7 Hz, 1H), 5.44−5.57 (m, 3H), 5.72−5.87 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 22.4, 23.8, 25.3, 26.7, 27.6, 28.3, 39.0, 42.7, 56.8, 60.1, 124.4, 125.2, 125.5, 126.0, 128.7, 139.4, 205.2; LRMS *m/e* 318 (74), 303 (32), 211 (16), 173 (42), 171 (42); HRMS calcd for $C_{18}H_{22}OS_2$ 318.1112, found 318.1117.

17b: 77 mg (22%); IR (CCl_4) ν 2954, 1706, 1550, 1249 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.67 (s, 3H), 1.98 (quin, J = 5.8 Hz, 2H), 2.10 (quin, J = 8 Hz, 2H), 2.31 (m, 1H), 2.50 (m, 1H), 2.75 (m, 2H), 2.85−3.10 (m, 4H), 3.39 (t, J = 9.4 Hz, 1H), 3.73 (td, J = 8.6, 10.4 Hz, 1H), 5.44 (bd, J = 8.7 Hz, 1H), 5.88 (t, J = 9.6 Hz, 1H), 6.14 (d, J = 11.4, 1H), 6.23 (dd, J = 5.4, 10.1 Hz, 1H), 6.36 (dd, J = 5.3, 11.3 Hz, 1H): ^{13}C NMR ($CDCl_3$) δ 24.7, 24.9, 25.1, 27.4, 28.1, 28.5, 40.4, 52.4, 57.7, 64.5, 71.2, 122.1, 127.4, 127.6, 128.1, 136.2, 138.4, 198.9; LRMS *m/e* 318 (34), 303 (16), 173 (19), 145 (100); HRMS calcd for $C_{18}H_{22}OS_2$ 318.1112, found 318.1116.

3a,8-Methano-3,3-(1,3-propylenedithio)-11-[(triethylsilyl)oxy]-1,2,8,9,11a-pentahydro-3a*H*-cyclopentacyclodeca-4,6,10-trien-12-one (19a). A solution of s-BuLi in cyclohexane (1.3 M, 5.5 mmol, 4.23 mL) was added dropwise to a stirred solution of 3-[(triethylsilyl)oxy]-1,4-pentadiene (5.0 mmol, 980 mg) in dry THF (6 mL) at −78 °C under argon. After 30 min, a solution of 2-methylene-1,3-dithiane (5 mmol, 660 mg) in dry THF (2 mL) was added. The reaction was slowly warmed to −23 °C and stirred until all of the starting material was consumed. At this point, a solution of 2-chlorotropone (4 mmol, 562 mg) in dry THF was added dropwise to the reaction at −78 °C, and the reaction was then stirred at −78 °C for a few minutes. The reaction mixture was quenched with saturated aqueous ammonium chloride solution and extracted with methylene chloride. The organic layer was washed with water and brine and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure to give 1.03 g (59%) of product: IR (CCl_4) ν 2947, 2832, 1631, 1562 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.63 (q, J = 7.9 Hz, 6H), 0.94 (t, J = 7.8 Hz, 9H), 1.92 (m, 2H), 2.16 (q, J = 7.2 Hz, 2H), 2.63 (m, 2H), 4.67 (t, J = 6.9 Hz, 1H), 4.90 (dd, J = 10.7, 1.2 Hz, 1H), 5.25 (dd, J = 1.1, 17 Hz, 1H), 6.12 (dd, J = 10.7 Hz, 17 Hz, 1H), 6.81 (d, J = 11.7 Hz, 1H), 7.00 (m, 3H), 8.03 (d, J = 8.6 Hz, 1H). Without further purification, a portion (628 mg, 2 mmol) of this product was dissolved in benzene and heated at reflux for 12 h. The reaction flask was then cooled to room temperature, and the solvent was removed under reduced pressure. Flash chromatography (silica gel, ether/hexanes, 70:30) yielded two compounds.

19a: 379 mg (60%); IR (CCl_4) ν 2958, 2877, 1701, 1653, 1457, 1413, 1357, 1214 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.70 (q, J = 7.8 Hz, 6H), 0.97 (t, J = 7.8 Hz, 9H), 1.85−3.2 (m, 12H), 3.54 (m, 1H), 3.85 (t, J = 8.5 Hz, 1H), 4.66 (ddd, J = 8.9, 6.0, 1 Hz, 1H), 5.48 (d, J = 11 Hz, 1H), 5.52 (dd, J = 10.3, 5.5 Hz, 1H), 5.71 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 4.8, 6.7, 20.1, 25.3, 26.6, 27.5, 28.2, 38.7, 44.1, 56.9, 60.4, 100.6, 124.6, 125.8, 126.1, 128.8, 152.6, 205.1; LRMS *m/e* 434 (31), 407 (22), 406 (61), 331 (2), 327 (27), 300 (22); HRMS calcd for $C_{23}H_{34}O_2S_2Si$: 434.1769, found 434.1773.

19b: 204 mg (32%); IR (CCl_4) ν 2957, 2877, 1706, 1652, 1415, 1245 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.68 (q, J = 7.7 Hz, 6H), 0.98 (t, J = 7.7 Hz, 9H), 1.75−2.09 (m, 3H), 2.24−2.49 (m, 2H), 2.68−3.11 (m, 7H), 3.48 (dt, J = 9.4, 2 Hz, 1H), 3.71 (td, J = 11.2, 8.2 Hz, 1H), 4.90 (dd, J = 7.4, 1.7 Hz, 1H), 5.89 (t, J = 9.9 Hz, 1H), 6.12 (d, J = 11.5 Hz, 1H), 6.24 (dd, J = 10.2, 5.4 Hz, 1H), 6.34 (dd, J = 11.4, 5.4 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 5.1, 6.7, 22.6, 24.7, 27.3, 27.9, 28.1, 40.0, 51.8, 58.0, 64.7, 69.6, 103.9, 127.5, 127.8, 128.0, 135.3, 154.3, 199.2; LRMS *m/e* 434 (75), 289 (82), 287 (49); HRMS calcd for $C_{23}H_{34}O_2S_2Si$ 434.1769, found 434.1774.

Tricarbonyl[η^6-2-(hepta-4′(*E*),6′(*E*)-dienyl)-1-oxo-2,4,6-cycloheptatrienyl]chromium(0) (20). To tricarbonyl(trisacetonitrile)chromium[32] prepared from $Cr(CO)_6$ (360 mg, 1.80 mmol) was added a solution of **3** (180 mg, 0.90 mmol) in THF (15 mL) and the solution stirred for about 5−6 h at room temperature. The resultant solution was passed through a plug of silica gel, and the solvent was removed under reduced pressure to give 175 mg (58%) of product, which was used without further purification: IR (neat) ν 3070, 2922, 2852, 1958, 1922 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.62 (br, s, 1H), 1.84 (br, s, 1H), 2.21 (m, 3H), 2.73 (m, 3H), 4.97 (m, 2H), 5.11 (d, J = 16.8 Hz, 1H), 5.72 (m, 5H), 6.10 (m, 1H), 6.31 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 30.9, 33.6, 35.1, 89.3, 96.1, 96.2, 101.0, 102.2, 111.7, 115.4, 131.8, 134.3, 137.3.

1,2,3,8,9,11a-Hexahydro-3a,8-methano-3a*H*-cyclopentacyclodecen-12-one (21). A solution of **20** (100 mg, 0.30 mmol) in degassed hexanes (200 mL) was photolyzed (450 W Canrad-Hanovia, medium-pressure Hg lamp, Pyrex filter) for 15 min. The solvent was removed *in vacuo*, and the crude mixture was stirred with 5% v/v $P(OMe)_3$ in diethyl ether. Flash chromatography (silica gel, CH_2Cl_2/hexanes, 60:40) gave cycloadduct **21**: 31 mg (52%); IR (neat) ν 3023, 2957, 2877, 1947, 1689, 1669, 1450, 1164 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.85 (m, 4H), 2.16 (m, 1H), 2.35 (m, 3H), 2.44 (dd, J = 6.6, 4.2 Hz, 2H), 2.62 (m, 1H), 3.57 (td, J = 7.2, 3.6 Hz, 1H), 5.31 (d, J = 11.4 Hz, 1H), 5.49 (m, 1H), 5.66−5.79 (m, 3H), 5.85−5.93 (m, 1H); ^{13}C NMR δ 20.4, 28.6, 30.3, 34.1, 45.5, 56.6, 68.3, 123.8, 124.5, 127.8, 129.3, 129.9, 136.5; LRMS *m/e* 200 (25), 157 (13), 120 (100); HRMS calcd for $C_{14}H_{16}O$ 200.1201, found 200.1200. Anal. Calcd for $C_{14}H_{16}O$: C, 83.94; H, 8.05. Found: C, 83.98, H, 8.04.

Tricarbonyl[η^6-2-(octa′4′(*E*),6′(*E*)-dienyl)-1oxo-2,4,6-cycloheptatrienyl]chromium(0) and Tricarbonyl[η^6-2-(octa-4′(*Z*),6′(*E*)-dienyl)-1-oxo-2,4,6-cycloheptatrienyl]chromium(0) (22). To tricarbonyl(trisacetonitrile)chromium(0) (from $Cr(CO)_6$ (1.0 g, 4.55 mmol) was added a solution of **6** (400 mg, 1.87 mmol) in THF (25 mL), and the resulting mixture was stirred for 8 h at room temperature. The crude mixture was filtered and the solvent removed under reduced pressure. The resultant red oil was dissolved in ether and filtered through a plug of silica gel to obtain **22** (393 mg, 60%), which was used without further purification: IR (neat) ν 3007, 2922, 2859, 1992, 1922 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.60−1.82 (m, 6H), 2.14−2.29 (m, 2H), 2.72 (m, 1H), 4.93 (d, J = 10.5 Hz, 1H), 5.28 (m, 1H), 5.55−5.76 (m, 5H), 6.00 (m, 1H), 6.35 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 17.9, 18.2, 27.3, 27.5, 30.9, 31.2, 32.4, 34.9, 89.1, 96.0, 100.9, 102.1, 126.8, 127.2, 128.4, 129.3, 129.6, 130.7, 131.0, 131.5, 175.7, 227.9.

1,2,3,8,9,11a-Hexahydro-3a,8-methano-9α-methyl-3a*H*-cyclopenta-cyclodecen-12-one (23b) and Its Tricarbon-

(32) Tate, D. P.; Knipple, W. R.; Augl, J. M. *Inorg. Chem.* **1962**, *1*, 433.

ylchromium(0) Complex (23a). A solution of **22** (160 mg, 0.46 mmol) in hexanes (400 mL) was irradiated as in the previous example for 1 h. The resulting solution was filtered, and the solvent was removed *in vacuo*. The crude mixture was chromatographed (silica gel, hexanes) to give (10 mg, 10%) of **23b**: IR (neat) ν 3010, 2955, 2870, 1700, 1450, 1360 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.27 (d, J = 7.2 Hz, 3H), 1.64 (m, 1H), 1.71 (m, 1H), 1.80−1.85 (m, 2H), 2.11−2.17 (m, 1H), 2.27−2.34 (m, 1H), 2.62−2.76 (m, 1H), 2.87−3.02 (m, 1H), 3.42 (dd, J = 7.2, 2.1 Hz, 1H), 5.28 (d, J = 11.7 Hz, 1H), 5.53−5.83 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 19.7, 20.3, 30.3, 33.9, 34.1, 45.8, 64.0, 124.7, 125.5, 129.1, 134.7, 135.7, 137.2; LRMS *m/e* 214 (32), 171 (7), 131 (7); HRMS calcd for $C_{15}H_{18}O$ 214.1357, found 214.1360.

23a: 15 mg (15%); IR(neat) ν 2985, 2929, 2858, 1978, 1908, 1689, 1429 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.45−1.58 (m, 2H), 1.70 (d, J = 7.2 Hz, 3H), 2.08−2.15 (m, 1H), 2.33−2.45 (m, 1H), 2.46−2.66 (m, 3H), 2.84 (m, 1H), 3.30 (d, J = 6.3 Hz, 1H), 4.68 (d, J = 9.3 Hz, 1H), 4.81 (m, 1H), 5.15 (m, 1H), 5.24 (m, 1H), 5.82 (d, J = 10.2 Hz, 1H), 5.94 (d, J = 10.5 Hz, 1H); ^{13}C NMR δ 20.2, 20.6, 31.4, 38.0, 42.4, 52.5, 68.7, 69.8, 84.9, 89.7, 95.7, 98.0, 116.5, 122.9, 208.0; LRMS *m/e* 350 (0.5), 266 (11), 214 (12), 178 (27); HRMS calcd for $C_{18}H_{18}CrO_4$ 350.0610, [exp-$(CO)_3$] 266.0762, found 266.0760.

1,2,3,8,9,11a-Hexahydro-3a,8-methano-3a*H*-cyclopentacyclodecene (27). A two-necked, round-bottomed flask was charged with dried (under *vacuo*) magnesium turnings (137 mg, 5.71 mmol) and a crystal of I_2. A few drops of a solution of 7-bromohepta-1,3-diene (500 mg, 2.86 mmol) in THF (10 mL) was added to the reaction mixture at room temperature. When the color of the I_2 disappeared, the rest of the bromide solution was added portionwise at 0 °C, and the mixture was stirred for an additional 2 h. This solution was transferred to a vigorously stirred solution of tricarbonyl(tropylium)chromium(0) tetrafluoroborate (1.17 g, 3.71 mmol) in THF (10 mL) via cannula and was allowed to stir for 0.5 h at room temperature. The mixture was quenched with water and then extracted with ether (2 × 50 mL). The organic phase was washed with brine and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure and the residue dissolved in CH_2Cl_2. This solution was passed through a plug of silica gel to give, after removal of the solvent under reduced pressure, 487 mg (53%) of product, which was taken onto the next step without further purification: IR (neat) ν 3070, 3004, 2923, 2854, 1969, 1899, 1872 cm^{-1}; ^{1}H NMR ($CDCl_3$) 0.27 (br, s, 2H), 1.14 (s, 2H), 1.98 (s, 2H), 2.90 (m, 1H), 3.72 (t, J = 8.1 Hz, 2H), 4.79 (s, 2H), 2.97 (d, J = 9.9 Hz, 1H), 5.09 (d, J = 16.8 Hz, 1H), 5.56 (m, 1H), 5.97 (s, 4H), 6.28 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 23.2, 31.8, 35.9, 38.4, 67.8, 97.8, 98.8, 115.0, 131.2, 134.4, 137.1.

A solution of **25** (487 mg, 1.5 mmol) in 1,4-dioxane (20 mL) was refluxed for 6 h. The solvent was removed *in vacuo*, and the products were purified by column chromatography (silica gel, 100% hexanes) to obtain the desired 1-substituted product **26** contaminated with trace amounts of other isomers: 244 mg (50%); IR (neat) ν 3014, 2922, 2850, 1964, 1879 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.40 (m, 1H), 1.60 (m, 1H), 1.83 (dd, J = 13.5, 3.0 Hz, 1H), 1.95 (m, 1H), 2.10 (m, 2H), 2.33 (m, 1H), 2.69 (dd, J = 13.8, 9.0 Hz, 1H), 3.22 (dt, J = 9.0, 3.6 Hz, 1H), 4.59 (d, J = 6.9 Hz, 1H), 4.90 (t, J = 7.8 Hz, 1H), 5.04 (m, 2H), 5.70 (m, 1H), 5.85 (m, 2H), 6.06 (m, 1H), 6.30 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 27.5, 28.5, 32.0, 40.0, 52.8, 78.1, 96.4, 97.9, 98.0, 100.2, 115.3, 131.7, 134.0, 137.0.

A solution of **26** (45 mg, 0.14 mmol) in hexanes (400 mL) was photolyzed for 30 min. The crude mixture was decomplexed with $(MeO)_3P$ as before and purified by flash chromatography (silica gel, 100% hexanes) to provide **27** (22 mg, 85%); IR (neat) ν 3006, 2957, 2921, 2858, 1442 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.55 (m, 2H), 1.72−1.91 (m, 4H), 2.03 (m, 1H), 2.35−2.48 (m, 3H), 2.70 (br, s, 2H), 5.55−5.82 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 21.3, 31.3, 31.9, 37.5, 42.0, 43.2, 49.1, 50.4, 123.5, 124.6, 130.6, 136.9, 137.9, 138.5; LRMS *m/e* 186 (18), 129 (22), 117 (44), 104 (50); HRMS calcd for $C_{14}H_{18}$, 186.1408, found 186.1410. Anal. Calcd for $C_{14}H_{18}$: C, 90.25; H, 9.75. Found: C, 90.08; H, 10.03.

1,2,3,8,9,11a-Hexahydro-3a,8-methano-9-methyl-3a*H*-cyclopentacyclodecene (29). To a flask containing dried magnesium turnings (254 mg, 10.58 mmol) and a crystal of I_2 was added a few drops of a solution of 1-bromo-4(*E*/*Z*),6(*E*)-octadiene (1.0 g, 5.29 mmol) in THF (20 mL) at 0 °C. When the color of I_2 disappeared, the rest of the solution was added portionwise and stirred for 2 h. The alkylmagnesium bromide solution thus prepared was transferred via cannula to a solution of tricarbonyl(tropylium)chromium(0) tetrafluoroborate (1.7 g, 5.29 mmol) in THF (15 mL) and the resultant mixture stirred for 30 min. The reaction mixture was then quenched with water and extracted with ether. The organic layer was washed with brine and dried over anhydrous sodium sulfate and the solvent removed under reduced pressure. The residue was dissolved in CH_2Cl_2 and filtered through silica gel to give 888 mg (50%) of product, which was used in the next step without further purification: IR (neat) ν 3006, 2929, 2851, 1964, 1887; ^{1}H NMR δ 0.20−0.35 (m, 2H), 1.00−1.20 (m, 2H), 1.72−1.78 (m, 6H), 1.80−1.87 (m, 0.5H), 1.91−1.98 (m, 0.5H), 2.80−3.00 (m, 1H), 3.72 (t, J = 8.4 Hz, 2H), 4.78 (m, 2H), 5.05−5.20 (m, 0.5H), 5.30−5.70 (m, 1.5H), 5.87−6.00 (m, 3.5H), 6.10−6.30 (m, 0.5H); ^{13}C NMR ($CDCl_3$) δ 18.0, 18.3, 23.4, 23.8, 27.0, 31.9, 35.9, 38.5, 38.6, 67.9, 97.8, 98.9, 126.7, 127.2, 128.7, 128.9, 129.5, 130.6, 131.0, 131.5.

A solution of **28** (225 mg, 0.67 mmol) in 1,4-dioxane (40 mL) was heated at 160 °C in a sealed tube for 15 h. The resultant mixture was concentrated under reduced pressure, and the crude product was chromatographed (silica gel, hexanes) to obtain the cycloadduct **29** (110 mg, 82%): IR (neat) ν 3006, 2950, 2922, 2865, 1457 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.86−0.98 (m, 1H), 1.22 (d, J = 7.2 Hz, 3H), 1.47−1.58 (m, 1H), 1.66−1.81 (m, 2H), 1.86−1.93 (m, 2H), 1.97−2.09 (m, 1H), 2.31−2.36 (m, 1H), 2.50 (m, 1H), 2.63-2.72 (m, 1H), 2.74−2.80 (m, 1H), 5.33 (m, 1H), 5.46−5.52 (m, 1H), 5.54−5.77 (m, 3H), 5.89−5.95 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 21.0, 21.4, 31.2, 37.6, 41.7, 43.3, 43.9, 49.0, 123.5, 125.5, 134.8, 134.9, 138.0, 138.2; LRMS *m/e* 200 (44), 185 (12), 171 (12), 158 (12), 157 (17), 145 (21); HRMS calcd for $C_{15}H_{20}$ 200.1564, found 200.1562.

Photochemical Preparation of 1,2,3,8,9,11a-Hexahydro-3a,8-methano-9-methyl-3a*H*-cyclopentacyclodecene (29). A solution of **30** (80 mg, 0.24 mmol), prepared from **28** as before, in hexanes (400 mL) was photolyzed under standard conditions for 20 min, and the crude product was decomplexed with $(MeO)_3P$ and purified by column chromatography (silica gel, hexanes) to provide the cycloadduct **29** (22 mg, 46%). All spectral data were identical to **29** prepared thermally.

Tricyclo[5.4.1.0^{1,5}]dodeca-4,8-diene (32a). A two-necked, round-bottomed flask was charged with dried (under *vacuo*) magnesium turnings (322 mg, 13.42 mmol) and a crystal of I_2. A few drops of a solution of 5-bromo-1-pentene (1.0 g, 6.71 mmol) in THF (20 mL) was added to the reaction mixture at room temperature. When the color of I_2 disappeared, the rest of the bromide solution was added portionwise at 0 °C, and the mixture was stirred for an additional 2 h. This solution was transferred via cannula to a vigorously stirred solution of tricarbonyl(tropylium)chromium(0) tetrafluoroborate (2.0 g, 6.71 mmol) in THF (20 mL) and stirred for 0.5 h at room temperature. The reaction was quenched with water and diluted with ether. The organic layer was separated, washed with brine, and dried over anhydrous sodium sulfate and the solvent removed under reduced pressure. The residue was dissolved in CH_2Cl_2 and passed through a plug of silica gel. The solvent was removed to provide the product **31a** (1.07 g, 54%), which was used in the next step without further purification: IR (neat) ν 3070, 2930, 2853, 1968, 1905, 1871, 1629, 1465 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.57 (q, J = 7.8 Hz, 2H), 1.13 (quintet, J = 7.5 Hz, 2H), 1.84 (q, J = 6.9 Hz, 2H), 2.91 (quintet, J = 8.1 Hz, 1H), 3.73 (t, J = 8.7 Hz, 2H), 4.79 (m, 2H), 4.93 (m, 2H), 5.67 (m, 1H), 5.97 (br, s, 2H); ^{13}C NMR ($CDCl_3$) δ 22.9, 33.1, 35.9, 38.4, 67.9, 97.8, 97.9, 98.0, 100.2, 115.2, 137.9.

A solution of **31a** (150 mg, 0.51 mmol) in 1,4-dioxane (15 mL) was heated at 150 °C in a sealed tube for 15 h. The reaction mixture was then cooled to room temperature, and the solvent was removed under reduced pressure. The crude mixture was purified by flash chromatography (silica gel, hexanes) to obtain the product **32a** (60 mg, 90%, on the basis

of recovery of 27 mg of starting material): IR (neat) ν 3002, 2929, 2849, 1592, 1445 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.36−1.69 (br, m, 6H), 1.77 (dd, J = 11.7, 4.5 Hz, 1H), 1.87 (br, m, 1H), 1.97 (dd, J = 12.0, 2.7 Hz, 1H), 2.32 (m, 1H), 2.58 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 25.1, 33.6, 39.4, 40.8, 42.3, 50.0, 54.6, 54.8, 122.7, 123.8, 137.7, 146.9; LRMS *m/e* 160 (44), 131 (21), 119 (30), 105 (17); HRMS calcd for $C_{12}H_{16}$ 160.1251, found 160.1249.

[η^6-7-*exo*-(5′-carbethoxypent-4′(*E*)-enyl)-1,3,5-cycloheptatriene]tricarbonylchromium(0) (31b). Zinc (1.09 g, 16.68 mmol) was added to a dried round-bottom flask equipped with a rubber septum and a nitrogen outlet, followed by 2.5 mL of THF and 0.15 mL of 1,2-dibromoethane. The reaction mixture was heated with a heat gun for 30 s and allowed to cool to room temperature. This process was repeated two times before 0.15 mL of chlorotrimethylsilane was added. The resulting mixture was stirred for 30 min at which time a THF (4 mL) solution of ethyl 6-iodo-2-hexenoate (2.23 g, 8.34 mmol) was added via syringe pump over a period of 1 h. The resultant reaction mixture was stirred at room temperature for 24 h. Copper cyanide (0.627 g, 7 mmol) was added to predried LiCl (150 °C, 3 h under vacuum, 0.593 g, 14 mmol) in a round-bottom flask equipped with a rubber septum and a nitrogen outlet. The reaction mixture was cooled to 0 °C, 10 mL of THF was added, and the mixture was stirred at room temperature until all the solid was dissolved, at which point the solution was cooled to −78 °C and the above organozinc iodide was added dropwise to the reaction mixture. The resulting light green solution was stirred at 0 °C for 30 min and then added to a vigorously stirred suspension of tricarbonyl(tropylium)chromium tetrafluoroborate (1.31 g, 4.17 mmol) in 5 mL of THF at 0 °C under nitrogen. A homogeneous solution was obtained after the reaction was stirred at 25 °C for 3 h. The reaction mixture was then quenched with saturated aqueous ammonium chloride solution at 0 °C and diluted with 100 mL of 50% ether/hexane. The layers were separated, and the aqueous layer was extracted with ether (2 × 50 mL). The combined organic layers were washed with water (3 × 100 mL) and saturated aqueous sodium chloride solution (3 × 100 mL), dried over anhydrous $MgSO_4$, filtered, and concentrated in *vacuo*. Purification by flash chromatography (10% EtOAc/hexane) gave 1.09 g (71%) of the chromium complex **31b** as a red oil: IR (neat) 3049, 2983, 2937, 2857, 1982, 1921, 1879, 1708, 1653, 1470, 1368 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 0.24−0.29 (m, 2H), 1.17−1.23 (m, 1H), 1.28 (t, J = 7.1 Hz, 3H), 1.95−2.00 (m, 2H), 2.87−2.93 (m, 1H), 3.70 (t, J = 8.7 Hz, 2H), 4.17 (q, J = 7.1, 2H), 4.78−4.79 (m, 2H), 5.72 (d, J = 15.7 Hz, 1H), 5.95−5.96 (m, 2H), 6.80 (dt, J = 15.7, 7.8 Hz, 1H); ^{13}C NMR (125 Hz, $CDCl_3$) δ 14.3, 22.2, 31.5, 35.9, 38.3, 60.2, 67.3, 97.8, 98.9, 121.6, 148.3, 166.5; LRMS *m/e* 368 (M^+, 6), 284 (12), 206 (14), 144 (16), 117 (20), 91 (100); HRMS calcd for $C_{18}H_{20}O_5Cr$ 368.0716, found 368.0723. Anal. Calcd for $C_{18}H_{20}O_5Cr$: C, 58.69; H, 5.47. Found: C, 58.47; H, 5.54.

6α-Carbethoxytricyclo[5.4.1.0^{1,5}]-1β,5$H\alpha$,7$H\beta$-dodeca-8,10-diene (32b). A solution of the chromium complex **31b** (450 mg, 1.22 mmol) in freshly distilled 1,4-dioxane (40 mL) was added to a Carius tube, which was freeze−pump−thaw degassed and sealed under vacuum. This solution was heated at 150 °C for 24 h in a silicone oil bath and the reaction mixture cooled and filtered through Celite. The solvent was removed in vacuo, and the crude mixture was purified by flash chromatography (silica gel, 3% EtOAc/hexane) to give 229 mg (81%) of cycloadduct as a colorless oil: IR (neat) 3016, 2978, 2951, 2861, 1724, 1596, 1454, 1240 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 1.26 (t, J = 7.1 Hz, 3H), 1.44−1.59 (m, 3H), 1.68−1.76 (m, 2H), 1.81−1.90 (m, 2H), 2.08 (d, J = 11.9 Hz, 1H), 2.65 (dd, J = 9.4, 6.1 Hz, 1H), 2.92−2.98 (m, 2H), 4.11 (d_{ABq}, 1H, J = 11.6, 7.1 Hz), 4.20 (d_{ABq}, 1H, J = 11.6, 7.1 Hz), 5.58 (dd, J = 10.6, 7.1 Hz, 1H), 5.74−5.82 (m, 2H), 5.91 (d, J = 10.6 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.4, 25.0, 33.1, 39.0, 40.9, 44.1, 53.8, 55.2, 60.1, 65.7, 122.9, 126.4, 133.6, 146.7, 172.6; LRMS *m/e* 232 (M^+, 76), 154 (93), 144 (42), 129 (33), 117 (61), 105 (34); HRMS calcd for $C_{15}H_{20}O_2$ 232.1463, found 232.1462; Anal. Calcd for $C_{15}H_{20}O_2$: C, 77.55; H, 8.68. Found: C, 77.48; H, 8.72.

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Supporting Information Available: Copies of NMR spectra (16 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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