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Molecular Complexity from Aromatics: A Novel, Stereoselective Route to Tricyclo[5.2.2.0^{1,5}]undecenones, Tricyclo[6.2.2.0^{1,6}]Dodecenones, and [*n*.3.3]Propellanes

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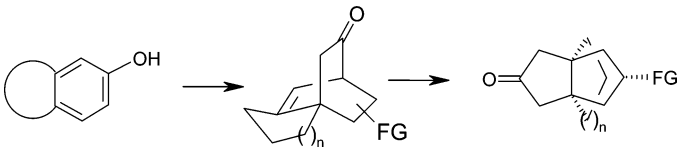

A general stereoselective route to functionalized and substituted tricyclo [5.2.2.0^{1,5}]undecenones, tricyclo-[6.2.2.0^{1,6}]dodecenones, and [3.3.3]- and [4.3.3]propellanes from simple aromatic precursors is reported. The methodology involves generation and cycloaddition of annulated cyclohexa-2,4-dienones with various acrylates followed by manipulation of the resulting tricyclic adducts, leading to functionalized tricyclo-[5.2.2.0^{1,5}]undecenones and tricyclo[6.2.2.0^{1,6}]dodecenones endowed with a β,γ-enone chromophore. Photochemical reaction of the tricyclic chromophoric systems followed by reductive cleavage provided an efficient entry into propellanes.

Introduction

Propellanes, a unique class of organic compounds having three rings conjoined together across a common C−C bond, have fascinated chemists for a long time presumably because of their unusual molecular structure, reactivity, and properties.[1] Among various types, [3.3.3]propellanes belonging to the polyquinane family have attracted greater attention due to isolation[2] of the sesquiterpenoid natural product modhephene **1** (Figure 1) that contains a [3.3.3]propellane framework in its molecular architecture. Recently, more functionalized derivatives of modhephene such as **1b**,**c** were isolated from *Leontopodium alpinum* and *Psiadia anchusifolia*.[3] Most recently, natural products containing a [3.3.3]propellane in their framework have also been isolated from *Taxus canadensis*.[4] Polyquinanes, in general, have elicited intense interest for a long time due to their molecular architecture and biological properties.[5−7] Several elegant methods leading to various types of polyquinanes have been developed.[5−11] However, the methods leading to [3.3.3]-propellanes are only a few as compared to other polyquinanes, and the search for the development of a new and efficient methodology is continuing.[8,12−14]

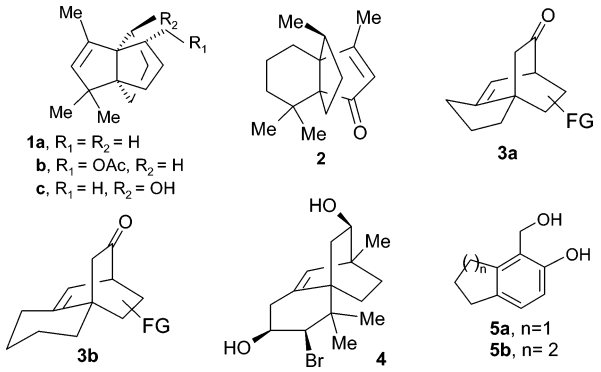

FIGURE 1. [3.3.3]- and [4.3.3]propellanes, tricyclic compound, sesquiterpene containing tricyclo[5.2.2.0^{1,6}]dodecane system, and aromatic precursor.

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(1) (a) Levin, M. D.; Kaszynski, P.; Michl, J. *Chem. Rev.* **2000**, *100*, 169−234. (b) Ginsberg, D. *Propellanes: Structure and Reactions*; Verlag Chemie: Weinheim, Germany, 1975 and references therein.

(2) (a) Zalkow, L. H.; Harris, R. N.; Van Derveer, D. *J. Chem. Soc., Chem. Commun.* **1978**, 420−421 (b) Zalkow, L. H.; Harris, R. N.; Burke, N. I. *J. Nat. Prod.* **1979**, *42*, 96−102. (c) Bohlmann, F.; Zdero, C.; Bohlmann, R.; King, R. M.; Robinson, H. *Phytochemistry* **1980**, *19*, 579−582.

(3) (a) Gauvin, A.; Susperregui, J.; Barth, P.; Louis, R.; Deleris, G.; Smadja, J. *Phytochemistry* **2004**, *65*, 897−901. (b) Comey, N.; Grey, A. I.; Hook, I. L.; James, P.; Sheridan, H. *Phytochemistry* **1999**, *50*, 1057−1060.

(4) (a) Shi, Q. W.; Sauriol, F.; Mamer O.; Zamir, L. O. *Chem. Commun.* **2003**, 68−69. (b) Shi, Q. W.; Sauriol, F.; Lesimple, A.; Zamir, L. O. *Chem. Commun.* **2004**, 544−545.

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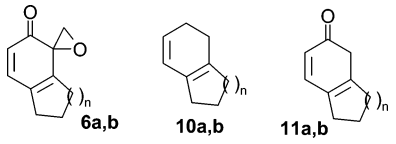
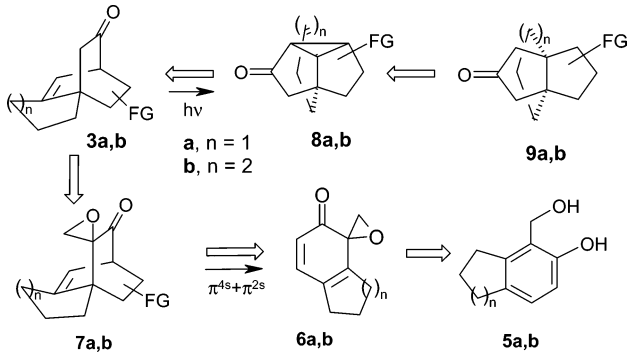


FIGURE 2. Cyclohexa-2,4-dienones and annulated cyclohexadiene.

[4.3.3]Propellanes have not elicited much attention presumably because of a lack of natural products containing this framework. Although, recently, [4.3.3]propellanes of type **2** have generated interest by virtue of their olfactory properties.[15] For example, propellane **2** and its congeners have been found to possess woody amber odors.[15a] Therefore, it is not surprising that there are only a few methods for their synthesis and that these involve carbenium ion rearrangements.[15a−c] Recently, Mattay and co-workers developed a route to [4.3.3]propellane employing a PET reaction.[15d]

Tricycloundecenones of type **3a** are versatile synthetic intermediates,[11b,16] and this type of unusual tricyclo[5.2.2.0^{1,5}]-undecane framework is present in complex natural products such as eremolactones[17a] and antheridic acid.[17b] Similarly, the compounds of type **3b** having a tricyclo[5.2.2.0^{1,6}]dodecane framework are also important precursors for sesquiterpenoids,[18] and this framework is present in diterpenoid secoatisanes, which were recently isolated from Chinese mangrove *Excoecaria agallocha L.*[19a,b] The sesquiterpene **4**, isolated from alga *Caloglossa leprieuri*, also contains this framework.[19c] There are only a few methods for the synthesis of tricyclic compounds of type **3a**,**b**, and existing methods have limitations with regard to the introduction of functionality and substituents in the tricyclic framework.

SCHEME 1



In view of the above findings and our continuing interest in the development of new methodology via cycloaddition of cyclohexadienones,[20] we considered developing a general route to functionalized tricyclic compounds of type **3a**,**b**, [3.3.3]- and [4.3.3]propellanes. We contemplated that functionalized tricyclic compounds **3** may be easily derived from the keto-epoxide **7** via manipulation of the oxirane ring. The key tricyclic precursor **7** was thought to be assembled from the aromatic precursor **5** via its transformation to cycohexa-2,4-dienone **6** and cycloaddition with an appropriate 2π-partner (Scheme 1). Further, it was thought that a photochemical 1,2-acyl shift in tricyclic compound **3** would lead to the tetracyclic compound **8** that upon reductive cleavage of the cyclopropane ring would give propellanes of type **9** (Scheme 1).

(5) (a) Mehta G.; Srikrishna, A. *Chem. Rev.* **1997**, *97*, 671−720 and references therein. (b) Little, R. D. *Chem. Rev.* **1996**, *96*, 93−114. (c) Gupta, A. K.; Fu, X.; Snyder, J. P.; Cook, J. M. *Tetrahedron* **1991**, *47*, 3665−3710. (d) Paquette, L. A.; Doherty, A. M. *Polyquinane Chemistry*; Springer-Verlag: Berlin, 1987 and references therein.

(6) (a) Austin, K. A. B.; Banwell, M. G.; Harfoot, G. J.; Willis, A. C. *Tetrahedron Lett.* **2006**, *47*, 7381−84. (b) Wu, Y. T.; Vidovic, D.; Magull, J.; De Meijere, A. *Eur. J. Org. Chem*. **2005**, *8*, 1625−1636. (c) Tripp, J. C.; Schiesser, C. H.; Curran, D. P. *J. Am. Chem. Soc.* **2005**, *127*, 5518−5527. (d) Banwell, M. G.; Edward, A. J.; Harfoot, G. J.; Jolliffe, K. A. *Tetrahedron* **2004**, *60*, 535−547. (e) Maiti, A.; Gerken, J. B.; Masjedizadeh, M. R.; Minieux, Y. S.; Little, R. D. *J. Org. Chem*. **2004**, *69*, 8574−8582. (f) Davis, C. E.; Duffy, B. C.; Coates, R. M. *J. Org. Chem*. **2003**, *68*, 6935−6943. (g) Dhimane, A.; Aissa, C.; Malacria, M. *Angew. Chem., Int. Ed*. **2003**, *41*, 3284−3287. (h) Srikrishna, A.; Dethe, D. H. *Org. Lett*. **2003**, *5*, 2295−2298. (i) Mehta, G.; Murthy, A. S. K. *Tetrahedron Lett.* **2003**, *44*, 5243−5246. (j) Wang, J.-C.; Krische, M. J. *Angew. Chem., Int. Ed*. **2003**, *41*, 5855−5857.

(7) (a) Banwell, M. G.; Edward, A. J.; Harfoot, G. J.; Jolliffe, K. A. *J. Chem. Soc., Perkin Trans. 1* **2002**, 2439−2441. (b) Paquette, L. A.; Geng, F. *J. Am. Chem. Soc*. **2002**, *124*, 9199−9203. (c) Russu, W. A.; Villalon, V. P.; Wang, V. R.; Miranda, J. A.; Little, R. D. *Tetrahedron Lett.* **2002**, *43*, 8459−8461. (d) Harrowven, D. C.; Lucas, M. C.; Howes, P. D. *Tetrahedron* **2001**, *57*, 9157−9162. (e) Harrowven, D. C.; Lucas, M. C.; Howes, P. D. *Tetrahedron Lett.* **2000**, *41*, 8985−8987. (f) Ader, T. A.; Champey, C. A.; Kuznetsova, L. V.; Li, T.; Lim, Y. H.; Rucando, D.; Sieburth, S. M. *Org. Lett*. **2001**, *3*, 2165−2167. (g) Varma, S. K.; Eleisher, E. B.; Moore, H. W. *J. Org. Chem.* **2000**, *65*, 8564−8573. (h) Rawal, V. H.; Reddy, J. *Org. Lett.* **2000**, *2*, 2711−2712.

(8) De Boeck, B.; Harrington-Frost, N. M.; Pattenden, G. *Org. Biomol. Chem*. **2005**, *3*, 340−347.

(9) Curran, D. P.; Shen, W. *Tetrahedron* **1993**, *49*, 755−770 and references therein.

(10) Wender, P. A.; Dore, T. M. In *CRC Handbook of Organic Photochemistry and Photobiology*; Horspool, W. M., Song, P. S., Eds.; CRC Press: Boca Raton, FL, 1995; pp 280−300.

(11) (a) Pattenden, G.; Teague, H. J. *Tetrahedron* **1987**, *43*, 5637−5652. (b) Mehta, G. Subrahmanyam, D. *J. Chem. Soc., Perkin Trans. 1* **1991**, 395−401. (c) Zhao, S.; Mehta, G.; Helquist, P. *Tetrahedron Lett.* **1991**, *32*, 5753−5756. (d) Lange, G. L.; Gottardo, C. *J. Org. Chem*. **1995**, *60*, 2183−2187.

(12) (a) Dvorak, C. A.; Rawal, V. H. *J. Chem. Soc., Chem. Commun*. **1997**, 2381−2382. (b) Dvorak, C. A.; Dufour, C.; Iwasa, S.; Rawal, V. H. *J. Org. Chem.* **1998**, *63*, 5302−5303. (c) Lee, H.-Y.; Kim, D.; Kim, S. *Bull. Korean Chem. Soc.* **1999**, *20*, 269−270.

(13) (a) Laxmisha, M. S.; Subba Rao, G. S. R. *Tetrahedron Lett.* **2000**, *41*, 3759−3761. (b) Bertolini, T. M.; Nguyen, Q. H.; Harvey, D. F. *J. Org. Chem.* **2002**, *67*, 8675−8678. (c) Tzvetkov, N.; Schmidtmann, M.; Muller, A.; Mattay, J. *Tetrahedron Lett.* **2003**, *44*, 5979−5982.

(14) (a) Uyehara, T.; Murayama, T.; Sakai, K.; Ueno, M.; Sato, T. *Tetrahedron Lett.* **1996**, *37*, 7295−7298. (b) Fitjer, L.; Majewski, M.; Monzo-Oltra, H. *Tetrahedron* **1995**, *51*, 8835−8852. (c) Fitjer, L.; Rissom, B.; Kanschik, A.; Egert, E. *Tetrahedron* **1994**, *50*, 10879−10892. (d) Sha, C.-K.; Jean, T.-S.; Wang, D.-C. *Tetrahedron Lett.* **1990**, *31*, 3745−3748.

(15) (a) Frater, G.; Helmlinger, D.; Kraft, P. *Helv. Chim. Acta* **2006**, *86*, 678−696. (b) Marcos, I. S.; Martinez, B.; Sexmero, M. J.; Diez, D.; Basabe, P.; Urones, J. G. *Synthesis* **2006**, 3865−3873. (c) Helmlinger, D.; Frater, G. *Tetrahedron Lett.* **1992**, *33*, 6119−6122. (d) Tzvetkov, N. T.; Neumann, B.; Stammler, H.-G.; Mattay, J. *Eur. J. Org. Chem.* **2006**, 351−370.

(16) (a) John Biju, P.; Laxmisha, M. S.; Subbarao, G. S. R. *J. Chem. Soc., Perkin Trans. 1* **2000**, 4512−4519. (b) Janaki, S. N.; Subba Rao, G. S. R. *J. Chem. Soc., Perkin Trans. 1* **1997**, 195−200. (c) Hagiwara, H.; Uda, H. *J. Chem. Soc., Perkin Trans. 1* **1986**, 629−632. (d) Weber, W.; Spitzner, D.; Kraus, W. *J. Chem. Soc., Chem. Commun.* **1980**, 1212−1213. (e) Yamada, Y.; Nagaoka, H.; Kimura, M. *Synlett* **1977**, 581−582.

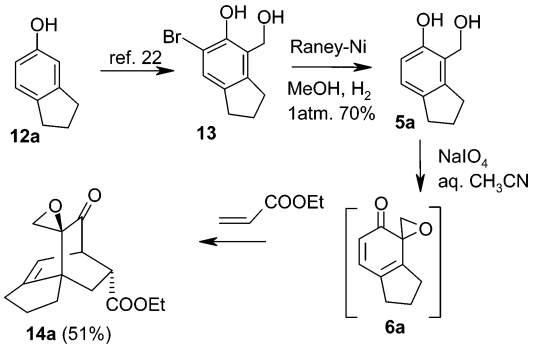
(17) (a) ApSimon, J. *The Total Synthesis of Natural Products*; John Wiley and Sons: New York, 1992; Vol. 8, p 222. (b) King, G. R.; Mander, L. N.; Monck, N. J. T.; Morris, J. C.; Zhang, H. *J. Am. Chem. Soc.* **1997**, *119*, 3828−3829. (c) Corey, E. J.; Myers, A. G.; Takahashi, N.; Yamane, H.; Schraudolf, H. *Tetrahedron Lett.* **1986**, *27*, 5083−5086.

(18) (a) Sathya Shankar, P.; Subba Rao, G. S. R. *J. Chem. Soc., Perkin Trans. 1* **1998**, 539−548. (b) Bartoletti, A.; Barettoni, M.; Catteruccia, F.; De Chiara, G.; Marini Bettolo, R.; Mastrangeli, C.; Scarpelli, R.; Tozzi, C.; Lamba, D. *Gazz. Chim. Ital.* **1996**, *126*, 223−226. (c) Hagiwara, H.; Okamoto, T.; Harada, N.; Hisashi, U. *Tetrahedron* **1995**, *51*, 9891−9898.

(19) (a) Wang, J. D.; Li, Z. Y.; Xiang, W. S.; Guo, Y.-W. *Helv. Chim. Acta* **2006**, *89*, 1367−1372. (b) Wang, J. D.; Li, Z. Y.; Guo, Y.-W. *Helv. Chim. Acta* **2005**, *88*, 979−985. (c) Xu, X. H.; Chang, J.; Lu, J. H.; Yao, G. M.; Li, Y. M. *Chin. Chem. Lett.* **2002**, *13*, 953−954.

(20) (a) Singh, V. *Acc. Chem. Res*. **1999**, *32*, 324−333. (b) Singh, V.; Pal, S.; Mobin, S. M. *J. Org. Chem*. **2006**, *71*, 3014−3025.

SCHEME 2



We wish to report herein a novel and efficient synthesis of tricyclic compounds of type **3a**,**b**, and **7a**,**b** endowed with a β,γ-enone chromophore from simple aromatic precursors of type **5a**,**b** and their photochemical transformation leading to a stereoselective route to [3.3.3]- and [4.3.3]propellanes.

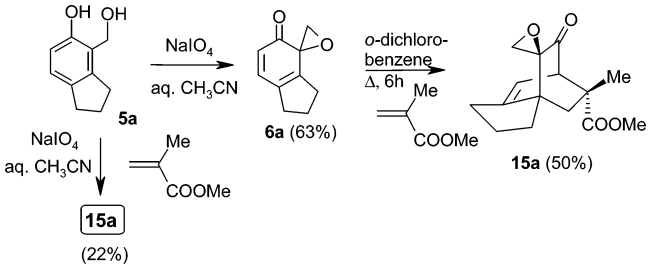
Results and Discussion

Synthesis of Tricyclic Compounds of Type 3 and 7 and Their Congeners. While the compounds of type **3a**,**b** having functional groups in both the ethano bridges are not known, their simpler analogues are generally prepared by Diels−Alder reaction of annulated dienes of type **10** with ketene equivalents.[21] However, the preparation of the diene of type **10** via Birch reduction followed by isomerization is cumbersome and often gives a mixture of adducts. Moreover, this method does not permit introduction of functionality in the other ethano bridge of the bicyclo[2.2.2]octane framework. Conceptually, the tricyclic compounds **3a**,**b** may also be directly obtained through Diels−Alder reaction of cyclohexadienone **11a**,**b** (Figure 2). However, cyclohexa-2,4-dienones of type **11** are keto-tautomers of the corresponding phenols and not easily accessible.

Therefore, we considered to develop an indirect, general, and stereoselective route to the tricyclic compounds of type **3a**,**b** via cycloaddition of annulated spiroepoxy cyclohexadienones of type **6a**,**b**, which were thought to be generated by the oxidation of annulated *o*-hydroxymethyl phenols **5a**,**b**.

Initially, we focused our attention toward the synthesis of tricycloundecenones **7a**, and hence, the hydroxymethyl indanol **5a** was required. Thus, 5-indanol **12a** was brominated, and the resulting bromo compound was hydroxymethylated to give **13**.[22] The reduction of **13** with Raney Ni by a modification of the earlier method[22] gave the 4-hydroxymethyl-5-indanol **5a**. Oxidation of **5a** with aqueous sodium metaperiodate[23] in the presence of ethyl acrylate according to a method developed in our laboratory[23c] furnished adduct **14a** in good yield, as a result of a regio- and stereoselective cycloaddition of the in situ generated spiroepoxycyclohexa-2,4-dienone **6a** (Scheme 2). The structure of adduct **14a** was deduced from its ^{1}H NMR and ^{13}C NMR spectral data, COSY spectrum, and comparison.

SCHEME 3



Thus, the IR spectrum of **14a** showed a characteristic absorption band at 1731 cm^{-1} for the carbonyl group. The ^{1}H NMR (300 MHz, $CDCl_3$) spectrum displayed a diagnostic signal at δ 5.84 (d with str, J = 6 Hz, 1H) for one olefinic proton and a highly characteristic AB pattern for the oxymethylene protons of the oxirane ring at δ 3.12 (part of an AB system, J_{AB} = 6 Hz, 1H) and 2.87 (part of an AB system, J_{AB} = 6 Hz, 1H). In addition, signals were observed at δ 4.15 (q with str, J = 7.2 Hz, 2H, -OCH_2 of the ester group), and the proton at the bridgehead exhibited a signal at δ 3.65 (dd, J_1 = 6 Hz, J_2 = 2.4 Hz, 1H). Further resonances were shown at δ 3.06 (dd of d, J_1 = 9.9 Hz, J_2 = 4.8 Hz, J_3 = 2.4 Hz, 1H), 2.56−2.40 (m, 2H), 2.32 (dd, J_1 = 12.9 Hz, J_2 = 10.2 Hz, 1H), 2.0−1.86 (overlapped m, 2H), 1.80−1.50 (complex m, 3H), 1.26 (t, J = 7.2 Hz, CH_3).

The structure of the adduct was also supported by the derived ^{13}C NMR spectral data that exhibited characteristic signals at δ 204.9 and 172.5 for the carbonyl groups present in the ethano bridge and ester group, respectively. It also displayed signals at δ 156.3 and 114.1 for the olefinic carbons. It further exhibited signals at δ 61.1, 58.4, 51.0, 50.0, 48.6, 41.3, 31.3, 30.1, 29.7, 26.5, and 14.0 for the other carbons, thus accounting for all the carbons of the adduct. The stereochemistry of the oxirane ring was suggested on the basis of a general tendency of cyclohexadienones during their cycloaddition[20] and comparison with other adducts whose structure was determined by X-ray single-crystal analysis (vide infra).

Similar oxidation of *o*-hydroxymethyl indanol **5a** in the presence of methyl methacrylate, however, gave the corresponding adduct **15a** in low yield (22%) after a long reaction time. Therefore, we considered the possibility of isolation of the spiroepoxycyclohexa-2,4-dienone **6a** and attempted its cycloaddition with methyl methacrylate at higher temperatures, although we were aware that cyclohexa-2,4-dienones are generally unstable, readily dimerize, and disintegrate upon heating. Hence, **5a** was oxidized with $NaIO_4$ in aqueous Acetonitrile, and the product mixture was chromatographed to give the cyclohexadienone **6a** in good yield (63%) as a yellow solid. Subsequent heating of **6a** with methyl methacrylate in *o*-dichlorobenzene in a sealed tube furnished the adduct **15a** in good yield (50%) (Scheme 3).

To extend the scope of methodology, we also explored the oxidation of *o*-hydroxymethyl indanols **13**, **17**, and **19** and the cycloaddition of the resulting cyclohexadienones with acrylates. 6-Hydroxymethyl-5-indanol (**16**) and bis-hydroxymethylated **17** were prepared by hydroxymethylation of 5-indanol **12a**.[24a] Reduction of **16** with a Ni−Al alloy gave the known compound **18**[24b] that upon hydroxymethylation readily gave the precursor **19** (Scheme 4).

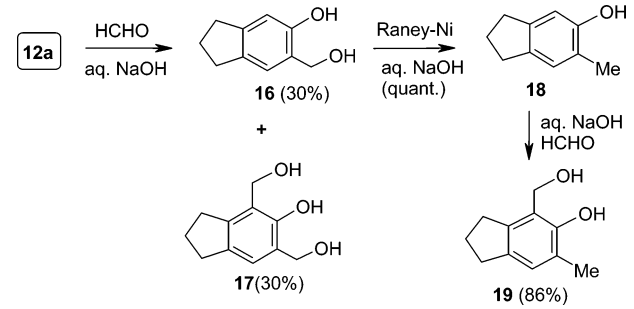
(21) (a) Selvakumar, N.; Janaki, S. N.; Pramod, K. Subbarao, G. S. R. *J. Chem. Soc., Perkin Trans. 1* **1995**, 839−846 and references therein. (b) Hariprakasha, H. K.; Subbarao, G. S. R. *Tetrahedron Lett.* **1997**, *38*, 5343−5346. (c) Mehta, G.; Subrahmanyam, D. *J. Chem. Soc., Chem. Commun.* **1985**, 768−769.

(22) Andreetti, G. D.; Bohmer, V.; Jordan, G. J.; Tabayabai, M.; Ugozzoli, F.; Vogt, W.; Wolff, A. *J. Org. Chem.* **1993**, *58*, 4023−4032.

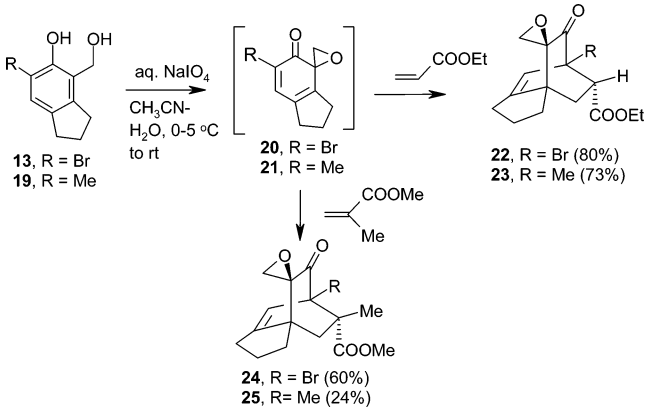
(23) (a) Adler, E.; Brasen, S.; Miyake, H. *Acta Chem. Scand.* **1971**, *25*, 2055−2069. (b) Becker, H. D.; Bremholt, T.; Adler, E. *Tetrahedron Lett.* **1972**, *13*, 4205−4208. (c) Singh, V.; Prathap, S. *Synlett* **1994**, 542−545.

(24) (a) Singh, V.; Sahu, P. K.; Mobin, S. M. *Tetrahedron* **2004**, *60*, 9925−9930. (b) Dean, R. E.; Midgley, A.; White, E. N.; Mcneil, D. *J. Chem. Soc.* **1961**, 2773−2779.

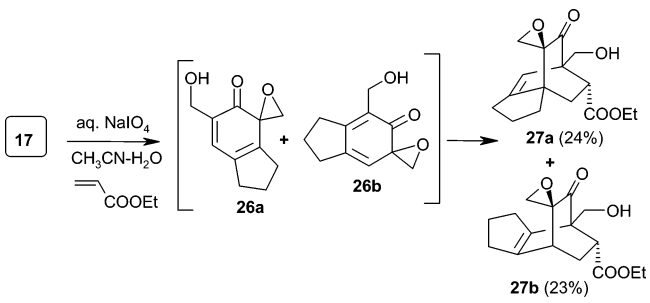
SCHEME 4



SCHEME 5



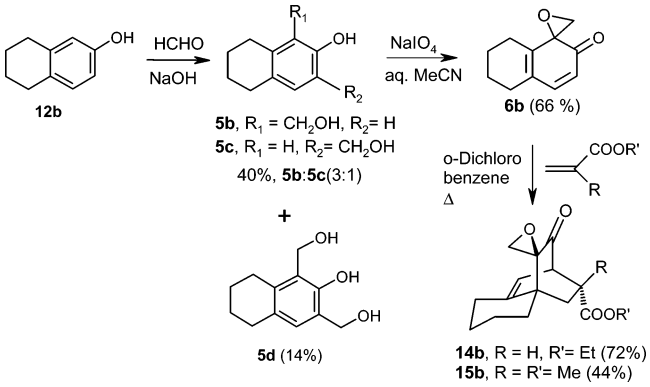
SCHEME 6



Thus, 6-bromo-4-hydroxymethyl-5-indanol **13** was oxidized with $NaIO_4$ in aqueous acetonitrile containing ethyl acrylate, which furnished the adduct **22** in excellent yield (80%) as a result of in situ generation of cyclohexadienone **20** and cycloaddition (Scheme 5). Similar oxidation of **19** with sodium *m*-periodate in the presence of ethyl acrylate also gave the tricyclic adduct **23** in excellent yield (73%). In situ generation of **20** and **21** and their reaction with methyl methacrylate also gave the corresponding adducts **24** and **25**, respectively (Scheme 5). The cycloaddition of **21** with methyl methacrylate was relatively less efficient as compared to the cyclohexa-2,4-dienone **20** containing an electron withdrawing group at C2.

The oxidation of bis-hydroxymethyl indanol **17** provided an interesting situation, as it generated two types of cyclohexadienones (**26a** and **26b**), which may undergo cycloaddition. Thus, treatment of **17** with aqueous $NaIO_4$ in the presence of ethyl acrylate gave adducts **27a** and **27b** in almost equal amounts, whose structures were deduced from their spectral data (Scheme 6). The structure of adduct **27a** was also confirmed through single-crystal structure determination (see Supporting Information).

SCHEME 7



Synthesis of Tricyclododecenones of Types 3b and 7b. To prepare the tricyclic compounds of type **3b** and **7b**, the hydroxymethyltetrahydronaphthol **5b** was required. This compound was prepared earlier by hydroxymethylation of 5,6,7,8-tetrahydro-2-naphthol **12b** in low yield.[22] Gesson and co-workers reported the reaction of **12b** with formaldehyde in the presence of phenyl boronic acid and subsequent oxidation of the resulting dioxaborin, which gave **5b** and the regioisomer **5c**, the former being a major product.[25] We employed a slightly modified hydroxymethylation method. Thus, tetrahydronaphthol **12b** was treated with HCHO and aqueous NaOH, and the reaction was quenched with ammonium chloride (instead of acetic acid). Usual workup and chromatography of the product gave an inseparable mixture of **5b** and **5c** (40%) having the desired regioisomer **5b** as a major component **(5b**/**5c**; 3:1, ^{1}H NMR) and bis-hydroxymethylated product **5d** (15%) (Scheme 7). It is interesting to note that hydroxymethylation of **12b** gave the desired regioisomer **5b** (major product) as a result of the reaction at the more hindered carbon, which is in contrast to the behavior of indanol **12a** (vide supra). Such a difference in the regioselectivity has also been observed in other electrophilic reactions of indanol and tetrahydronaphthol.[26]

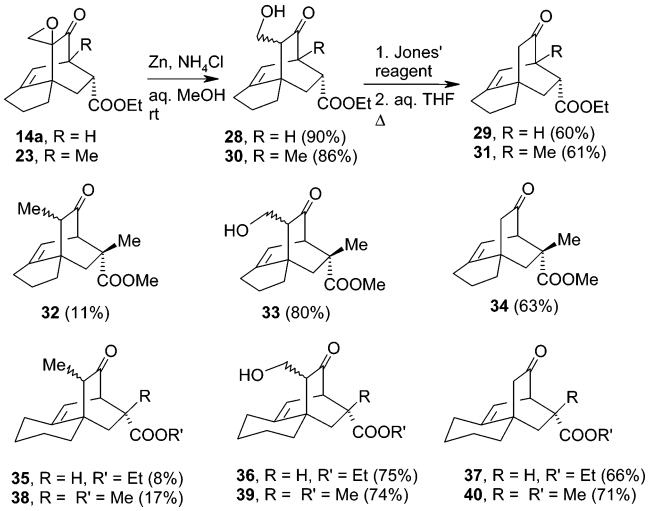
To prepare the adduct **14b**, we examined the cycloaddition of isolated cyclohexadienone **6b**. Hence, the mixture of **5b**,**c** was oxidized with $NaIO_4$ following our earlier procedure, which gave the known spiroepoxycyclohexa-2,4-dienone **6b**[25] in 66% yield as a major product (Scheme 7). Heating a solution of cyclohexadienone **6b** and ethyl acrylate in *o*-dichlorobenzene in a sealed tube followed by chromatography gave the adduct **14b** in excellent yield (72%) (Scheme 7). Similarly, the reaction of **6b** with methyl methacrylate also furnished the adduct **15b** in good yield (Scheme 7).

The presence of a contiguous keto-epoxide functionality in adducts provided the opportunity for further manipulation. Thus, the adduct **14a** was subjected to reduction with zinc-NH_4Cl in aqueous methanol at ambient temperature, which gave the β-hydroxyketone **28** (as a mixture of syn/anti isomers, ^{1}H NMR) in excellent yield (90%). Subsequent oxidation of the keto-alcohol **28** with Jones' reagent followed by decarboxylation furnished the desired tricyclic keto-ester **29** (Scheme 8). Similarly, the adduct **23** was also transformed into the keto-ester **31**. Reduction of the adduct **15a** under the aforementioned

(25) Gesson, J.-P.; Mondon, M.; Pokrovska, N. *Synlett* **1997**, 1395−1396.

(26) (a) Nilsson, J. L. G.; Selander, H.; Sievertsson, H.; Scanberg, I.; Svenssom, K. G. *Acta Chem. Scand.* **1971**, *25*, 94−100. (b) Touzeau, F.; Arrault, A.; Guillaumet, G.; Scalbert, E.; Pfeiffer, B.; Rettori, M. C.; Renard, P.; Merour, J. Y. *J. Med. Chem.* **2003**, *46*, 1962−1979.

SCHEME 8

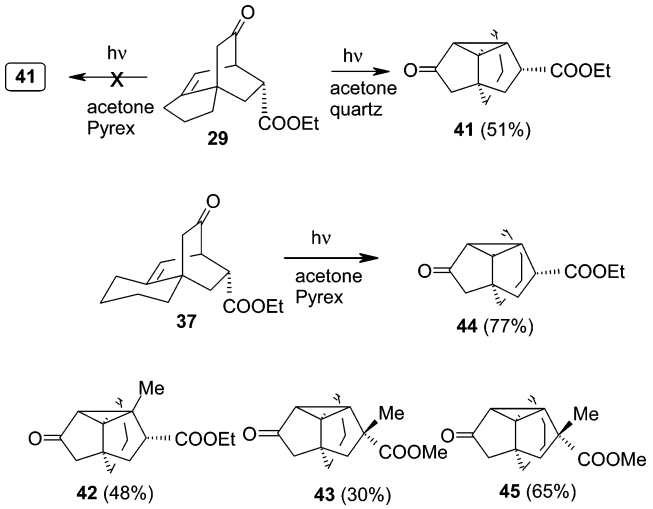


conditions gave the keto-alcohol **33** as a major product along with the ketone **32** as a minor product arising as a result of deoxygenation of the oxirane ring. Similarly, the keto-epoxides **14b** and **15b** were also transformed into the tricyclic keto-esters **37** and **40**, respectively.

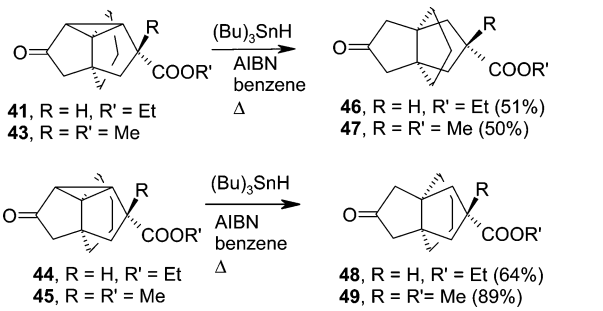
It may be mentioned that the tricyclic compounds of type **14**, **15**, **22**−**25**, and **28**−**40** having a β,γ-enone chromophore are not so readily accessible otherwise, and the present methodology provides an efficient route to such types of systems from simple and readily available aromatic precursors.

Photochemical Reaction of Chromophoric Systems 29, 31, 34, 37, and 40 and Cleavage of the Cyclopropane Ring: Synthesis of [3.3.3]- and [4.3.3]Propellanes. After having developed syntheses of the tricyclic compounds, we first explored the photochemical reaction of **29**, **31**, and **34** upon sensitized irradiation. Photochemical reactions of β,γ-enones have generated interest for a long time,[27] which has considerably increased recently due to their synthetic potential.[27−30] In general, triplet sensitized irradiation leads to a 1,2-acyl shift or oxa-di-π-methane rearrangement, whereas a 1,3-acyl shift is observed upon direct excitation (1S). Demuth and co-workers examined the oxa-di-π-methane reaction in several simple bicyclo[2.2.2]octenones and demonstrated their synthetic application.[28] Subsequently, the photoreaction of more complex β,γ-enone systems was reported.[21c,28,29] Although these reactions are quite characteristic of their excited states, the photochemical reactions depend on the structure of the chromophoric system and the functional groups in a subtle fashion.[27,28b] Keeping the previous facts in mind, a solution of the tricyclic **29** (λ_{max}: 222 and 296 nm) in acetone (solvent as well as sensitizer) was first

SCHEME 9



SCHEME 10



irradiated with a mercury vapor lamp (APP, 125 W) in a Pyrex immersion well (λ > 290 nm). However, no significant reaction was observed (Scheme 9).

The unreactivity of **29** under the aforementioned irradiation conditions could be presumably due to the annulation of the strained five-membered ring through the β-carbon of the β,γ-ene moiety since other tricyclic systems in which the β,γ-ene carbons are not part of such type of an annulation undergo a photochemical 1,2-acyl shift in a facile manner under similar experimental conditions.[27,28b] Therefore, a solution of **29** in acetone was irradiated in a quartz immersion well (λ > 200 nm) for 1 h upon which a reasonably clean reaction was observed (TLC). Removal of the solvent followed by chromatography of the photolysate furnished the tetracyclic photoproduct **41** having a [3.3.3]propellane framework, in good yield (52%) as a result of a 1,2-acyl shift. The structure of the photoproduct **41** was revealed through spectroscopic data and comparison with spectral features of its precursor. Similar irradiation of **31** and **34** also gave the corresponding 1,2-acyl shift (or oxa-di-π-methane) products **42** and **43**, respectively.

Interestingly, irradiation of **37** and **40** in a Pyrex immersion well proceeded smoothly and gave the photoproducts **44** (77%) and **45** (65%) having a [4.3.3]propellane framework, respectively (Scheme 9). These observations further suggest that the unusual behavior of tricyclic **29**, **31**, and **34** could be due to the presence of a strained five-membered ring. Treatment of the tetracyclic **41** and **43**−**45** with tributyltin hydride[31] gave propellanes **46** and **47**−**49**, respectively, as a result of selective cleavage of the peripheral cyclopropane bond (Scheme 10).

(27) (a) Schuster, D. I. In *Rearrangement in Ground and Excited States*; de Mayo, P., Ed.; Academic Press: New York, 1980; Vol. 3, pp 167−279. (b) Engel, P. S.; Schexnayder, M. A. *J. Am. Chem. Soc.* **1975**, *97*, 145−153. (c) Coffin, R. L.; Givens, R. S.; Carlson, R. G. *J. Am. Chem. Soc.* **1974**, *96*, 7554−7556.

(28) (a) Demuth, M.; Hisken, W. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 973−975. (b) Demuth, M.; Schaffner, K. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 820−836.

(29) Zimmerman, H. E.; Armesto, D. *Chem. Rev.* **1996**, *96*, 3065−3112 and references therein.

(30) (a) Armesto, D.; Ortiz, M. J.; Romano, S.; Agarrabeitia, A. R.; Gallega, M. G.; Ramos, A. In *CRC Handbook of Organic Photochemistry and Photobiology*; Horspool, W. M., Lenci, F., Eds.; CRC Press: Boca Raton, FL, 2004; Ch. 95. (b) Singh, V. In *CRC Handbook Organic Photochemistry and Photobiology*; Horspool, W. M., Lenci, F., Eds.; CRC Press: Boca Raton, FL, 2004; Chs. 78 and 79.

(31) Enholm, E. J.; Jia, Z. J. *J. Org. Chem.* **1997**, *62*, 174−181.

Conclusion

In summary, we have described a novel and stereoselective route to functionalized tricycloundecenones, tricyclododecenones, and their photochemical transformation to propellanes. The methodology involves the synthesis of bicyclo[2.2.2]-octenones annulated through one of the bridgeheads via cycloaddition of annulated cyclohexa-2,4-dienones with various acrylates and a photochemical 1,2-acyl shift as key features. The methodology generates all the three rings of propellane in a single stereoselective sequence. We have also presented an efficient cycloaddition of annulated cyclohexa-2,4-dienones with ethyl acrylate and its derivative to various tricyclic compounds containing a β,γ-enone chromophore that are not readily accessible otherwise. The present work also constitutes a nice example of the generation of molecular complexity from simple precursors, which is an important aspect of design and development of new methodology.[32,33]

Experimental Section

4-Hydroxymethyl-5-indanol (5a). To a solution of **13** (22.0 g, 90 mmol) in methanol (100 mL) was added KOH (4.5 g, 80.3 mmol) and Raney nickel (20 g, excess), and the resulting mixture was stirred under a hydrogen atmosphere. After completion of the reaction (TLC, 14 h), the reaction mixture was filtered, and the wet catalyst was washed with methanol (3 × 20 mL) cautiously. Methanol was removed, and an aqueous solution of ammonium chloride was added. It was extracted with ethyl acetate (4 × 50 mL). The combined organic extract was dried over anhydrous sodium sulfate. Removal of solvent followed by chromatography [petroleum ether-ethyl acetate (80:20)] furnished the known compound **5a** in good yield (8.4 g, 57%), mp 109−110 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44 (br s, 1H), 7.03 (d, J = 7.8 Hz, 1H), 6.67 (d, J = 7.8 Hz, 1H), 4.89 (br s, 2H), 2.84−2.76 (m, 4H), 2.02−2.07 (m, 2H). These spectral features are in good agreement with the reported values.[22] ^{13}C NMR (100 MHz, $CDCl_3$): δ 154.1, 142.6, 135.6, 124.1, 120.4, 114.2, 61.0, 32.0, 30.8, 25.3.

Ethyl-11-oxo-10-spiroepoxytricyclo[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (14a). To a solution of **5a** (3.0 g, 18.3 mmol) in acetonitrile (90 mL) was added ethyl acrylate (15 mL, excess), and the reaction mixture was cooled in an ice bath (0−5 °C). A saturated aqueous solution of sodium *m*-periodate (7.7 g, 36 mmol) was added dropwise to the reaction mixture and stirred for 3 h. The reaction mixture was brought to ambient temperature and stirred overnight. The organic layer was separated, and the aqueous layer was saturated with sodium chloride and extracted with ethyl acetate (3 × 40 mL). The combined organic layer was washed with brine and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was chromatographed on silica gel. Elution with petroleum ether-ethyl acetate (95:5) gave the desired adduct **14a** (2.44 g, 51%) as a colorless liquid. IR (neat) ν_{max}: 1731 cm^{-1} (br). ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.84 (d with str, J = 6 Hz, 1H, olefinic H), 4.15 (q with str, J = 7.2 Hz, 2H, -OCH_2), 3.65 (dd, J_1 = 6 Hz, J_2 = 2.4 Hz, 1H), 3.12 (part of an AB system, J_{AB} = 6 Hz, 1H), 3.06 (ddd, J_1 = 9.9 Hz, J_2 = 4.8 Hz, J_3 = 2.4 Hz, 1H), 2.87 (part of an AB system, J_{AB} = 6 Hz, 1H), 2.56−2.40 (m, 2H), 2.32 (dd, J_1 = 12.9 Hz, J_2 = 10.2 Hz, 1H), 2.0−1.86 (overlapped m, 2H), 1.80−1.50 (complex m, 3H), 1.26 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 204.9, 172.5, 156.3, 114.1, 61.1, 58.4, 51.0, 50.0, 48.6, 41.3, 31.3, 30.1, 29.7, 26.5, 14.0. HRMS (*m*/*z*): found 263.1291 [M + H]$^+$; calcd for $C_{15}H_{19}O_4$ 263.1283 [M + H]$^+$.

Methyl-11-oxo-8-methyl-10-spiroepoxytricyclo[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (15a). To a solution of **5a** (1.0 g, 6.1 mmol) and methyl methacrylate (5 mL, excess) in acetonitrile (30 mL) was added an aqueous solution of sodium *m*-periodate (1.5 g, 7 mmol) dropwise at 0−5 °C. After stirring for ∼3 h at 0−5 °C, the reaction mixture was stirred at ambient temperature for 72 h. The organic layer was separated, and the aqueous layer was saturated with sodium chloride and extracted with ethyl acetate (3 × 20 mL). The combined organic layer was washed with brine and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was chromatographed on silica gel. Elution with petroleum ether-ethyl acetate (90:10) gave the desired adduct **15a** (0.352 g, 22%) as a colorless liquid. IR (neat) ν_{max}: 1730 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.86 (m, 1H), 3.71(s, 3H), 3.46 (d, J = 6.4 Hz, 1H), 3.16 (part of the AB system, J_{AB} = 6 Hz, 1H), 2.86 (part of the AB system, J_{AB} = 6 Hz, 1H), 2.40 (m, 2H), 2.32 (d, J = 13.2 Hz, 1H), 1.93−1.90 (d merged with m, J = 13.2 Hz, total 2H), 1.75−1.60 (m merged with signal due to H_2O present in $CDCl_3$, 2H), 1.59−1.40 (m, 1H), 1.31 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 205.2, 176.0, 156.1, 115.9, 58.3, 56.1, 52.4, 50.9, 48.6, 48.0, 40.0, 29.9, 29.7, 26.5, 25.5. HRMS (*m*/*z*): found 285.1033 [M + Na]$^+$, calcd for $C_{15}H_{18}O_4Na$ 285.1020 [M + Na]$^+$.

2,3-Dihydrospiro[indene-4,2′-oxiran]-5(1*H*)-one (6a). To a solution of **5a** (1.0 g, 6.1 mmol) in acetonitrile (15 mL) was added a saturated aqueous solution of sodium *m*-periodate (2.6 g, 12 mmol) dropwise (20 min) at 0−5 °C. The reaction mixture was saturated with sodium chloride, the organic layer was separated, and the aqueous layer was extracted with ethyl acetate (3 × 20 mL). The combined organic extract was dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was chromatographed on silica gel. Elution with petroleum ether-ethyl acetate (90:10) gave the desired cyclohexadienone **6a** (0.623 g, 63%) which solidified in a refrigerator, mp 66−68 °C. IR (KBr) ν_{max}: 1667, 1630 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.16 (d, J = 9.9 Hz, 1H), 6.05 (d, J = 9.9 Hz, 1H), 3.27 (s, 2H), 2.68−2.60 (m, 2H), 2.60−2.51 (m, 1H), 2.40−2.28 (m, 1H), 2.11−2.01 (m, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 197.1, 147.8, 141.2, 139.4, 124.4, 58.6, 57.2, 33.9, 30.9, 23.0. HRMS (*m*/*z*): found 163.0767 [M + H]$^+$; calcd for $C_{10}H_{11}O_2$ 163.0759 [M + H]$^+$.

Preaparation of 15a by Reaction of Isolated Cyclohexa-2,4-dienone 6a and Methyl Methacrylate. A mixture of cyclohexadienone **6a** (0.5 g, 3 mmol) and methyl methacrylate (3 mL) in *o*-dichlorobenzene (3 mL) was heated in a sealed tube at 80 °C for 8 h. The reaction mixture was charged on a column of silica gel and chromatographed. Elution with petroleum ether-ethyl acetate (90:10) gave the adduct **15a** (0.400 g, 50%), which was found to be identical to the sample obtained by the method described previously.

6-Methyl-5-indanol (18). To a stirred solution of 6-hydroxymethyl-5-indanol **16** (1.0 g, 6.1 mmol) in aqueous KOH (3.7 M, 20 mL), a Raney nickel alloy (1.2 g, 30 mmol) was added in portions at 0−10 °C. The reaction mixture was stirred under hydrogen atmosphere. After completion of the reaction (TLC, 24 h), the reaction mixture was decanted into a beaker containing crushed ice and concd hydrochloric acid (6.4 mL). The residual wet Raney nickel was washed with aqueous KOH solution (5 M, 3 × 10 mL), and the combined acidic aqueous layer was extracted with diethyl ether (3 × 30 mL) and washed with brine (1 × 20 mL). The organic layer was dried over anhydrous sodium sulfate. Removal of solvent furnished **18**, which was recrystallized from petroleum ether (0.9 g, quantitative), mp 83−84 °C (lit. mp 79−80.5 and 83−84 °C[24b]). IR (KBr) ν_{max}: 3431 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.97 (s, 1H), 6.66 (s, 1H), 4.59 (br s, 1H, hydroxyl proton), 2.87−2.78 (m, 4H), 2.21 (s, 3H), 2.09−2.00 (m, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 152.4, 143.4, 136.3, 126.5, 121.3, 111.1, 32.9, 32.2, 26.0, 15.9.

(32) (a) Trost, B. M. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 259−281. (b) Corey, E. J.; Cheng, X.-M. *The Logic of Chemical Synthesis*; John Wiley and Sons: New York, 1989.

(33) Chanon, M.; Barone, R.; Baralotto, C.; Julliard, M.; Hendrickson, J. B. *Synthesis* **1998**, 1559−1583.

4-Hydroxymethyl-6-methyl-5-indanol (19). To a stirred solution of **18** (3.0 g, 20.27 mmol) in aqueous sodium hydroxide (2 M, 200 mL) was added formaldehyde (10 mL, excess) and stirred for 24 h at ambient temperature. The reaction mixture was neutralized with ammonium chloride and extracted with ethyl acetate (3 × 30 mL). The organic layer was dried over anhydrous sodium sulfate. Removal of the solvent followed by chromatography (petroleum ether-ethyl acetate, 95:5) first gave some unreacted starting material followed by the desired compound **19** as a colorless solid (3.1 g, 86%), mp 84−85 °C. IR (KBr) ν_{max}: 3440 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.50 (br s, 1H, hydroxyl proton), 6.94 (s, 1H), 4.86 (s, 2H), 2.83−2.72 (m, 4H), 2.20 (s, 3H), 2.16−1.98 (m, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 152.8, 139.5, 134.9, 125.8, 123.2, 119.5, 61.9, 32.1, 30.9, 25.3, 15.8. HRMS (*m*/*z*): found 201.0896 [M + Na]$^+$; calcd for $C_{11}H_{14}O_2Na$ 201.0891 [M + Na]$^+$.

Ethyl-7-bromo-11-oxo-10-spiroepoxytricyclo[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (22). To a stirred solution of 6-bromo-4-hydroxymethyl-5-indanol **13** (1.0 g, 4.1 mmol) and ethyl acrylate (3 mL, excess) in acetonitrile (30 mL) was added an aqueous solution of sodium metaperiodate (1.9 g, 8.8 mmol) dropwise at ∼0−5 °C. After stirring the reaction mixture for 12 h, sodium chloride was added, and the stirring was continued for another 1 h. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (3 × 50 mL). The combined organic layer was washed with brine and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was chromatographed on silica gel. Elution with petroleum ether-ethyl acetate (95:5) gave the desired adduct **22** as a colorless liquid (1.12 g, 80%). IR (neat) ν_{max}: 1736 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.03 (s, 1H), 4.32−4.01 (m, 2H), 3.28−3.21 (part of an AB system, J_{AB} = 5.5 Hz merged with a signal due to another proton, total 2H), 2.94 (part of an AB system, J_{AB} = 5.5 Hz, 1H), 2.68−2.38 (m, 3H), 2.06−1.88 (m, 1H), 1.84−1.46 (m, 4H), 1.30 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 195.7, 171.5, 154.1, 120.3, 66.5, 61.3, 57.4, 51.5, 49.2, 48.7, 35.8, 29.9, 29.6, 26.5, 14.1. HRMS (*m*/*z*): found 363.0205 [M + Na]$^+$; calcd for $C_{15}H_{17}O_4BrNa$ 363.0208 [M + Na]$^+$.

Ethyl-7-methyl-10-spiroepoxytricyclo[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (23). Oxidation of 6-methyl-4-hydroxymethyl-5-indanol **19** (1.72 g, 9.6 mmol), with sodium *m*-periodate (4.3 g, 20 mmol) in the presence of ethyl acrylate (15 mL, excess) in acetonitrile as described earlier followed by workup and chromatography (petroleum ether-ethyl acetate 95:5) of the crude product furnished the adduct **23** (2.0 g, 73%). IR (neat) ν_{max}: 1734 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.53 (s, 1H), 4.17−4.11 (m, 2H), 3.14 (part of an AB system, J_{AB} = 5.7 Hz, 1H), 2.87 (part of an AB system, J_{AB} = 5.7 Hz, 1H), 2.74 (dd, J_1 = 9.9 Hz, J_2 = 5.4 Hz, 1H), 2.55−2.35 (m, 3H), 1.91−1.80 (m, 1H), 1.74−1.50 (m merged with signal due to H_2O in $CDCl_3$, 4H), 1.30−1.24 (s merged with triplet, total 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 205.1, 173.2, 154.6, 119.2, 60.7, 58.3, 51.2, 51.1, 48.5, 46.2, 34.8, 30.0, 29.8, 26.6, 15.8, 14.2. HRMS (*m*/*z*): found 277.1444 [M + H]$^+$; calcd for $C_{16}H_{21}O_4$: 277.1440 [M + H]$^+$.

Methyl-7-bromo-8-methyl-11-oxo-10-spiroepoxytricyclo-[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (24). Oxidation of 6-bromo-4-hydroxymethyl-5-indanol **13** (0.5 g, 2.05 mmol), with sodium *m*-periodate (0.860 g, 4 mmol) in the presence of methyl methacrylate (5 mL, excess) in acetonitrile as described earlier followed by workup and chromatography (petroleum ether-ethyl acetate 95:5) of the crude product furnished the adduct **24** (0.423 g, 60%) as a colorless liquid. IR (neat) ν_{max}: 1734 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.07 (t, J = 2 Hz, 1H), 3.74 (s, 3H), 3.32 (part of an AB system, J_{AB} = 5.5 Hz, 1H), 2.93 (part of an AB system, J_{AB} = 5.5 Hz, 1H), 2.62−2.4 (m, 2H), 2.13 (q, J = 12.4 Hz, 2H), 2.03−1.89 (m, 1H), 1.79−1.58 (m, merged with signal due to H_2O in $CDCl_3$, 2H), 1.54−1.4 (m, 1H), 1.36 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 195.7, 173.7, 153.7, 122.5, 73.9, 57.1, 52.5, 52.3, 51.4, 49.0, 43.8, 29.9, 29.7, 26.6, 22.8. HRMS (*m*/*z*): found 341.0387 [M + H]$^+$; calcd for $C_{15}H_{18}O_4Br$ 341.0388 [M + H]$^+$.

Methyl-7,8-dimethyl-11-oxo-10-spiroepoxytricyclo[5.2.2.0^{1,5}]-undec-5-en-8-carboxylate (25). Oxidation of 6-methyl-4-hydroxymethyl-5-indanol **19** (0.5 g, 2.80 mmol), with sodium *m*-periodate (1.0 g, 4.6 mmol) in the presence of methyl methacrylate (5 mL, excess) in acetonitrile as described earlier, followed by workup and chromatography [petroleum ether-ethyl acetate (95:5)] of the crude product furnished the adduct **25** (0.186 g, 24%). IR (neat) ν_{max}: 1736 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.52 (s, 1H), 3.68 (s, 3H), 3.21 (part of an AB system, J_{AB} = 6 Hz, 1H), 2.86 (part of an AB system, J_{AB} = 6 Hz, 1H), 2.6−2.45 (m, 2H), 2.17 (part of AB system, J_{AB} = 12 Hz, 1H), 1.97 (part of an AB system, J_{AB} = 12 Hz, partly merged with another m, 1H), 1.95 (m, 1H), 1.8−1.5 (m, 2H), 1.5−1.4 (m, 1H), 1.25 (s, 3H), 1.21 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 205.2, 175.5, 154.4, 121.4, 58.1, 55.5, 52.0, 51.0, 49.6, 48.3, 43.9, 30.0, 29.9, 26.5, 21.8, 13.6. HRMS (*m*/*z*): found 299.1266 [M + Na]$^+$; calcd for $C_{16}H_{20}O_4Na$ 299.1259 [M + Na]$^+$.

Ethyl-7-hydroxymethyl-11-oxo-10-spiroepoxytricyclo[5.2.2.0^{1,5}]-undec-5-en-8-carboxylate (27a) and Ethyl-1-hydroxymethyl-10-oxo-11-spiroepoxytricyclo[5.2.2.0^{2,6}]undec-2-en-9-carboxylate (27b). Oxidation of 4,6-bis-hydroxymethyl-5-indanol **17** (2 g, 10.3 mmol) with sodium *m*-periodate (2.35 g, 11 mmol) in the presence of ethyl acrylate (10 mL, excess) in acetonitrile-methanol (60 mL, 5:1) as described earlier followed by workup and chromatography [petroleum ether-ethyl acetate (90:10)] first gave the adduct **27a** (0.73 g, 24%) as a solid, mp 98−100 °C. Continued elution furnished the other adduct **27b** in moderate yield (0.69 g, 23%) as a liquid.

Data for 27a. IR (KBr) ν_{max}: 3481, 1732 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.71 (s, 1H), 4.15 (q, J = 6.9 Hz, 2H), 3.99 (ddd, J_1 = 16.5 Hz, J_2 = 12.3, J_3 = 7.8 Hz, 2H), 3.16 (part of an AB system, J_{AB} = 5.7 Hz, 1H), 3.03 (dd, J_1 = 10.2 Hz, J_2 = 4.8 Hz, 1H), 2.90 (part of an AB system, J_{AB} = 5.7 Hz, 1H), 2.62−2.41 (m, 4H), 2.05−1.88 (m, 1H), 1.80−1.60 (m, 3H), 1.60−1.45 (m, 1H), 1.27 (t, J = 6.9 Hz, 3H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 206.9, 172.5, 155.3, 115.5, 61.6, 61.0, 58.8, 56.4, 51.2, 48.6, 41.9, 34.5, 30.2, 29.8, 26.5, 14.1. HRMS (*m*/*z*): found 315.1219 [M + Na]$^+$; calcd for $C_{16}H_{20}O_5Na$ 315.1208 [M + Na]$^+$.

Crystal Data. $C_{16}H_{20}O_5$, M = 292.32, monoclinic, space group *P*21/*a*, *a* = 8.8668(7) Å, *b* = 12.9797(15) Å, *c* = 13.0907(10) Å, $\alpha = \gamma = 90°$, β = 106.213(4)°, U 1446.7(6) Å^3, D_c = 1.342 mg/m^3, *Z* = 4, *F*(0,0,0) = 624, λ = 71073 Å, μ = 0.099 mm^{-1} total/unique reflections = 2723/2542 [R(int) = 0.0146], *T* = 293(2) K, θ range = 1.62−24.97^o, final R[$I>2\sigma(I)$], R1 = 0.0489, wR2 = 0.1181, R (all data): R1 = 0.1027, wR2 = 0.1381.

Data for 27b. IR (neat) ν_{max}: 3428, 1735 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.20−3.95 (m, 4H), 3.17 (part of an AB system partly merged with a m, J_{AB} = 6 Hz, 1H), 3.14 (m,1H), 2.90 (part of an AB system, J_{AB} = 6 Hz, 1H), 2.66−2.64 (m, 1H), 2.54−2.47 (m, 6H), 2.15−1.90 (m, 2H), 1.81 (ddd, J_1 = 7.5, J_2 = 5.1, J_3 = 2.5 Hz, 1H), 1.27 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 205.2, 172.6, 144.4, 136.4, 60.9, 60.2, 58.2, 57.4, 52.7, 41.2, 38.3, 32.9, 31.1, 28.8, 23.4, 14.1. HRMS (*m*/*z*): found 315.1220 [M + Na]$^+$; calcd for $C_{16}H_{20}O_5Na$ 315.1208 [M + Na]$^+$.

1-Hydroxymethyl-5,6,7,8-tetrahydro-2-naphthol (5b), 3-Hydroxymethyl-5,6,7,8-tetrahydro-2-naphthol (5c), and 1,3-Dihydroxymethyl-5,6,7,8-tetrahydro-2-naphthol (5d). To 5,6,7,8-tetrahydro-2-naphthol **12b** (5.0 g, 33.8 mmol) was added aq NaOH [1.4 g, 35 mmol dissolved in water (50 mL)] at ∼5 °C, and then aq formaldehyde (36%, 2.8 mL, 34 mmol) was added. The reaction mixture was stirred at ambient temperature for 12 h. It was quenched with solid ammonium chloride and extracted with ethyl acetate (4 × 50 mL). The combined extract was dried on sodium sulfate. The solvent was removed under vacuum, and the residue was chromatographed on silica gel. Elution with petroleum ether-ethyl acetate (90:10) first gave some unreacted starting material. Further elution with petroleum ether-ethyl acetate (80:20) furnished a mixture of **5b** and **5c** (2.4 g, 40%), which solidified in the refrigerator. Subsequent elution with ethyl acetate gave the dihydroxymethylated compound **5d** as a solid (1.0 g, 14%).

Data for 5b,c. Mp 52−56 °C. IR (KBr) ν_{max}: 3402, 1596 cm^{-1}, ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.87 (d, J = 8.4 Hz), 6.72 (s), 6.62 (d, J = 8.4 Hz), 6.54 (s), 4.82 (s), 4.70 (s), 2.68−2.56 (m), 1.78−1.68 (m) (signals due to major isomer). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 153.8, 153.1, 138.3, 134.7, 129.7, 128.9, 128.6, 128.5, 122.5, 122.1, 116.2, 114.0, 63.9, 59.9, 29.4, 29.2, 28.4, 26.1, 23.3, 23.1, 23.0, 22.7 (signals due to both isomers). HRMS (*m*/*z*): found 201.0893 [M+Na]$^+$; calcd for $C_{11}H_{14}O_2Na$ 201.0891 [M+Na]$^+$.

Data for 5d. Mp 120−122 °C. IR (KBr) ν_{max}: 3460, 3228 cm^{-1}. ^{1}H NMR (400 MHz, CD_3OD): δ 6.83 (s, 1H), 4.76 (s, 2H), 4.63 (s, 2H), 2.73−2.66 (m, 4H), 1.79−1.71 (m, 4H). ^{13}C NMR (100 MHz, CD_3OD): δ 153.7, 136.2, 129.3, 129.2, 126.0, 124.9, 62.3, 58.3, 30.6, 27.0, 24.6, 24.3. HRMS (*m*/*z*): found 231.0988 [M + Na]$^+$; calcd for $C_{12}H_{16}O_3Na$ 231.0997 [M + Na]$^+$.

5,6,7,8-Tetrahydro-2*H*-spiro[naphthalene-1,2′-oxiran]-2-one (6b). To a mixture of **5b,c** (2.3 g, 12.8 mmol) in acetonitrile (50 mL) was added aqueous solution of sodium *m*-periodate (6 g, 28 mmol) dropwise (30 min) at 0−5 °C. The reaction mixture was saturated with sodium chloride, the organic layer was separated, and the aqueous layer was extracted with ethyl acetate (3 × 50 mL). The combined organic extract was dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was chromatographed on silica gel. Elution with petroleum ether-ethyl acetate (85:15) gave the desired cyclohexadienone **6b** (1.5 g, 66%) as a yellow liquid, which solidified after being kept in a refrigerator, mp 80−82 °C. IR (KBr) ν_{max}: 1669, 1636 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.96 (d, J = 9.9 Hz, 1H), 6.11 (d, J = 9.9 Hz, 1H), 3.21 (part of an AB system, J_{AB} = 8 Hz, 1H), 3.13 (part of an AB system, J_{AB} = 8 Hz, 1H), 2.33−2.20 (m, 3H), 1.94−1.55 (m, 5H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 196.4, 147.0, 141.7, 132.0, 123.3, 58.6, 58.5, 28.9, 22.5, 22.2, 21.3. HRMS (*m*/*z*): found 177.0907 [M + H]$^+$; calcd for $C_{11}H_{13}O_2$ 177.0916 [M + H]$^+$.

Ethyl-12-oxo-11-spiroepoxytricyclo[6.2.2.0^{1,6}]dodec-6-en-9-carboxylate (14b). A mixture of cyclohexadienone **6b** (1.15 g, 6.5 mmol), ethyl acrylate (5.3 mL, excess), and *o*-dichlorobenzene (5 mL) was taken in a sealed tube and heated to 110 °C for 10 h, after which the reaction mixture was charged on a column of silica gel and chromatographed. Elution with petroleum ether-ethyl acetate (90:10) furnished the adduct **14b** (1.3 g, 72%) as a solid, mp 60−62 °C. IR (KBr) ν_{max}: 1731 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.81 (d, J = 6.4 Hz, 1H), 4.19−4.13 (m, 2H), 3.64 (dd, J_1 = 6 Hz, J_2 = 2 Hz, 1H), 3.10 (part of an AB system, J_{AB} = 5.6 Hz, 1H), 3.04 (ddd, J_1 = 10 Hz, J_2 = 5.2 Hz, J_3 = 2.4 Hz, 1H), 3.00 (part of an AB system, J_{AB} = 5.6 Hz, 1H), 2.50−2.43 (m, 1H), 2.33−2.25 (m, 1H), 2.17−1.95 (m, 2H), 1.77−1.30 (m merged with triplet, 6H), 1.27 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 204.1, 172.6, 149.3, 117.6, 61.1, 58.8, 50.0, 49.3, 40.3, 32.9, 27.9, 24.5, 21.6, 20.8, 14.1. HRMS (*m*/*z*): found 299.1269 [M + Na]$^+$; calcd for $C_{16}H_{20}O_4Na$ 299.1259 [M + Na]$^+$.

Methyl-9-methyl-12-oxo-11-spiroepoxytricyclo[6.2.2.0^{1,6}]dodec-6-en-9-carboxylate (15b). Compound **6b** (1.4 g, 7.95 mmol), methyl methacrylate (4 mL, excess), and *o*-dichlorobenzene (5 mL) were heated in a sealed tube at ∼110 °C for 8 h. Chromatography of the reaction mixture [petroleum ether-ethyl acetate (90:10)] gave the adduct **15b** (0.960 g, 44%) as a solid, mp 70−72 °C. IR (KBr) ν_{max}: 1738, 1732 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.84 (d with str J = 6.2 Hz, 1H), 3.71 (s, 3H), 3.46 (d, J = 6.4 Hz, 1H), 3.14 (part of an AB system, J_{AB} = 5.6 Hz, 1H), 3.00 (part of an AB system, J_{AB} = 5.6 Hz, 1H), 2.48−2.36 (m, 2H), 2.28−2.21 (m, 1H), 1.75−1.61 (m, 3H), 1.60−1.50 (m, 1H), 1.49−1.35 (m, 2H), 1.31−1.24 (m merged with s, total 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 204.5, 176.3, 149.1, 119.7, 58.9, 55.4, 52.6, 50.1, 46.9, 41.7, 40.1, 28.0, 25.8, 24.8, 21.8, 21.1. HRMS (*m*/*z*): found 277.1446 [M + H]$^+$; calcd for $C_{16}H_{21}O_4$ 277.1440 [M + H]$^+$.

Ethyl-11-oxo-tricyclo[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (29). To a solution of the adduct **14a** (2.0 g, 7.6 mmol) in methanol-water (6:1, 70 mL) was added zinc (activated 18 g, excess) and NH_4Cl (3.3 g, 59 mmol). The reaction mixture was stirred at ambient temperature (∼30 °C) for 8 h (TLC). It was filtered on a Celite bed and washed with ethyl acetate. The filtrate was concentrated under reduced pressure and diluted with water and extracted with ethyl acetate (4 × 40 mL). The combined organic layer was washed with brine and dried. The solvent was removed under reduced pressure, and the residue was chromatographed. Elution with petroleum ether-ethyl acetate (88:12) gave the alcohol **28** (syn/anti mixture) as a colorless liquid (1.81 g, 90%) [IR (neat) ν_{max}: 3480, 1718 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.77−5.71 (m, 1H), 4.17−4.05 (m, 2H), 3.85−3.62 (m, 2H), 3.51 (dd, J_1 = 6 Hz, J_2 = 2.4 Hz, 1H), 3.0−2.65 (m, 2H), 2.6−2.42 (m, 1H), 2.4−2.22 (m, 1H), 2.00−1.64 (m, 7H), 1.64−1.58 (m, 1H), 1.25 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 215.2, 172.8, 159.1, 112.1, 61.4, 61.0, 52.8, 51.4, 48.8, 40.4, 34.0, 30.1, 29.5, 25.9, 14.1].

The keto-alcohol **28** thus obtained was subjected to oxidation and decarboxylation as described next. Thus, a solution of the β-keto-alcohol **28** (1.5 g, 5.64 mmol) in acetone (50 mL) was oxidized with freshly prepared Jones' reagent at 0 °C. After completion of the reaction (TLC), acetone was removed under vacuum at ambient temperature, and the residue was diluted with water (10 mL) and extracted with diethyl ether (3 × 25 mL). The combined organic layer was washed with brine and dried over anhydrous sodium sulfate. The solvent was removed, and the resulting β-keto acid was dissolved in a THF-water mixture (1:1, 30 mL) and refluxed for 10 h. It was brought to ambient temperature, and sodium chloride was added. The organic layer was separated, and the aqueous layer was extracted with diethyl ether (3 × 30 mL). The combined organic layer was washed with saturated sodium bicarbonate and brine and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was chromatographed on silica gel. Elution with petroleum ether-ethyl acetate (98:2) gave **29** (0.780 g, 60%) as a colorless liquid. IR (neat) ν_{max}: 1732 cm^{-1} (br). UV (MeOH) λ_{max}: 220, 290 nm. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.72 (d, J = 6.3 Hz, 1H), 4.12 (q with structure, J = 7 Hz, 2H), 3.46 (dd, J_1 = 6.3 Hz, J_2 = 2.1 Hz, 1H), 2.92 (m, 1H), 2.50−2.45 (m, 1H), 2.34−2.32 (m, 1H), 2.11 (d, J = 18 Hz, 1H), 1.99−1.70 (m, 7H), 1.24 (t, J = 7 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 211.6, 173.2, 157.8, 112.5, 60.9, 51.5, 46.9, 44.7, 40.1, 35.5, 34.1, 30.2, 25.9, 14.1. HRMS (*m*/*z*): found 257.1143 [M + Na]$^+$; calcd for $C_{14}H_{18}O_3Na$ 257.1154 [M + Na]$^+$.

Ethyl-7-methyl-11-oxo-tricyclo[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (31). To a solution of the adduct **23** (1.5 g, 5.43 mmol) in methanol-water (6:1, 70 mL) was added NH_4Cl (1.3 g, 21.5 mmol) and activated zinc (12 g, excess). The reaction mixture was stirred at ambient temperature for 6 h (TLC). It was filtered on a Celite bed and washed with ethyl acetate. The filtrate was concentrated under reduced pressure and diluted with water and extracted with ethyl acetate (4 × 30 mL). The combined organic layer was washed with brine and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was chromatographed. Elution with petroleum ether-ethyl acetate (90:10) gave the alcohol **30** (syn/anti mixture) as a colorless liquid (1.30 g, 86%). [IR(neat) ν_{max}: 3499, 1716 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.44 (s, 1H), 4.24−4.00 (m, 2H), 3.90−3.60 (m, 2H), 2.8 (br s, 1H) 2.65−2.42 (m, 1H), 2.4−2.23 (m, 1H), 2.06−2.02 (m, 1H), 2.02−1.60 (m, 5H), 1.50 (ddd, J_1 = 8.4 Hz, J_2 = 6.6 Hz, J_3 = 1.8 Hz, 1H), 1.6−1.4 (m, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 214.8, 173.2, 157.4, 117.2, 61.8, 60.6, 52.9, 51.9, 48.4, 45.3, 34.1, 33.1, 30.0, 25.7, 15.5, 14.1].

The keto-alcohol **30** thus obtained was subjected to oxidation and decarboxylation to give **31** as follows. A solution of the β-keto-alcohol **30** (1.0 g, 3.59 mmol) in acetone (40 mL) was oxidized with freshly prepared Jones' reagent at 0 °C. After completion of reaction (TLC), isopropyl alcohol was added to destroy excess oxidant. Acetone was removed in vacuum at ambient temperature, and the residue was diluted with water (10 mL) and extracted with diethyl ether (3 × 25 mL). The combined organic layer was washed

with brine and dried over anhydrous sodium sulfate. The solvent was removed, and the resulting β-keto acid was dissolved in a THF-water mixture (1:1, 45 mL) and refluxed for 10 h. Workup as described earlier followed by chromatography [petroleum ether-ethyl acetate (98:2)] gave the titled compound **31** (0.545 g, 61%) as a colorless liquid. IR (neat) ν_{max}: 1729 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.40 (s, 1H), 4.15−4.07 (m, 2H), 2.63−2.51 (m, 2H), 2.35−2.25 (m, 1H), 2.25−1.76 (m, 7H), 1.68−1.61 (m, 1H), 1.35−1.20 (triplet merged with a singlet, total 6H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 211.2, 173.7, 156.3, 117.4, 60.5, 51.7, 46.5, 44.9, 44.4, 37.7, 35.5, 30.1, 25.8, 15.7, 14.2. HRMS (*m*/*z*): found 249.1479 [M + H]$^+$; calcd for $C_{15}H_{21}O_3$ 249.1491 [M + H]$^+$.

Methyl-8,10-dimethyl-11-oxo-tricyclo[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (32) and Methyl-10-hydroxymethyl-8-methyl-11-oxo-tricyclo[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (33). To a solution of the adduct **15a** (0.75 g, 2.9 mmol) in methanol-water (6:1, 84 mL) was added NH_4Cl (0.75 g, excess) and activated zinc (5 g, excess). The reaction mixture was stirred at ambient temperature for 8 h (TLC). It was filtered on a Celite bed and washed with ethyl acetate. The filtrate was concentrated under reduced pressure and diluted with water and extracted with ethyl acetate (4 × 20 mL). The combined organic layer was washed with brine and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was chromatographed. Elution with petroleum ether-ethyl acetate (90:10) first gave the minor ketone **32** (0.080 g, 11%) as a colorless liquid. IR (neat) ν_{max}: 1722 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.77−5.74 (m, 1H), 3.67 (s, 3H), 3.27 (d, J = 6 Hz, 1H), 2.46−2.40 (m, 1H), 2.32−2.22 (m, 1H), 2.15 (dd, J_1 = 13.6 Hz, J_2 = 2 Hz, 1H), 1.88−1.72 (m, 3H), 1.70−1.65 (m merged with signal due to H_2O present in $CDCl_3$, 5H), 1.22 (s, 3H), 1.07 (d, J = 7.6 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 215.8, 178.7, 158.9, 114.8, 57.5, 52.4, 50.3, 48.0., 47.1, 35.7, 34.1, 30.3, 25.9, 25.5, 11.0. HRMS (*m*/*z*): found 271.1323 [M + Na]$^+$; calcd for $C_{15}H_{20}O_3Na$ 271.1310 [M + Na]$^+$.

Continued elution with petroleum ether-ethyl acetate (80:20) furnished the β-keto-alcohol **33** as a colorless liquid (0.600 g, 80%). IR (neat) ν_{max}: 3512, 1720 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.78−5.76 (m, 1H), 3.87−3.72 (m, 1H), 3.70−3.66 (m merged with s, total 4H), 3.32 (d, J = 6 Hz, 1H), 2.46−2.41 (m, 1H), 2.31−2.27 (m, 1H), 2.20 (dd, J_1 = 13.6 Hz, J_2 = 2 Hz, 1H), 2.09−2.00 (m, 1H), 2.00−1.82 (m, 1H), 1.82−1.73 (m, 3H), 1.56 (d, J = 14 Hz, 1H), 1.28 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 217.2, 176.3, 158.9, 114.7, 61.0, 57.7, 54.0, 52.6, 48.9, 48.4, 37.0, 34.0, 30.1, 26.2, 25.2. HRMS (*m*/*z*): found 265.1451 [M + H]$^+$; calcd for $C_{15}H_{21}O_4$ 265.1440 [M + H]$^+$.

Methyl-8-methyl-11-oxo-tricyclo[5.2.2.0^{1,5}]undec-5-en-8-carboxylate (34). The keto-alcohol **33** (0.540 g, 2 mmol) thus obtained was oxidized with Jones' reagent as described earlier, and the resulting β-keto acid was decarboxylated in refluxing aq THF. Usual workup and chromatography [petroleum ether-ethyl acetate (90:10)] gave **34** as a colorless liquid (0.300 g, 63%). IR ν_{max}: 1732 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.76 (d, J = 6 Hz, 1H), 3.67 (s, 3H), 3.30 (d, J = 6 Hz, 1H), 2.46−2.26 (m, 3H), 2.08 (part of an AB system J_{AB} = 18.3 Hz, 1H), 1.94 (d of part of an AB system, J_{AB} = 18.3 Hz, J_2 = 3.3 Hz, 1H), 1.87−1.70 (m, 4H), 1.52 (d, J = 12.8 Hz, 1H), 1.28 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 212.0, 176.3, 157.5, 114.6, 57.6, 52.3, 47.17, 47.15, 45.0, 42.7, 35.4, 30.1, 26.9, 25.9. HRMS (*m*/*z*): found 235.1329 [M + H]$^+$; calcd for $C_{14}H_{19}O_3$ 235.1334 [M + H]$^+$.

Ethyl-11-methyl-12-oxo-tricyclo[6.2.2.0^{1,6}]dodec-6-en-9-carboxylate (35) and Ethyl-11-hydroxymethyl-12-oxo-tricyclo-[6.2.2.0^{1,6}]dodec-6-en-9-carboxylate (36). To a solution of epoxy ketone **14b** (2.5 g, 9.06 mmol) in methanol-water (6:1, 35 mL) was added zinc (activated, 18 g, excess) and ammonium chloride (1.8 g, excess). The reaction mixture was stirred at ambient temperature for 8 h. The reaction mixture was then filtered through a Celite bed and washed with ethyl acetate (2 × 5 mL). The filtrate was concentrated under vacuum, and the residue was diluted with water and extracted with ethyl acetate (3 × 50 mL). The combined extract was washed with brine and dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was purified by column chromatography. Elution with petroleum ether-ethyl acetate (92:8) first gave **35** (0.189 g, 8%) as a colorless liquid. Further elution with petroleum ether-ethyl acetate (80:20) gave the keto-alcohol **36** (1.882 g, 75%, mixture of syn/anti isomers) as a thick colorless liquid.

Data for 35. IR (neat) ν_{max}: 1727 cm^{-1}, ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.69 (d with str, J = 6.3 Hz, 1H), 4.17−4.07 (m, 2H), 3.42 (dd, J_1 = 2.1 Hz, J_2 = 6.6 Hz, 1H), 2.81 (ddd, J_1 = 9.9 Hz, J_2 = 6.0 Hz, J_3 = 2.1 Hz, 1H), 2.36−2.30 (m, 2H), 1.92−1.83 (m, 2H), 1.75−1.51 (m, 7H), 1.25 (t, J = 7.2 Hz, 3H), 1.02 (d, J= 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 213.8, 173.3, 153.2, 115.9, 61.0, 50.6, 45.4, 42.7, 40.3, 28.9, 28.2, 26.5, 20.5, 18.1, 14.2, 11.3. HRMS (*m*/*z*): found 263.1660 [M + H]$^+$; calcd for $C_{16}H_{23}O_3$ 263.1647 [M + H]$^+$.

Data for 36. IR (neat) ν_{max}: 3479, 1731 cm^{-1}, ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.71 and 5.65 (two d, J = 6.3 Hz, total 1H), 4.20−4.05 (m, 2H), 3.95−3.80 (m, 1H), 3.74−3.64 (m, 1H), 3.53−3.47 (m, 1H), 2.98−2.89 (m, 1H), 2.41−2.23 (m, 2H), 2.08−1.84 (m, 3H), 1.80−1.62 (m, 7H), 1.25 (t, J = 7 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 214.0, 173.2, 153.3, 115.6, 61.0, 60.0, 52.0, 50.9, 42.1, 40.4, 30.7, 28.1, 26.3, 20.3, 18.0, 14.1 (signals due to one isomer). HRMS (*m*/*z*): found 279.1602 [M + H]$^+$; calcd for $C_{16}H_{23}O_4$ 279.1596 [M + H]$^+$.

Ethyl-12-oxo-tricyclo[6.2.2.0^{1,6}]dodec-6-en-9-carboxylate (37). To a solution of β-keto-alcohol **36** (1.882 g, 6.77 mmol) in acetone (30 mL) was added freshly prepared Jones' reagent at 5 °C. After completion of the reaction (TLC), acetone was removed under vacuum. The residue was diluted with water (20 mL) and extracted with ethyl acetate (4 × 20 mL). The extract was combined and dried over anhydrous sodium sulfate, and the solvent was removed under vacuum to give the crude acid, which was dissolved in the THF-H_2O mixture (1:1, 40 mL) and refluxed for 12 h. The reaction mixture was saturated with NaCl, and the organic layer was separated. The aqueous layer was extracted with diethyl ether (3 × 20 mL). The combined organic extract was dried over sodium sulfate. The solvent was removed under reduced pressure, and the residue was chromatographed on silica gel. Elution with petroleum ether-ethyl acetate (90:10) gave **37** (1.110 g, 66%) as a colorless liquid. IR (neat) ν_{max}: 1728 cm^{-1}. UV (MeOH) λ_{max}: 215, 294 nm. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.68 (d, J = 6.2 Hz, 1H), 4.16−4.09 (m, 2H), 3.45 (dd, J_1 = 6.2 Hz, J_2 = 2.1 Hz, 1H), 2.95 (ddd, J_1 = 10.2 Hz, J_2 = 5.7 Hz, J_3 = 2.4 Hz, 1H), 2.38−2.24 (m, 2H), 2.06−1.76 (m, 3H), 1.73−1.58 (m, 7H), 1.25 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 210.2, 173.0, 151.1, 116.1, 60.7, 51.1, 44.9, 40.0, 39.9, 35.0, 30.9, 26.3, 20.9, 18.6, 14.0. HRMS (*m*/*z*): found 249.1487 [M + H]$^+$; calcd for $C_{15}H_{21}O_3$ 249.1491 [M + H]$^+$.

Methyl-9,11-dimethyl-12-oxo-tricyclo[6.2.2.0^{1,6}]dodec-6-en-9-carboxylate (38) and Methyl-9-methyl-11-hydroxymethyl-12-oxo-tricyclo[6.2.2.0^{1,6}]dodec-6-en-9-carboxylate (39). To a solution of epoxy ketone **15b** (0.900 g, 3.2 mmol) in methanol-water (6:1, 84 mL) was added zinc (activated, 5 g, excess) and ammonium chloride (0.900 g, excess). The reaction mixture was stirred at ambient temperature for 8 h. Workup as described earlier and chromatography [petroleum ether-ethyl acetate (92:8)] of the product mixture first gave **38** (0.150 g, 17%). Further elution (80:20) gave the keto-alcohol **39** (0.670 g, 74%) as a colorless liquid.

Data for 38. IR (neat) ν_{max}: 1722 (br) cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.61 (d with str, J = 5.8 Hz, 1H), 3.54 (s, 3H), 3.12 (d, J = 5.8 Hz, 1H), 2.17−2.11 (m, 3H), 1.82−1.74 (m, 1H), 1.58−1.40 (m, 6H), 1.34 (d, J = 13.6 Hz, 1H), 1.09 (s, 3H), 0.90 (d, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 214.7, 176.4, 152.8, 118.1, 56.5, 52.2, 47.7, 46.3, 42.3, 35.9, 27.9, 26.3, 25.4, 20.3, 17.8, 10.0. HRMS (*m*/*z*): found 263.1636 [M + H]$^+$; calcd for $C_{16}H_{23}O_3$ 263.1647 [M + H]$^+$.

Data for 39. IR (neat) ν_{max}: 3504, 1719 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.74 (d, J = 5.6 Hz, 1H), 3.80−3.72 (m, 2H),

3.68 (s, 3H), 3.30 (d, J = 6.4 Hz, 1H), 3.26 (dd, J_1 = 8.5 Hz, J_2 = 4 Hz, 1H), 2.35 (dd, J_1 = 14.0 Hz, J_2 = 2.4 Hz, 1H), 2.27−2.24 (m, 2H), 2.09−2.05 (m, 1H), 1.74−1.57 (m, 6H), 1.39 (d, J = 14 Hz, 1H), 1.28 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 216.6, 176.3, 152.9, 118.1, 60.0, 56.9, 53.1, 52.5, 48.3, 41.9, 37.5, 27.9, 26.3, 25.2, 20.2, 17.9. HRMS (*m*/*z*): found 279.1604 $[M + H]^+$; calcd for $C_{16}H_{23}O_4$ 279.1596 $[M + H]^+$.

Methyl-9-methyl-12-oxo-tricyclo[6.2.2.0^{1,6}]dodec-6-en-9-carboxylate (40). A solution of β-keto-alcohol **39** (0.650 g, 2.33 mmol) in acetone (30 mL) was oxidized with Jones' reagent as described previously. After completion of the reaction (TLC), acetone was removed under vacuum. The residue was diluted with water (20 mL) and extracted with ethyl acetate (4 × 20 mL). The extract was combined and dried over anhydrous sodium sulfate, and the solvent was removed under vacuum to give the crude acid, which was dissolved in a THF-H_2O mixture (1:1, 40 mL) and refluxed for 12 h. The reaction mixture was saturated with NaCl, and the organic layer was separated. The aqueous layer was extracted with ether (3 × 20 mL). Combined organic extract was dried over sodium sulfate. The solvent was removed under reduced pressure, and the crude product was purified by column chromatography. Elution with petroleum ether-ethyl acetate (90:10) gave **40** (0.413 g, 71%) as colorless liquid. IR (neat) ν_{max}: 1732 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.71 (d, J = 6.2 Hz, 1H), 3.67 (s, 3H), 3.30 (d, J = 6.2 Hz, 1H), 2.41 (dd, J_1 = 13.2 Hz, J_2 = 3.3 Hz, 1H), 2.26−2.24 (br m, 2H), 2.04 (d of part of an AB system, J_{AB} = 18.3 Hz, J_2 = 3.3 Hz, 1H), 1.83 (part of AB system, J = 18 Hz, 1H), 1.71−1.56 (m, 6H, overlapped with signal due water in $CDCl_3$), 1.31−1.28 (s merged with a m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 210.9, 176.3, 150.9, 118.2, 57.1, 52.3, 46.8, 45.3, 43.5, 39.8, 30.9, 26.9, 26.3, 20.9, 18.6. HRMS (*m*/*z*): found 249.1497 $[M + H]^+$; calcd for $C_{15}H_{21}O_3$ 249.1491 $[M + H]^+$.

Ethyl-10-oxo-tetracyclo[4.3.2.0^{2,6}0^{1,9}]undec-8-carboxylate (41). A solution of **29** (0.070 g, 0.3 mmol) in acetone (100 mL) was irradiated with a medium-pressure mercury vapor lamp (125 W, λ_{max}: 254 nm) in a quartz immersion well for 3 h under nitrogen. The solvent was removed, and the residue was chromatographed. Elution with petroleum ether-ethyl acetate (95:5) first gave some unreacted starting material. Continued elution gave the photoproduct **41** as a colorless liquid (0.036 g, 51%). IR (neat) ν_{max}: 1731 cm^{-1} (br). ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.16 (q, J = 7.2 Hz, 2H), 2.85 (ddd, J_1 = 11.4, J_2= 6.6, and J_3 = 1.5 Hz, 1H), 2.42 − 2.24 (m, 2H), 2.22−1.82 (m, 9H), 1.62 (dt, J_1 = 8.4, J_2 = 7.8 Hz, 1H), 1.26 (t, J = 7.5 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 215.1, 174.1, 60.9, 58.0, 56.8, 53.2, 49.0, 46.2, 43.1, 37.9, 37.7, 28.4, 27.6, 14.2. HRMS (*m*/*z*): found 235.1338 $[M + H]^+$; calcd for $C_{14}H_{19}O_3$ 235.1334 $[M + H]^+$.

Ethyl-1-methyl-10-oxo-tetracyclo[4.3.2.0^{2,6}0^{1,9}]undec-8-carboxylate (42). A solution of **31** (0.074 g, 0.3 mmol) in acetone (100 mL) was irradiated with a medium-pressure mercury vapor lamp (125 W, λ_{max}: 254 nm) in a quartz immersion well for 3 h under nitrogen. The solvent was removed, and the residue was chromatographed (petroleum ether-ethyl acetate 95:5) to give some unreacted starting material. Continued elution gave the photoproduct **42** as a colorless liquid (0.036 g, 48%). IR (neat) ν_{max}: 1733 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.24−4.03 (m, 2H), 2.94 (dd, J_1 = 11.5 Hz, J_2 = 6 Hz, 1H), 2.41−2.23 (m, 2H), 2.23−1.92 (m, 4H), 1.91−1.56 (m, 5H), 1.28 (t, J = 7 Hz, 3H), 1.14 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 214.5, 172.9, 62.6, 60.8, 56.2, 53.7, 50.3, 50.1, 47.0, 44.2, 38.2, 28.5, 24.9, 16.9, 14.5. HRMS (*m*/*z*): found 249.1482 $[M + H]^+$; calcd for $C_{15}H_{21}O_3$ 249.1491 $[M + H]^+$.

Methyl-8-methyl-10-oxo-tetracyclo[4.3.2.0^{2,6}0^{1,9}]undec-8-carboxylate (43). A solution of **34** (0.170 g, 0.72 mmol) in acetone (300 mL) was irradiated with a medium-pressure mercury vapor lamp (125 W, APP) in a quartz immersion well for 2 h under nitrogen. The solvent was removed, and the residue was chromatographed. Elution with petroleum ether-ethyl acetate (85:15) gave the photoproduct **43** as a colorless liquid (0.052 g, 30%). IR (neat) ν_{max}: 1731 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.70 (s, 3H), 2.54−2.32 (m, 4H), 2.09−1.84 (m, 6H), 1.72−1.60 (m merged with signal due to H_2O in $CDCl_3$, 2H), 1.26 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 216.0, 177.7, 60.8, 57.7, 55.6, 55.3, 53.9, 52.5, 46.4, 43.3, 39.6, 28.8, 28.4, 23.3. HRMS (*m*/*z*): found 235.1334 $[M + H]^+$; calcd for $C_{14}H_{19}O_3$ 235.1334 $[M + H]^+$.

Ethyl-11-oxo-tetracyclo[5.3.2.0^{2,7}0^{1,10}]dodecan-9-carboxylate (44). A solution of ketone **37** (0.095 g, 0.4 mmol) in degassed acetone (100 mL, solvent as well as sensitizer) was irradiated with mercury vapor lamp (125 W) in a Pyrex immersion well for 2 h under nitrogen. Acetone was removed under vacuum, and the residue was chromatographed. Elution with petroleum ether-ethyl acetate (85:15) furnished tetracyclic compound **44** (0.074 g, 77%). IR (neat) ν_{max}: 1728 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 4.20−4.14 (m, 2H), 2.80 (ddd, J_1 = 10.5 Hz, J_2 = 6.5 Hz, J_3 = 1.2 Hz, 1H), 2.42−2.16 (m, 3H), 2.00−1.60 (m, 11H), 1.27 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 213.8, 174.2, 60.8, 52.9, 49.8, 47.7, 46.9, 45.4, 43.2, 38.6, 31.2, 24.4, 20.3, 18.2, 14.2. HRMS (*m*/*z*): found 249.1498 $[M + H]^+$; calcd for $C_{15}H_{21}O_3$ 249.1491 $[M + H]^+$.

Methyl-9-methyl-11-oxo-tetracyclo[5.3.2.0^{2,7}0^{1,10}]dodecan-9-carboxylate (45). A solution of the ketone **40** (0.100 g, 0.4 mmol) in degassed acetone (100 mL, solvent as well as sensitizer) was irradiated with a mercury vapor lamp (125 W) in a Pyrex immersion well for 1 h and 10 min under nitrogen. Acetone was removed under vacuum, and the residue was chromatographed. Elution with petroleum ether-ethyl acetate (90:10) furnished the product **45** as a colorless liquid (0.065 g, 65%). IR (neat) ν_{max}: 1732 cm^{-1}, ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.72 (s, 3H), 2.65 (dd, J_1 = 13.6 Hz, J_2 = 2.2 Hz, 1H), 2.48 (m of d, J = 18 Hz, 1H), 2.33 (dd, J_1 = 10.0 Hz, J_2 = 1.3 Hz, 1H), 2.15 (d, J = 18 Hz, 1H), 1.85 (d, J = 10 Hz, 1H), 1.78−1.60 (m, 8H), 1.57 (d with str, J = 13.3 Hz, 1H), 1.33 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 214.9, 177.6, 55.6, 54.8, 52.3, 50.9, 50.6, 48.1, 47.9, 44.7, 31.8, 24.5, 23.3, 19.9, 17.7. HRMS (*m*/*z*): found 249.1498 $[M + H]^+$; calcd for $C_{15}H_{21}O_3$ 249.1491 $[M + H]^+$.

Ethyl-7-oxo-tricyclo[3.3.3.0^{1,5}]undec-3-carboxylate (46). To a stirred solution of **41** (0.100 g, 0.43 mmol) in dry benzene (30 mL), AIBN (0.07 g, 0.42 mmol) and tributyltin hydride (0.5 mL, 1.7 mmol) were added, and the reaction mixture was refluxed for 6 h under an atmosphere of nitrogen. Benzene was removed, and the residue was chromatographed on silica gel. The column was eluted with petroleum ether to remove the tin impurity. Further elution with petroleum ether-ethyl acetate (98:2) furnished propellane **46** (0.053 g, 51%) as a colorless liquid. IR (neat) ν_{max}: 1738, 1732 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.13 (q, J = 7.5 Hz, 2H), 2.77 (m, 1H), 2.36 (q of AB type, J_1 = 13.1 Hz, J_2 = 6 Hz, 4H), 2.15−2.00 (m, 2H), 2.00−1.90 (m, 2H), 1.83−1.60 (m, 4H), 1.45−1.30 (m, 2H), 1.26 (t, J = 7.5 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 218.2, 174.3, 60.4, 55.9, 52.7, 44.7, 43.6, 41.4, 24.6, 14.1. HRMS (*m*/*z*): found 237.1498 $[M + H]^+$; calcd for $C_{14}H_{21}O_3$ 237.1491 $[M + H]^+$.

Methyl-3-methyl-7-oxo-tricyclo[3.3.3.0^{1,5}]undec-3-carboxylate (47). To a stirred solution of **43** (0.07 g, 0.3 mmol) in dry benzene (10 mL), AIBN (0.04 g, 2.4 mmol) and tributyltin hydride (0.5 mL, 1.7 mmol) were added, and the reaction mixture was refluxed for 12 h under an atmosphere of nitrogen. Benzene was removed, and the residue was chromatographed on silica gel. Elution with petroleum ether-ethyl acetate (95:5) furnished the propellane **47** (0.035 g, 50%) as a colorless liquid. IR (neat) ν_{max}: 1732 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.68 (s, 3H), 2.56 (d, J = 13.6 Hz, 2H), 2.40 (AB system, J_{AB} = 18.3 Hz, 4H), 1.80−1.50 (cluster of m, 8H), 1.28 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 219.6, 178.4, 57.4, 54.4, 52.2, 51.3, 42.0, 26.8, 25.3, 23.6. HRMS (*m*/*z*): found 237.1485 $[M + H]^+$; calcd for $C_{14}H_{21}O_3$ 237.1491 $[M + H]^+$.

Ethyl-11-oxo-tricyclo[4.3.3.0^{1,6}]dodecan-8-carboxylate (48). A solution of **44** (0.164 g, 0.66 mmol), tributyltin hydride (0.3 mL, 0.3 g, 0.99 mmol), and AIBN (0.108 g) in dry benzene (65 mL)

was refluxed for 12 h under nitrogen atmosphere. Solvent was removed under vacuum, and the residue was chromatographed. Tin impurities were removed by elution with petroleum ether. Elution with petroleum ether-ethyl acetate (95:5) furnished the product **48** (0.105 g, 64%). IR (neat) ν_{max}: 1738 (br) cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 4.16 (q, $J = 7.6$ Hz, 2H), 3.10−3.03 (m, 1H), 2.30−2.14 (m, 6H), 1.94−1.88 (m, 2H), 1.67−1.36 (m, 8H), 1.27 (t, $J = 7.2$ Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 218.5, 176.5, 60.6, 49.2, 48.3, 40.2, 39.8, 31.5, 21.5, 14.2. HRMS (*m*/*z*): found 251.1658 $[M + H]^+$; calcd for $C_{15}H_{23}O_3$ 251.1647 $[M + H]^+$.

Methyl-8-methyl-11-oxo-tricyclo[4.3.3.0^{1,6}]dodecan-8-carboxylate (49). A solution of **45** (0.100 g, 0.4 mmol), tributyltin hydride (0.5 mL, 0.50 g, 1.7 mmol,), and AIBN (0.045 g) in dry benzene (10 mL) was refluxed for 6 h under nitrogen atmosphere. Removal of solvent followed by chromatography [petroleum ether-ethyl acetate (95:5)] gave the product **49** (0.090 g, 89%). IR (neat) ν_{max}: 1738, 1732 cm^{-1}, ^1H NMR (400 MHz, $CDCl_3$): δ 3.65 (s, 3H), 2.60 (d, $J = 14$ Hz, 2H), 2.18 (d, $J = 4$ Hz, 4H), 1.55 (d, $J = 14$ Hz, 2H), 1.42−1.18 (m merged with s, 11H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 219.0, 179.5, 52.3, 49.9, 48.6, 47.8, 47.4, 31.4, 30.1, 21.3. HRMS (*m*/*z*): found 251.1657 $[M + H]^+$; calcd for $C_{15}H_{23}O_3$ 251.1647 $[M + H]^+$.

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Supporting Information Available: ^1H NMR and ^{13}C NMR spectra of **14a**,**b**, **15a**,**b**, **5a**−**d**, **6a**,**b**, **19**, **22**−**25**, **27a**,**b**, and **49** and CIF data and ORTEP diagram of **27a**. This material is available free of charge via the Internet at http://pubs.acs.org.

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