Total Synthesis of (±)-Culmorin and (±)-Longiborneol: An Efficient Construction of Tricyclo[6.3.0.0^{3,9}]undecan-10-one by Intramolecular Double Michael Addition

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Received February 9, 2000

The treatment of 4-[(5*E*)-6-methoxycarbonyl-5-hexenyl]-3,4-dimethyl-2-cyclopenten-1-one (**5**) with LHMDS, TMSI−HMDS, Bu_2OTf−HMDS, or TMSCl−NEt_3−$ZnCl_2$ caused the intramolecular double Michael addition to afford tricyclo[6.3.0.0^{3,9}]undecan-10-one **12** in high yields with perfect stereoselectivity. The methodology was further elaborated to achieve efficient total syntheses of (±)-culmorin (**1**) and (±)-longiborneol (**2**). The common precursor **13** of them was obtained from **14** in 94% yield as a single isomer by the treatment with LHMDS. After the conversion of **13** into the corresponding acid **24** by hydrolysis, oxidative decarboxylation using *S*-(1-oxido-2-pyridinyl)-1,1,3,3-tetramethylthiouronium hexafluorophosphate (HOTT, **27**), followed by the Birch reduction, stereoselectively afforded (±)-culmorin (**1**). (±)-Longiborneol (**2**) was synthesized from **24** by the standard transformation. Additionally, the treatment of **24** with $Pb(OAc)_4$ led to **28** via uncommon migration. Its structure was determined by X-ray analysis after the transformation into the diketone **29**.

Introduction

Culmorin (**1**)[1] and longiborneol (juniperol, macrocarpol; **2**)[2,3] are longifolane sesquiterpenes having a tricyclo-[6.3.0.0^{3,9}]undecane skeleton; the framework sometimes appears in natural products, e.g., (+)-longifolene (**3**)[4] and (+)-longicyclene (**4**)[5] (Figure 1). (−)-Culmorin (**1**) was isolated as a metabolite of *Fusarium culmorum* with antifungal activity against a variety of fungi, especially ones in wheat and corn.[6] (+)-Longiborneol (**2**) and its antipode were isolated from *Cupressus macrocarpa*[2a] and *Scapenia undulata*,[3] respectively. Although there have been several efforts to synthesize these natural products, their strategies were not very simple; especially the tactics employed for the construction of the tricyclic ring system were almost stepwise. In 1969, Welch reported the total synthesis of **1** by utilizing the Dieckman condensation twice to form a tricyclic skeleton, but the chemical yield and the stereoselectivity were unsatisfactory.[7] Welch and Money independently reported the total synthesis of **2**.[8,9] Additionally, Nayak reported the partial synthesis of (+)-**1** from naturally occurring (+)-longifolene (**3**) in 10 steps with low yield.[10]

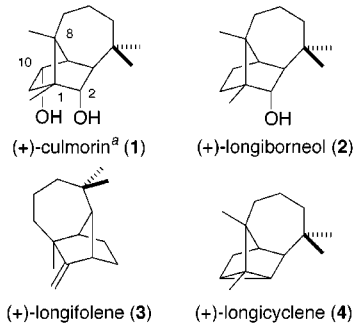

Figure 1. Key: (*a*) The antipode of the natural product (−)-**1** is shown.

Recently, we have reported highly stereoselective constructions of the tricyclo[5.3.0.0^{3,8}]decane and tricyclo-[6.3.0.0^{3,9}]undecane frameworks[11] utilizing the intramolecular double Michael addition[12,13] under several conditions (Scheme 1). This strategy has advantages for the following reasons. First, the tricyclo system could be built in a single operation. Second, several protective and

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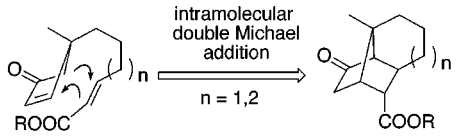
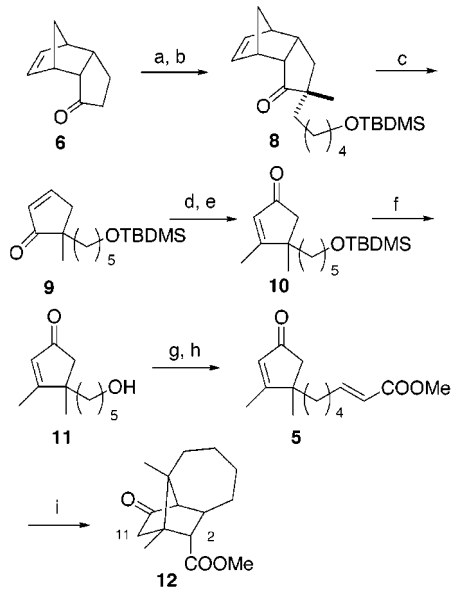
10.1021/jo000185s CCC: $19.00
Published on Web 06/03/2000

Scheme 1



Scheme 2[a]



[a] Conditions: (a) $NaCH_2S(O)CH_3$, $I(CH_2)_5OTBDMS$ (**7**); (b) $NaCH_2S(O)CH_3$, MeI (45% for two steps); (c) 250 °C in Ph2O (79%); (d) MeLi; (e) PCC, 4 Å molecular sieves (75% for two steps); (f) TBAF (94%); (g) PCC, 4 Å molecular sieves; (h) $Ph_3P{=}CHCO_2Me$ (57% for two steps); (i) see Table 1.

deprotective processes could be omitted. Finally, the stereo- and regioselectivities could be highly controlled. Herein, we report efficient syntheses of (±)-culmorin (**1**) and (±)-longiborneol (**2**) by the application of this methodology.[14]

Results and Discussion

Construction of Tricyclo[6.3.0.0^{3,9}]undecan-10-one as a Preliminary Experiment. We first planned the intramolecular double Michael addition of the *β*-methylcyclopentenone derivative **5** as a model reaction (Scheme 2). α-Alkylation of the known ketone **6**[15] using the iodide **7**,[16] followed by α-methylation, led to **8**. The retro Diels−Alder reaction of **8** at a high temperature (*ca*. 250 °C) provided **9**. After 1,2-addition of MeLi to the enone **9**, the corresponding allyl alcohol was oxidized by PCC in the presence of 4 Å molecular sieves to give the *O*-migrated enone **10**. After its deprotection, oxidation of **10** with PCC in the presence of 4 Å molecular sieves, followed by the Wittig olefination, afforded the (*E*)-α,*β* unsaturated ester **5** as the key substrate.

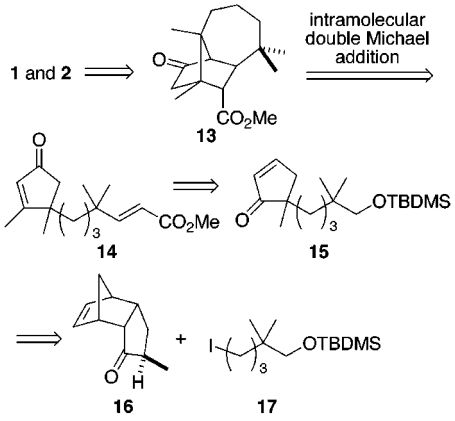
According to our previous studies,[11,12] the intramolecular double Michael addition was performed under four representative conditions: (A) LHMDS,[12b] (B) TMSI−HMDS,[11,17,18] (C) Bu_2BOTf−HMDS,[11,19] and (D) TMSCl−NEt_3−ZnX_2[11,20] (Table 1). Under all conditions, the tricyclic product **12** was obtained as the sole diastereoisomer in 46−87% yield, and formation of the mono Michael adduct was not observed; especially condition A gave the best yield. The stereochemistry of **12** was confirmed on the basis of the long-range coupling (J = 2.2 Hz) derived from the W-shaped configuration between the C(2) and C(11) equatorially oriented hydrogens in the ^{1}H NMR spectrum. The complete stereoselectivity under these conditions can be explained by a chelated transition state. The chelation among one oxygen of the ester group, another oxygen of the enolate derived from the enone, and the countercation should fix the conformation of the transition state.

Table 1. Intramolecular Double Michael Addition of 5

entry	conditions	yield (%)[a]
1	(A) LHMDS, −78 °C	87
2	(B) TMSI, HMDS, 0 °C to rt	79
3	(C) Bu_2OTf, HMDS, 0 °C to rt	69
4	(D) TMSCl, NEt_3, $ZnCl_2$, 180 °C	46

[a] No diastereoisomer was obtained in all conditions.

Scheme 3



Construction of the (±)-Culmorin Skeleton. Since we succeeded in the efficient construction of the tricyclo[6.3.0.0^{3,9}]undecan-10-one system for the above model system, the retrosynthetic analysis for (±)-culmorin (**1**) and (±)-longiborneol (**2**) using the intramolecular double Michael addition as the key step was designed (Scheme 3). (±)-Culmorin and (±)-longiborneol would be derived through stereoselective reduction of the ketone and oxidative decarboxylation from **13**. The tricyclo[6.3.0.0^{3,9}]-undecan-10-one derivative **13** could be obtained by the intramolecular double Michael addition of **14**, which can be transformed from the cyclopentenone **15**. α-Alkylation of the known ketone **16**[21] with **17** would afford **15**.

The side chain moiety **17** was synthesized as follows (Scheme 4). *O*-Protection of **18**[22] with the TBDMS group,

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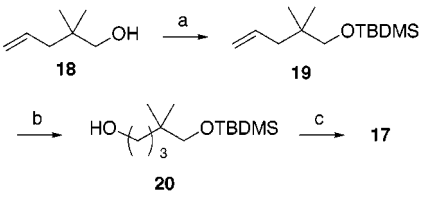
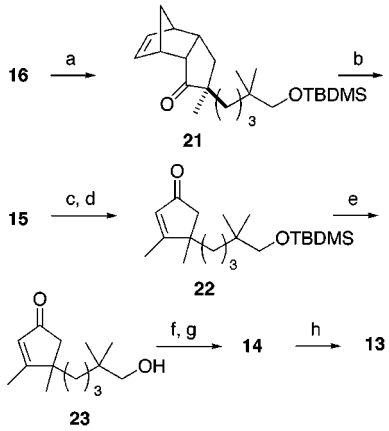
Scheme 4[a]



[a] Conditions: (a) TBDMSCl, NEt_3, DMAP (93%); (b) BH_3·THF; H_2O_2, NaOH (95%); (c) PPh_3, I_2, imidazole (92%).

Scheme 5[a]



[a] Conditions: (a) $NaCH_2S(O)CH_3$, **17** (94%); (b) 250 °C in Ph_2O (84%); (c) MeLi; (d) PCC, 4 Å molecular sieves (87% for two steps); (e) TBAF (98%); (f) PCC, 4 Å molecular sieves; (g) NaH, $(MeO)_2P(O)CH_2CO_2Me$ (88% for two steps); (h) see Table 2.

Table 2. Intramolecular Double Michael Addition of 14

entry	conditions	yield (%)[a]
1	(A) LHMDS, −78 °C to 0 °C	94
2	(B) TMSI, HMDS, 0 °C to rt	0
3	(C) Bu_2OTf, HMDS, 0 °C to rt	0
4	(D) TMSCl, NEt_3, $ZnBr_2$, reflux	39

[a] No diastereoisomer was obtained in all conditions.

followed by hydroboration−oxidation of **19**, gave the corresponding alcohol **20**, which was converted into **17** using PPh_3 and I_2.[23] The construction of the culmorin precursor **13** is depicted in Scheme 5. Thus, **21** was obtained by α-alkylation of **16**[21] using **17**, and then converted into **15** by pyrolysis. Using the same procedure as for the formation of **11** from **9**, the alcohol **23** was produced from **15** via **22**. The oxidation of **23**, followed by the Horner−Wadsworth−Emmons olefination, afforded the (*E*)-α,*β*-unsaturated ester **14**.

The intramolecular double Michael addition of **14** was investigated under the above four conditions A−D (Table 2). Condition A, carried out with LHMDS at −78 °C, gave the expected compound **13** as the sole stereoisomer in quite high yield (94% yield). The same product **13** was obtained in 39% yield by the treatment of **14** with TMSCl−NEt_3−$ZnBr_2$ at a refluxing temperature (condition D). The stereochemistry of **13** was determined by its ^{1}H NMR spectrum in the same manner as for the tricyclic compound **12** (long-range coupling, $J = 1.8$ Hz). On the other hand, neither condition B nor condition C gave the desired compound **13** (only produced complicated adducts as inseparable mixtures). We postulate,

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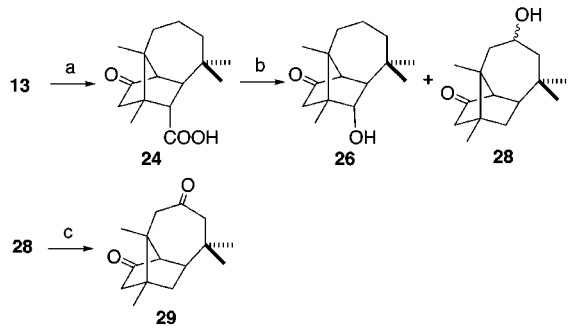
Scheme 6[a]



[a] Conditions: (a) KOH (100%); (b) see Table 3; (c) PCC (99%).

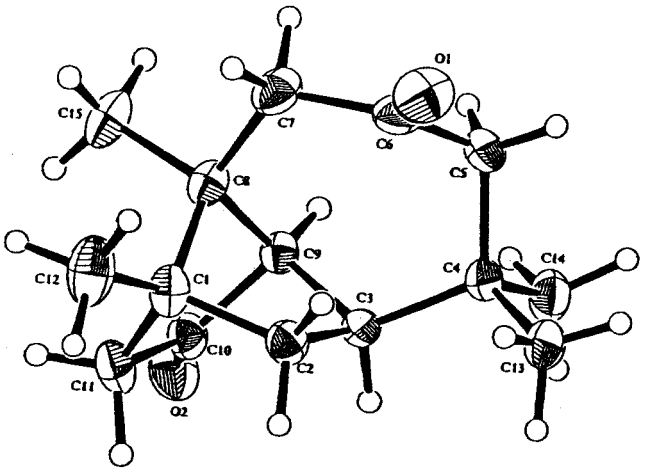


Figure 2. ORTEP drawing of **29**.

under the conditions of B and C for **14**, the steric hindrance caused by dimethyl substituents of the side chain moiety interrupts the selective intramolecular Michael addition during the first stage. On the contrary, in the case of **5**, the first Michael addition could be performed more easily and selectively.

Transformation into Hydroxyketones from Keto-ester 13. The hydrolysis of **13** quantitatively gave **24**. The next step was the conversion of the carboxylic group into the hydroxyl function at the C(2) position of **24** by the oxidative decarboxylation reaction (Scheme 6). We attempted several conditions, and the results are shown in Table 3.

A typical Barton procedure utilizing 2-mercaptopyridine *N*-oxide (**25**)[24] gave the desired alcohol **26** in 48% yield as the sole stereoisomer (entry 1). The compound **26** had been synthesized by degradation of natural culmorin.[1b,c] This compound also exhibited long-range coupling ($J = 1.6$ Hz) between the hydrogens at C(2) and C(11). Recently, Garner has reported an improved Barton method employing *S*-(1-oxido-2-pyridinyl)-1,1,3,3-tetramethylthiouronium hexafluorophosphate (HOTT, **27**)[25] We applied this method to the oxidative decarboxylation of **24** under an O_2 current. When the reaction was carried out in THF−benzene, the desired alcohol **26** and the undesired alcohols **28**[10] were obtained in 38% and 10% yields, respectively (entry 2). However, when 1,4-dioxane

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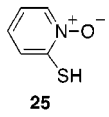
Table 3. Oxidative Decarboxylation of 24

entry	conditions	yield of **26** (%)[a]	yield of **28** (%)[a]
1	(i) NaH, $(COCl)_2$; (ii) **25**, NaH, *t*-BuSH, O_2, toluene, 80 °C; $P(OMe)_3$	48	0
2	HOTT (**27**), NEt_3, DMAP, THF; *t*-BuSH, O_2, benzene, 80 °C; $P(OMe)_3$	38	10
3	HOTT (**27**), NEt_3, DMAP, 1,4-dioxane; *t*-BuSH, O_2, 80 °C; $P(OMe)_3$	82	8
4	(i) $Pb(OAc)_4$, pyridine, benzene, reflux; (ii) K_2CO_3	0	50

[a] Isolated yield.



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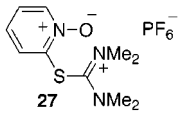
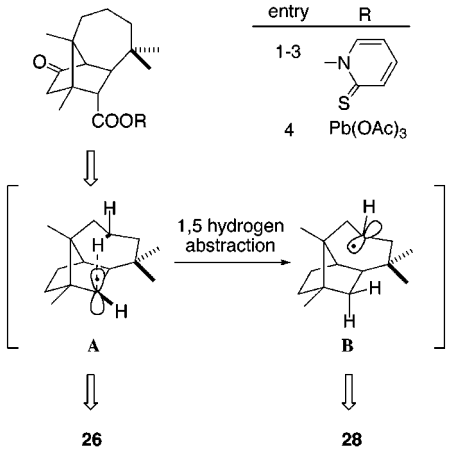
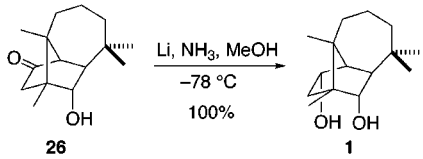


27

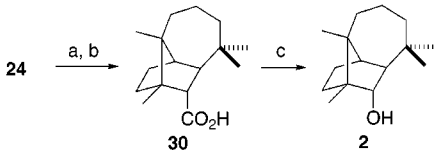
Scheme 7



Scheme 8



Scheme 9[a]



[a] Conditions: (a) $HS(CH_2)_2SH$, $BF_3{\cdot}OEt_2$; (b) Raney Ni (50% for two steps); (c) HOTT (**27**), NEt_3, DMAP, 1,4-dioxane; *t*-BuSH, O_2, 80 °C; $P(OMe)_3$ (51%).

was employed as the solvent, the yield of **26** increased to 82% and **28** was provided in 8% yield (entry 3). On the other hand, oxidative decarboxylation with $Pb(OAc)_4$,[26] followed by hydrolysis, afforded only a 5:1 epimeric mixture of regioisomeric alcohols **28** in 50% yield (entry 4). Their structures were determined by X-ray crystallography after oxidation of **28** to the diketone **29**[27] (Figure 2). This revealed that the free radical generated from the carboxylic function had migrated to the C(6) position from C(2).

A plausible mechanism can be proposed as indicated in Scheme 7. The desired product **26** could be obtained through path A. Thus, the radical intermediate **A** generated from the ketoester would be directly trapped by O_2 to give **26**. On the other hand, the formation of **28** by $Pb(OAc)_4$ could be explained by the 1,5-hydrogen abstraction[28] of the radical species (path B). The intermediate **A** would be interconverted to **B** by 1,5-hydrogen abstraction before the oxidation of $Pb(OAc)_4$, which is a larger molecule than O_2, because of the steric repulsion among that surrounding C(2). The radical intermediate **B** would then be oxidized to the corresponding cationic species, which was reacted with the acetate anion to yield the corresponding acetates. Consequently, the regioisomeric alcohols **28** were obtained.

Syntheses of Culmorin and Longiborneol. Barton had briefly mentioned the reduction of **26** to **1** with Na and *i*-PrOH (no detailed experimental procedure); however, its yield was low (*ca*. 14%), and the stereoselectivity at the C(10) position was not described.[1b] We achieved an improvement in this transformation. Thus, Birch reduction at low temperature quantitatively gave only the desired stereoisomer **1** (Scheme 8). Spectral data of the synthetic compound **1** were very consistent with the reported data.[1c]

(±)-Longiborneol (**2**) was synthesized from the keto carboxylic acid **24** (Scheme 9). After dithioketalization of **24** using 1,2-ethanedithiol and $BF_3{\cdot}OEt_2$, the corresponding dithioketal was treated with W-2 Raney Ni to afford **30**. The oxidative decarboxylation utilizing the HOTT method (see above) provided (±)-longiborneol (**2**). Spectral properties (^{1}H NMR and IR) of (±)-**2** were identical to the reported data.[8]

Conclusion

The application of the intramolecular double Michael addition of cyclopentenones having an α,β-unsaturated ester moiety permits the rapid assembly of the tricyclo-[6.3.0.0^{3,9}]undecan-10-one system with complete stereoselectivity. This methodology was applied to total syntheses of (±)-culmorin (**1**) (11 steps, 46% overall yield) and (±)-longiborneol (**2**) (12 steps, 14% overall yield). In addition, an unusual *O*-migration was observed during the oxidative decarboxylation of **24** using $Pb(OAc)_4$.

Experimental Section

General Procedure. All reactions were carried out under a positive atmosphere of N_2 or Ar unless otherwise indicated. Anhydrous THF, Et_2O, 1,4-dioxane, and CH_2Cl_2 were purchased from the Kanto Chemical Co., Inc. Toluene, benzene, DME, $ClCH_2CH_2Cl$, *o*-dichlorobenzene, and NEt_3 were distilled from CaH_2. HMDS and DMSO were distilled from CaH_2 under reduced pressure. Unless otherwise described, the materials were obtained from commercial suppliers and used without further purification. Organic extracts were dried over $MgSO_4$, filtered, and concentrated under reduced pressure using an

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evaporator. The ^{1}H and ^{13}C NMR spectra were recorded at 300 and 75 MHz, respectively, and were reported in parts per million downfield from TMS (δ = 0) for the ^{1}H NMR and relative to the central $CDCl_3$ resonance (δ = 77.00) for the ^{13}C NMR.

(±)-(1*S,2*R**,4*S**,6*S**,7*R**)-4-(5-*tert*-Butyldimethylsiloxypentyl)-4-methyltricyclo[5.2.1.0^{2,6}]deca-8-en-3-one (8).** A suspension of NaH (55% in oil; 0.68 g, 16 mmol) in DMSO (50 mL) was stirred at 60 °C until the end of the generation of H_2 gas and then cooled to rt. To the resulting solution was added a solution of **6**[15] (2.09 g, 14.1 mmol) in DMSO (5 mL) slowly at rt, and the mixture was stirred for 1 h. To this was added a solution of **7**[16] (6.95 g, 21.2 mmol) in DMSO (8 mL) at rt. The resulting solution was stirred for 4 h at rt. After dilution with AcOEt, the mixture was washed with H_2O and brine. The organic layer was then dried and concentrated. Column chromatography on silica gel (AcOEt:hexane = 1:39, v/v) afforded the corresponding α-alkylated ketone (1.49 g, 50%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 6.24 (dd, 1H, J = 5.7, 2.9 Hz), 6.06 (dd, 1H, J = 5.7, 3.0 Hz), 3.57 (t, 2H, J = 6.5 Hz), 3.24−3.18 (m, 1H), 3.00−2.96 (br s, 1H), 2.91−2.79 (m, 2H), 1.90 (ddd, 1H, J = 13.5, 8.1, 4.4 Hz), 1.79 (ddd, 1H, J = 13.5, 9.9, 1.9 Hz), 1.68−1.57 (m, 3H), 1.53−1.38 (m, 4H), 1.33−0.90 (m, 6H), 0.89 (s, 9H), 0.04 (s, 6H); IR (neat) 1730, 1105 cm^{-1}; LRMS m/z 291 (M$^+$ − t-Bu). Anal. Calcd for $C_{21}H_{36}O_2Si$: C, 72.36; H, 10.41. Found: C, 72.15; H, 10.52.

A suspension of NaH (55% in oil; 0.28 g, 6.4 mmol) in DMSO (15 mL) was stirred at 60 °C until the end of the generation of H_2 gas and then cooled to rt. To the resulting solution was added a solution of the above ketone (1.49 g, 4.27 mmol) in DMSO (3 mL) slowly at rt, and the mixture was stirred for 1 h. To this was added MeI (1.32 mL, 21.3 mmol) at rt. The resulting solution was stirred for 4 h at rt. After the same workup as above, the resulting residue was purified by column chromatography on silica gel (AcOEt:hexane = 3:97, v/v) to give **8** (1.39 g, 90%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 6.14 (dd, 1H, J = 5.8, 2.7 Hz), 6.05 (dd, 1H, J = 5.5, 2.7 Hz), 3.57 (t, 2H, J = 6.6 Hz), 3.15−3.11 (m, 2H), 3.00−2.90 (m, 2H), 1.75 (dd, 1H, J = 13.5, 9.1 Hz), 1.63−1.58 (m, 1H), 1.53−1.44 (m, 3H), 1.34−1.19 (m, 7H), 0.99 (s, 3H), 0.89 (s, 9H), 0.04 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 222.9, 137.2, 135.5, 63.3, 54.2, 53.7, 52.5, 46.1, 44.3, 37.4, 35.4, 32.8, 26.5, 26.0, 25.1, 24.1, 18.4, 5.3; IR (neat) 1735 cm^{-1}; LRMS m/z 305 (M$^+$ − t-Bu). Anal. Calcd for $C_{22}H_{38}O_2Si$: C, 72.87; H, 10.56. Found: C, 73.01; H, 10.78.

5-(5-*tert*-Butyldimethylsiloxypentyl)-5-methyl-2-cyclopenten-1-one (9). A solution of **8** (551 mg, 1.52 mmol) in diphenyl ether (4 mL) was stirred for 1 h at 250 °C. After being cooled, the mixture was directly purified by column chromatography on silica gel (AcOEt:hexane = 1:9 v/v) to give **9** (355 mg, 79%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 7.64 (dt, 1H, J = 5.8, 2.7 Hz), 6.14 (dt, 1H, J = 5.8, 2.2 Hz), 3.57 (t, 2H, J = 6.6 Hz), 2.65 (ddd, 1H, J = 19.2, 2.7, 2.5 Hz), 2.41 (ddd, 1H, J = 19.2, 2.5, 2.2 Hz), 1.64−1.10 (m, 8H), 1.09 (s, 3H), 0.88 (s, 9H), 0.04 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 215.3, 162.7, 133.1, 63.2, 46.3, 43.0, 38.0, 32.7, 26.4, 26.0, 24.4, 23.8, 18.3, −5.4; IR (neat) 1715 cm^{-1}; LRMS m/z 239 (M$^+$ − t-Bu). Anal. Calcd for $C_{17}H_{32}O_2Si$: C, 68.86; H, 10.88. Found: C, 68.61: H, 10.94.

4-(5-*tert*-Butyldimethylsiloxypentyl)-3,4-dimethyl-2-cyclopenten-1-one (10). To a solution of **9** (855 mg, 2.85 mmol) in THF (15 mL) was added MeLi (1.02 M solution in Et_2O; 8.37 mL, 8.54 mmol) dropwise at −78 °C. The resulting mixture was stirred for 40 min at −78 °C, and then quenched with saturated NH_4Cl at the same temperature. After dilution with Et_2O, the mixture was washed with saturated $NaHCO_3$ and brine. The organic layer was dried and concentrated. To a solution of the resulting residue in CH_2Cl_2 (30 mL) was added 4 Å molecular sieves (1 g) and PCC (920 mg, 4.27 mmol) at 0 °C. After being stirred for 10 min at 0 °C, the mixture was warmed to rt and stirred for an additional 1 h. After dilution with Et_2O and the addition of Florisil, the mixture was filtered through Celite. Evaporation of the filtrate gave a residue which was purified by column chromatography on silica gel (AcOEt:hexane = 1:4, v/v) to give **10** (662 mg, 75% for two steps) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 5.85 (d, 1H, J = 1.2 Hz), 3.58 (t, 2H, J = 6.3 Hz), 2.38 (d, 1H, J = 18.5 Hz), 2.13 (d, 1H, J = 18.5 Hz), 1.99 (d, 1H, J = 1.2 Hz), 1.60−1.21 (m, 6H), 1.19 (s, 3H), 1.17−0.96 (m, 2H), 0.89 (s, 9H), 0.04 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 208.4, 184.9, 130.6, 63.1, 48.3, 46.4, 38.4, 32.7, 26.3, 26.0, 25.8, 24.5, 18.3, 14.3, −5.4; IR (neat) 1715 cm^{-1}; LRMS m/z 253 (M$^+$ − t-Bu). Anal. Calcd for $C_{18}H_{34}O_2Si$: C, 69.62; H, 11.03. Found: C, 69.54; H, 10.97.

4-(5-Hydroxypentyl)-3,4-dimethyl-2-cyclopenten-1-one (11). To a solution of **10** (662 mg, 2.13 mmol) in THF (10 mL) was added TBAF (1.0 M solution in THF; 2.99 mL, 2.99 mmol) at 0 °C, which was stirred for 2 h at rt. After dilution with Et_2O, the mixture was washed with saturated $NaHCO_3$ and brine. The organic layer was dried and concentrated. The residue was purified by column chromatography on silica gel (AcOEt:hexane = 7:3, v/v) to give **11** (392 mg, 94%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 5.85 (d, 1H, J = 1.2 Hz), 3.63 (t, 2H, J = 6.5 Hz), 2.38 (d, 1H, J = 18.5 Hz), 2.14(d, 1H, J = 18.5 Hz), 1.99 (d, 3H, J = 1.2 Hz), 1.60−1.21 (m, 6H), 1.19 (s, 3H), 1.17−0.96 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 208.4, 184.9, 130.6, 62.8, 48.2, 46.4, 38.4, 32.5, 26.2, 25.8, 24.5, 14.2; IR (neat) 3425, 1695 cm^{-1}; LRMS m/z 196 (M$^+$). Anal. Calcd for $C_{12}H_{20}O_2$: C, 73.43; H, 10.27. Found: C, 72.99; H, 10.41.

4-[(5*E*)-6-Methoxycarbonyl-5-hexenyl]-3,4-dimethyl-2-cyclopenten-1-one (5). To a solution of **11** (376 mg, 1.92 mmol) in CH_2Cl_2 (30 mL) were added 4 Å molecular sieves (0.7 g) and PCC (743 mg, 3.45 mmol) at 0 °C. After being stirred for 10 min at 0 °C, the mixture was warmed to rt and stirred for an additional 2 h. After dilution with Et_2O and the addition of Florisil, the mixture was filtered through Celite, and then the filtrate was concentrated to give the corresponding crude aldehyde. A mixture of this crude aldehyde and $Ph_3P{=}CHCO_2Me$ (1.28 g, 3.83 mmol) in CH_2Cl_2 (10 mL) was stirred for 14 h at rt. After concentration, the mixture was directly purified by column chromatography on silica gel (AcOEt:hexane = 2:3, v/v) to give **5** (273 mg, 57% for two steps) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 6.93 (dt, 1H, J = 15.7, 6.9 Hz), 5.86 (d, 1H, J = 1.1 Hz), 5.81 (dt, 1H, J = 15.7, 1.6 Hz), 3.73 (s, 3H), 2.36 (d, 1H, J = 18.7 Hz), 2.19 (ddd, 1H, J = 16.5, 6.9, 1.6 Hz), 2.14 (d, 1H, J = 18.7 Hz), 1.99 (d, 3H, J = 1.1 Hz), 1.58−1.39 (m, 4H), 1.28−1.16 (m, 1H), 1.20 (s, 3H), 1.08−1.01 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 208.1, 184.5, 167.2, 149.1, 130.6, 121.2, 51.4, 48.1, 46.3, 38.1, 31.9, 28.4, 25.7, 24.2, 14.2; IR (neat) 1720, 1660 cm^{-1}; LRMS m/z 250 (M$^+$). Anal. Calcd for $C_{15}H_{22}O_3$: C, 71.97; H, 8.86. Found: C, 71.78; H, 8.93.

(±)-(1*S,2*S**,3*R**,8*S**,9*R**)-2-Methoxycarbonyl-1,8-dimethyltricyclo[6.3.0.0^{3,9}]undecan-10-one (12). Entry 1 in Table 1.** To a solution of HMDS (43 μL, 0.20 mmol) in Et_2O (2 mL) at 0 °C was added BuLi (1.56 M in hexane; 99 μL, 0.15 mmol). The solution was stirred at 0 °C for 3 h and then cooled to −78 °C. To this was added a solution of **5** (26 mg, 0.10 mmol) in Et_2O (3 mL) dropwise at −78 °C. The resulting mixture was stirred for 5 h at −78 °C. After dilution with Et_2O, the mixture was washed with 10% HCl and brine. The organic layer was dried and concentrated. Column chromatography on silica gel (AcOEt:hexane = 7:3, v/v) afforded **12** (22.4 mg, 87%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 3.70 (s, 3H), 2.81 (dd, 1H, J = 6.9, 2.2 Hz), 2.46 (ddd, 1H, J = 6.9, 4.6, 2.5 Hz), 2.32 (d, 1H, J = 18.7 Hz), 2.29 (s, 1H), 1.98 (ddd, 1H, J = 18.7, 2.2, 0.8 Hz), 1.87−1.77 (m, 2H), 1.70−1.26 (m, 6H), 1.15 (s, 3H), 0.94 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 215.2, 174.5, 64.4, 52.7, 51.9, 51.8, 51.4, 43.6, 39.6, 35.2, 29.7, 26.6, 25.0, 21.8, 14.1; IR (neat) 1739, 1725 cm^{-1}; LRMS m/z 250 (M$^+$). Anal. Calcd for $C_{15}H_{22}O_3$: C, 71.97; H, 8.86. Found: C, 71.80; H, 8.94.

Entry 2 in Table 1. To a solution of **5** (50 mg, 0.20 mmol) in $ClCH_2CH_2Cl$ (2 mL) were added HMDS (0.13 mL, 0.61 mmol) and TMSI (57 μL, 0.40 mmol) dropwise at 0 °C. The resulting mixture was stirred for 10 h at rt, followed by the same workup and purification procedure as above, yielding **12** (39 mg, 79%) as a colorless oil, which was identical with the authentic compound in all respects.

Entry 3 in Table 1. To a solution of **5** (49 mg, 0.20 mmol) in $ClCH_2CH_2Cl$ (2 mL) were added HMDS (0.13 mL, 0.61 mmol) and Bu_2BOTf (1.0 M in CH_2Cl_2, 0.39 mL, 0.39 mmol) dropwise at 0 °C. The resulting mixture was stirred for 7 h at

rt, followed by the same workup and purification procedure as above, yielding **12** (34 mg, 69%) as a colorless oil, which was identical with the authentic compound in all respects.

Entry 4 in Table 1. A mixture of **5** (26 mg, 0.10 mmol), $ZnCl_2$ (0.14 g, 1.0 mmol), NEt_3 (0.21 mL, 1.5 mmol), and TMSCl (0.13 mL, 1.0 mmol) in toluene (4 mL) was heated for 22 h at 180 °C in a sealed tube. After the mixture was cooled to rt, similar workup and purification as above gave **12** (12 mg, 46%) as a colorless oil, which was identical with the authentic compound in all respects.

1-*tert*-Butyldimethylsiloxy-2,2-dimethyl-4-pentene (19). To a solution of **18**[22] (14.1 g, 123 mmol), TBDMSCl (22.3 g, 148 mmol), and DMAP (1.51 g, 12.3 mmol) in CH_2Cl_2 (150 mL) was added NEt_3 (25.8 mL, 185 mmol) at 0 °C, which was stirred for 10 min at the same temperature. The resulting solution was then stirred for 20 h at rt. The mixture was washed with H_2O and brine, dried, and concentrated. The residue was purified by column chromatography on silica gel (AcOEt:hexane = 1:9, v/v) to give **19** (26.2 g, 93%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 5.88−5.73 (m, 1H), 5.03−4.95 (m, 2H), 3.22 (s, 2H), 1.98 (d, 2H, J = 7.4 Hz), 0.89 (s, 9H), 0.82 (s, 6H), 0.02 (s, 6H); IR (neat) 1640 cm^{-1}; LRMS m/z 171 (M^+ − t-Bu); HRMS calcd for $C_9H_{19}OSi$ 171.1205, found 171.1190.

1-*tert*-Butyldimethylsiloxy-2,2-dimethyl-5-pentanol (20). To a solution of **19** (24.4 g, 107 mmol) in THF (300 mL) was slowly added borane−THF complex (1.0 M in THF; 160 mL, 160 mmol) at 0 °C. The resulting solution was stirred for 4 h at 0 °C. To the mixture were added 3 M NaOH (110 mL) and 30% H_2O_2 (128 mL) at 0 °C, and the stirring was continued for 1 h at rt. The mixture was extracted with AcOEt, and the organic layer was washed with brine, dried, and concentrated. The residue was purified by column chromatography on silica gel (AcOEt:hexane = 2:3, v/v) to give **20** (25.0 g, 95%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 3.61 (t, 2H, J = 6.6 Hz), 3.24 (s, 2H), 1.58−1.46 (m, 2H), 1.41 (br s, 1H), 1.29−1.21 (m, 2H), 0.88 (s, 9H), 0.83 (s, 6H), 0.01 (s, 6H); IR (neat) 3330 cm^{-1}; LRMS m/z 189 (M^+ − t-Bu). Anal. Calcd for $C_{13}H_{30}O_2Si$: C, 63.35; H, 12.27. Found: C, 63.33; H, 12.25.

1-*tert*-Butyldimethylsiloxy-2,2-dimethyl-5-iodopentane (17). To a solution of **20** (4.26 g, 17.3 mmol) in toluene (50 mL) were added imidazole (2.35 g, 34.6 mmol), PPh_3 (6.80 g, 25.9 mmol), and I_2 (8.77 g, 34.6 mmol) at rt. The resulting mixture was stirred for 15 min at rt. The mixture was washed with saturated $Na_2S_2O_3$ and brine, dried, and concentrated. After dilution with Et_2O, the insoluble agent was filtered off carefully. The filtrate was concentrated. The residue was purified by column chromatography on silica gel (Et_2O/hexane = 1:19, v/v) to give **17** (5.66 g, 92%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 3.22 (s, 2H), 3.15 (t, 2H, J = 7.1 Hz), 1.84−1.73 (m, 2H), 1.33−1.26 (m, 2H), 0.89 (s, 9H), 0.82 (s, 6H), 0.02 (s, 6H); IR (neat) 2950 cm^{-1}; LRMS m/z 299 (M^+ − t-Bu). Anal. Calcd for $C_{13}H_{29}IOSi$: C, 43.82; H, 8.20; I, 35.61. Found: C, 43.85; H, 8.26; I, 35.62.

(±)-(1*S,2*R**,4*R**,6*S**,7*R**)-4-(5-*tert*-Butyldimethylsiloxy-4,4-dimethylpentyl)-4-methyltricyclo[5.2.1.0^{2,6}]dec-8-en-3-one (21).** A suspension of NaH (55% in oil; 118 mg, 2.71 mmol) in DMSO (4 mL) was stirred at 60 °C until the end of the generation of H_2 gas and then cooled to rt. To the resulting solution was added a solution of **16**[21] (367 mg, 2.26 mmol) in DMSO (4 mL) slowly at rt, and the resulting solution was stirred for 1 h. To this was added a solution of **17** (966 mg, 2.71 mmol) in THF (2 mL) slowly at rt. The resulting solution was stirred for 1 h at rt. After dilution with AcOEt, the mixture was washed with H_2O and brine. The organic layer was then dried and concentrated. Column chromatography on silica gel (AcOEt:hexane = 3:97, v/v) afforded **21** (833 mg, 94%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 6.15 (dd, 1H, J = 5.5, 2.7 Hz), 6.06 (dd, 1H, J = 5.5, 2.7 Hz), 3.19 (s, 2H), 3.14 (br s, 1H), 3.04 (dd, 1H, J = 9.3, 4.4 Hz), 2.96−2.83 (m, 2H), 1.97 (dd, 1H, J = 13.7, 8.8 Hz), 1.61 (br d, 1H, J = 8.2 Hz), 1.46 (br d, 1H, J = 8.2 Hz), 1.33−1.23 (m, 2H), 1.16−1.05 (m, 5H), 0.88 (s, 9H), 0.82 (s, 3H), 0.78 (s, 6H), 0.00 (s, 6H); IR (neat) 1725 cm^{-1}; LRMS m/z 333 (M^+ − t-Bu). Anal. Calcd for $C_{24}H_{42}O_2Si$: C, 73.79; H, 10.84. Found: C, 73.58; H, 10.77.

5-(5-*tert*-Butyldimethylsiloxy-4,4-dimethylpentyl)-5-methyl-2-cyclopenten-1-one (15). A solution of **21** (14.6 g, 37.3 mmol) in diphenyl ether (60 mL) was stirred for 30 min at 250 °C. After being cooled, the mixture was directly purified by column chromatography on silica gel (AcOEt:hexane = 1:19, v/v) to give **15** (10.2 g, 84%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 7.63 (dt, 1H, J = 5.8, 2.2 Hz), 6.14 (dt, 1H, J = 5.8, 2.2 Hz), 3.19 (d, 1H, J = 9.6 Hz), 3.16 (d, 1H, J = 9.6 Hz), 2.65 (dt, 1H, J = 18.0, 2.2 Hz), 2.41 (dt, 1H, J = 18.0, 2.2 Hz), 1.47−1.31 (m, 2H), 1.21−1.10 (m, 3H), 1.08 (s, 3H), 1.05−0.94 (m, 1H), 0.87 (s, 9H), 0.772 (s, 3H), 0.767 (s, 3H), 0.00 (s, 6H); IR (neat) 1715, 1595 cm^{-1}; LRMS m/z 267 (M^+ − t-Bu). Anal. Calcd for $C_{19}H_{36}O_2Si$: C, 70.31; H, 11.18. Found: C, 70.54; H, 11.08.

4-(5-*tert*-Butyldimethylsiloxy-4,4-dimethylpentyl)-3,4-dimethyl-2-cyclopenten-1-one (22). To a solution of **15** (4.59 g, 14.1 mmol) in THF (50 mL) was added MeLi (1.01 M solution in Et_2O; 28.0 mL, 28.3 mmol) dropwise at −78 °C. The resulting mixture was stirred for 2 h at rt, and then quenched with saturated NH_4Cl at the 0 °C. After extraction with Et_2O, the mixture was washed with brine. The organic layer was dried and concentrated to give the corresponding crude alcohol. To a solution of the crude alcohol in CH_2Cl_2 (60 mL) were added 4 Å molecular sieves (5 g) and PCC (4.57 g, 21.2 mmol) at 0 °C. After being stirred for 10 min at 0 °C, the mixture was warmed to rt and stirred for an additional 1 h. After dilution with Et_2O and the addition of Florisil, the mixture was filtered through Celite. Evaporation of the filtrate gave a residue which was purified by column chromatography on silica gel (AcOEt:hexane = 1:9, v/v) to give **22** (4.17 g, 87% for two steps) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 5.84 (d, 1H, J = 1.1 Hz), 3.18 (s, 2H), 2.38 (d, 1H, J = 18.4 Hz), 2.13 (d, 1H, J = 18.4 Hz), 1.98 (d, 3H, J = 1.1 Hz), 1.61−0.89 (m, 6H), 1.18 (s, 3H), 0.87 (s, 9H), 0.78 (s, 3H), 0.77 (s, 3H), 0.00 (s, 6H); IR (neat) 1695, 1620 cm^{-1}; LRMS m/z 281 (M^+ − t-Bu). Anal. Calcd for $C_{20}H_{38}O_2Si$: C, 70.94; H, 11.31. Found: C, 70.87; H, 11.21.

4-(5-Hydroxy-4,4-dimethylpentyl)-3,4-dimethyl-2-cyclopenten-1-one (23). To a solution of **22** (1.93 g, 5.71 mmol) in THF (24 mL) was added TBAF (1.0 M solution in THF; 11.4 mL, 11.4 mmol) at 0 °C, which was stirred for 5.5 h at rt. After dilution with Et_2O, the mixture was washed with brine. The organic layer was dried and concentrated. The residue was purified by column chromatography on silica gel (AcOEt:hexane = 1:1, v/v) to give **23** (1.26 g, 98%) as a yellow oil: ^{1}H NMR ($CDCl_3$) δ 5.86 (d, 1H, J = 1.1 Hz), 3.29 (s, 2H), 2.40 (d, 1H, J = 18.4 Hz), 2.15 (d, 1H, J = 18.4 Hz), 1.99 (d, 3H, J = 1.1 Hz), 1.70−0.88 (m, 7H), 1.20 (s, 3H), 0.84 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 208.5, 185.1, 130.6, 71.9, 48.2, 46.5, 39.3, 39.1, 35.1, 25.8, 23.79, 23.76, 19.0, 14.3; IR (neat) 3425, 1685, 1620 cm^{-1}; LRMS m/z 224 (M^+ − t-Bu); HRMS calcd for $C_{14}H_{24}O_2$ 224.1776, found 224.1783.

4-[(5*E*)-6-Methoxycarbonyl-4,4-dimethyl-5-hexenyl]-3,4-dimethyl-2-cyclopenten-1-one (14). To a solution of **23** (2.30 g, 10.3 mmol) in CH_2Cl_2 (50 mL) were added 4 Å molecular sieves (4.5 g) and PCC (4.42 g, 20.5 mmol) at 0 °C. After being stirred for 10 min at 0 °C, the mixture was warmed to rt and stirred for an additional 2.5 h. After dilution with Et_2O and the addition of Florisil, the mixture was filtered through Celite, and then the filtrate was concentrated to give the corresponding crude aldehyde. To a suspension of NaH (55% in oil; 537 mg, 12.3 mmol) in DME (90 mL) was slowly added trimethyl phosphonoacetate (2.16 mL, 13.3 mmol) at rt, which was stirred for 3.5 h at the same temperature. To this at 0 °C was slowly added a solution of the above aldehyde in DME (4 mL), which was stirred for 2 h at rt. After dilution with Et_2O, the mixture was washed with brine. The organic layer was dried and concentrated. The residue was purified by column chromatography on silica gel (AcOEt:hexane = 1:4, v/v) to give **14** (2.51 g, 88%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 6.88 (d, 1H, J = 15.9 Hz), 5.85 (d, 1H, J = 1.2 Hz), 5.70 (d, 1H, J = 15.9 Hz), 3.74 (s, 3H), 2.35 (d, 1H, J = 18.4 Hz), 2.12 (d, 1H, J = 18.4 Hz), 1.97 (d, 3H, J = 1.2 Hz), 1.67−0.80 (m, 6H), 1.18 (s, 3H), 1.02 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 208.2, 184.8, 167.7, 158.2, 130.5, 117.7, 51.5, 48.1, 46.4, 42.6, 39.0, 36.7, 26.2, 25.6, 19.6, 14.2; IR (neat) 1720, 1685, 1650, 1615 cm^{-1}; LRMS

m/*z* 278 (M^+). Anal. Calcd for $C_{17}H_{26}O_3$: C,73.35; H, 9.41. Found: C, 73.09; H, 9.23.

(±)-(1*S,2*S**,3*R**,8*S**,9*R**)-2-Methoxycarbonyl-1,4,4,8-tetramethyltricyclo[6.3.0.0^{3,9}]undecan-10-one (13). Entry 1 in Table 2.** To a solution of HMDS (1.16 mL, 5.52 mmol) in Et_2O (45 mL) at 0 °C was added BuLi (1.54 M in hexane; 2.69 mL, 4.14 mmol). The solution was stirred at 0 °C for 1 h and then cooled to −78 °C. To this was added a solution of **14** (768 mg, 2.76 mmol) in Et_2O (3 mL) dropwise at −78 °C. The resulting mixture was stirred for 1 h at −78 °C and for an additional 3 h at 0 °C. After dilution with Et_2O, the mixture was washed with 10% HCl and brine. The organic layer was dried and concentrated. Column chromatography on silica gel (AcOEt:hexane = 1:9, v/v) and recrystallization from *i*-Pr_2O afforded **13** (724 mg, 94%) as colorless needles: mp 150 °C; ^{1}H NMR ($CDCl_3$) δ 3.72 (s, 3H), 2.76 (dd, 1H, J = 6.9, 1.8 Hz), 2.46 (s, 1H), 2.26 (d, 1H, J = 17.8 Hz), 2.04 (d, 1H, J = 6.9 Hz), 1.94 (ddd, 1H, J = 17.8, 1.8, 0.8 Hz), 1.60−1.35 (m, 6H), 1.10 (s, 3H), 1.01 (s, 3H), 0.93 (s, 3H), 0.78 (s, 3H); IR ($CHCl_3$) 1735 cm^{-1}; LRMS *m*/*z* 278 (M^+). Anal. Calcd for $C_{17}H_{26}O_3$: C, 73.35; H, 9.41. Found: C, 73.26.; H, 9.42.

Entry 4 in Table 2. A mixture of **14** (0.20 g, 0.71 mmol), $ZnBr_2$ (1.6 g, 7.1 mmol), NEt_3 (1.5 mL, 11 mmol), and TMSCl (0.90 mL, 7.1 mmol) in *o*-dichlorobenzene (20 mL) was refluxed for 9 h. After the mixture was cooled to rt, the same workup and purification procedure as above gave **13** (77 mg, 39%) as colorless needles, which was identical with the authentic compound in all respects.

(±)-(1*S,2*S**,3*R**,8*S**,9*R**)-1,4,4,8-Tetramethyl-10-oxotricyclo[6.3.0.0^{3,9}]undecan-2-carboxylic Acid (24).** To a solution of **13** (22.2 mg, 80 μmol) in MeOH−H_2O (1:1, v/v; 5 mL) was added KOH (134 mg, 2.4 mmol), and the resulting mixture was refluxed for 63 h. After removal of MeOH under reduced pressure, the aqueous solution was washed with Et_2O and acidified with 10% HCl. After extraction with $CHCl_3$, the extract was dried and concentrated. The residue was purified by recrystallization from *i*-Pr_2O to give **24** (21.1 mg, 100%) as colorless plates: mp 219−221 °C; ^{1}H NMR ($CDCl_3$) δ 2.79 (dd, 1H, J = 6.6, 1.8 Hz), 2.48 (s, 1H), 2.28 (d, 1H, J = 17.5 Hz), 2.02 (d, 1H, J = 6.6 Hz), 2.00 (dd, 1H, J = 17.5, 1.8 Hz), 1.67−1.36 (m, 6H), 1.18 (s, 3H), 1.02 (s, 3H), 0.94 (s, 3H), 0.83 (s, 3H); IR ($CHCl_3$) 1735, 1695 cm^{-1}; LRMS *m*/*z* 264 (M^+). Anal. Calcd for $C_{16}H_{24}O_3$: C, 72.69; H, 9.15. Found: C, 72.67; H, 9.19.

Oxidative Decarboxylation of 24. Entry 1 in Table 3. To a solution of **24** (57.6 mg, 0.22 mmol) in benzene (3 mL) was added NaH (55% in oil; 14.3 mg, 0.33 mmol) at rt, which was stirred for 30 min. After the addition of $(COCl)_2$ (57 μL, 0.65 mmol), the mixture was refluxed for 3 h. After filtration, the filtrate was evaporated to give the corresponding acyl chloride (68 mg as crude). Without further purification, the acyl chloride was used in the following reaction. To a solution of 2-mercaptopyridine *N*-oxide (**25**; 30.5 mg, 0.22 mmol) in toluene (1 mL) was added NaH (55% in oil; 14.3 mg, 0.33 mmol) at rt under an Ar atmosphere, which was stirred for 10 min. After the addition of a solution of the above acyl chloride (67 mg) in toluene (2 mL) and *t*-BuSH (0.22 mL, 2.0 mmol) at rt, the mixture was stirred for 3 h at 80 °C under an O_2 current. To this was added $P(OMe)_3$ (0.26 mL, 2.2 mmol) at rt, and the resulting mixture was stirred for a further 2 h at rt. After the addition of saturated NH_4Cl, the mixture was extracted with Et_2O. The organic layer was then washed with brine, dried, and concentrated. Column chromatography on silica gel (AcOEt:hexane = 1:4, v/v) afforded **26** (24.7 mg, 48%) as colorless needles.

Entry 3 in Table 3. To a mixture of *S*-(1-oxido-2-pyridinyl)-1,1,3,3-tetramethylthiouronium hexafluorophosphate[25] (**27**, HOTT; 171 mg, 0.46 mmol) and DMAP (2.8 mg, 23 μmol) was added a solution of **24** (61 mg, 0.23 mmol) and NEt_3 (0.13 mL, 0.92 mmol) in 1,4-dioxane (2.5 mL), which was stirred for 12 h at rt under an Ar atmosphere. After the addition of *t*-BuSH (0.23 mL, 2.1 mmol), the mixture was stirred for 3 h at 80 °C under an O_2 current. To this was added $P(OMe)_3$ (0.27 mL, 2.3 mmol) at rt, and the resulting mixture was stirred for a further 2 h at rt. After the addition of saturated NH_4Cl, the mixture was extracted with Et_2O. The organic layer was then dried and concentrated. Column chromatography on silica gel (AcOEt:hexane = 1:4, v/v) afforded **28** (4.3 mg, 8%) as a colorless solid and the crude of **26**. The crude mixture was further purified by column chromatography on silica gel (Et_2O:benzene = 1:4, v/v) and recrystallization from cyclohexane−petroleum ether to give **26** (44.6 mg, 82%) as colorless needles.

Entry 4 in Table 3. To a solution of **24** (11.0 mg, 42 μmol) in benzene (3 mL) were added pyridine (5 μL, 62 μmol) and $Pb(OAc)_4$ (37 mg, 83 μmol) at rt, which was refluxed for 8.5 h. After filtration through Celite, the filtrate was washed with 10% NaOH, 10% HCl, and brine successively. The organic layer was dried and concentrated. Column chromatography on silica gel (AcOEt:hexane = 3:7, v/v) afforded a diastereomixture (5:1) of acetates (6.1 mg, 53%) as a colorless oil. To a solution of the above acetates as a diastereomeric mixture (17.7 mg, 64 μmol) in MeOH (1.5 mL) was added K_2CO_3 (17.6 mg, 127 μmol), and the mixture was stirred for 21 h at rt. After removal of MeOH under reduced pressure and then dilution with AcOEt, the mixture was washed with brine. The organic layer was dried and concentrated. The resulting residue was purified by column chromatography on silica gel (AcOEt:hexane = 3:7, v/v) to give **28** (14.3 mg, 40%; 5:1 epimeric ratio) as a colorless solid.

(±)-(1*R,2*S**,3*S**,8*S**,9*R**)-2-Hydroxy-1,4,4,8-tetramethyltricyclo[6.3.0.0^{3,9}]undecan-10-one (26):** mp 129−132 °C; ^{1}H NMR ($CDCl_3$) δ 4.06 (dd, 1H, J = 4.7, 1.6 Hz), 2.62 (d, 1H, J = 18.4 Hz), 2.37 (s, 1H), l.85 (dt, 1H, J = 18.4, 1.6 Hz), 1.65 (br s, 1H), 1.58−1.37 (m, 6H), 1.27 (d, 1H, J = 4.7 Hz), 1.04 (s, 3H), 1.01 (s, 3H), 0.98 (s, 3H), 0.91 (s, 3H); IR ($CHCl_3$) 3600, 3450, 1735 cm^{-1}; LRMS *m*/*z* 236 (M^+); HRMS calcd for $C_{15}H_{24}O_2$ 236.1776, found 236.1812.

(±)-(1*R,3*S**,8*S**,9*R**)-6-Hydroxy-1,4,4,8-tetramethyltricyclo[6.3.0.0^{3,9}]undecan-10-one (28) as a Diastereomixture at C(6) (Epimeric Ratio 5:1):** ^{1}H NMR ($CDCl_3$) δ 4.23−4.12 (m, 0.84 × 1H), 3.84−3.73 (m, 0.16 × 1H), 2.47 (s, 0.84 × 1H), 2.39 (s, 0.16 × 1H), 2.20−2.02 (m, 2H), 1.92−1.77 (m, 1H), 1.75−1.22 (m, 7H), 1.083 (s, 0.84 × 3H), 1.075 (s, 0.16 × 3H), 1.07 (s, 0.16 × 3H), 1.03 (s, 0.84 × 3H), 0.97 (s, 0.16 × 3H), 0.96 (s, 0.84 × 3H), 0.92 (s, 0.84 × 3H), 0.85 (s, 0.16 × 3H); IR (neat) 3420, 1735 cm^{-1}; LRMS *m*/*z* 236 (M^+); HRMS Calcd for $C_{15}H_{24}O_2$ 236.1776, found 236.1760.

(±)-(1*R,3*S**,8*S**,9*R**)-1,4,4,8-Tetramethyltricyclo-[6.3.0.0^{3,9}]undecanc-6,10-dione (29).** To a solution of **28** (6.4 mg, 27 μmol) in CH_2Cl_2 (1 mL) were added 4 Å molecular sieves (9 mg) and PCC (8.8 mg, 41 μmol) at 0 °C. After being stirred for 10 min at 0 °C, the mixture was warmed to rt and stirred for an additional 1 h. After dilution with Et_2O and the addition of Florisil, the mixture was filtered through Celite. Evaporation of the filtrate gave a residue, which was purified by column chromatography on silica gel (AcOEt:hexane = 3:7, v/v) and recrystallization from *i*-Pr_2O to give **29** (6.3 mg, 99%) as colorless prisms: mp 141 °C; ^{1}H NMR ($CDCl_3$) δ 2.67 (s, 1H), 2.65 (dd, 1H, J = 13.7, 1.0 Hz), 2.49 (d, 1H, J = 10.1 Hz), 2.27 (d, 1H, J = 13.7 Hz), 2.17−2.07 (m, 2H), 1.90 (d, 1H, J = 17.3 Hz), 1.79−1.71 (m, 1H), 1.64−1.47 (m, 2H), 1.10 (s, 3H), 1.08 (s, 3H), 0.99 (s, 3H), 0.97 (s, 3H); IR ($CHCl_3$) 1735, 1690 cm^{-1}; LRMS *m*/*z* 234 (M^+); HRMS calcd for $C_{15}H_{22}O_2$ 234.1620, found 234.1603.

X-ray Crystallography. Crystallographic data were collected at 13.0 °C on a RIGAKU AFC5R diffractometer with graphite-monochromated Mo Kα (λ = 0.71 Å) radiation and a rotating anode generator. The structure was solved using the programs in teXsan.

Structure of Compound 29. Prismatic crystals of **29** suitable for X-ray crystallography were grown by slow crystallization from *i*-Pr_2O. The compound **29** belongs to the triclinic space group $P1$ with a = 8.482(2) Å, b = 11.977(5) Å, c = 7.270-(2) Å, α = 99.65(3)°, β = 107.47(2)°, γ = 104.17(2)°, Z = 2, and D = 1.180 g/cm^3. R = 0.040 and R_w = 0.037 for 2640 unique reflections with $I > 3\sigma(I)$. GOF = 2.98.

(±)-Culmorin (1). To a solution of **26** (47.5 mg, 0.20 mmol) in THF (5.5 mL) at −78 °C were added NH_3 (18 mL), MeOH (5.5 mL), and Li (41.1 mg, 5.9 mmol). After being stirred for 1 h at −78 °C, the mixture was quenched with saturated

NH_4Cl and warmed to rt. After extraction with Et_2O, the mixture was washed with brine. The organic layer was dried and concentrated. Column chromatography on silica gel (AcOEt:hexane = 2:3, v/v) and recrystallization from *i*-Pr_2O afforded **1** (47.9 mg, 100%) as colorless needles, whose spectral data were well consistent with the reported ones:[1c] mp 167 °C; ^{1}H NMR ($CDCl_3$) δ 4.37 (ddd, 1H, J = 6.6, 6.6, 4.4 Hz), 3.84 (d, 1H, J = 4.9 Hz), 1.92 (d, 1H, J = 4.4 Hz), 1.76 (d, 1H, J = 4.9 Hz), 1.73 (br s, 2H), 1.66 (d, 2H, J = 6.6 Hz), 1.51−1.24 (m, 6H), 1.01 (s, 3H), 0.92 (s, 3H), 0.88 (s, 3H), 0.82 (s, 3H); IR ($CHCl_3$) 3630, 3470 cm^{-1}; LRMS *m*/*z* 238 (M^+); HRMS calcd for $C_{15}H_{26}O_2$ 238.1933, found 238.1917.

(±)-(1*S,2*S**,3*R**,8*S**,9*R**)-1,4,4,8-Tetramethyltricyclo-[6.3.0.0^{3,9}]undecan-2-carboxylic Acid (30).** To a stirred solution of **24** (109 mg, 0.41 mmol) in $ClCH_2CH_2Cl$ (4 mL) at 0 °C were slowly added 1,2-ethanedithiol (0.35 mL, 4.1 mmol) and BF_3·OEt_2 (0.52 mL, 4.1 mmol), and the mixture was stirred for 23 h at rt. After dilution with Et_2O, the mixture was washed with brine. The organic layer was dried and concentrated. Column chromatography on silica gel (AcOEt:hexane = 1:4, v/v) and recrystallization from *i*-Pr_2O afforded the corresponding dithioketal (136 mg, 97%) as colorless needles: mp 216−218 °C; ^{1}H NMR ($CDCl_3$) δ 3.39−3.30 (m, 1H), 3.27−3.17 (m, 1H), 3.10−3.04 (m, 2H), 2.86 (d, 1H, J = 6.9 Hz), 2.53 (dd, 1H, J = 6.9, 1.6 Hz), 2.39 (d, 1H, J = 15 Hz), 2.30 (s, 1H), 2.28 (dd, 1H, J = 15, 1.6 Hz), 1.55−1.19 (m, 6H), 1.21 (s, 3H), 1.02 (s, 3H), 1.00 (s, 3H), 0.83 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 180.7, 72.8, 58.9, 55.6, 55.2, 54.7, 52.1, 51.5, 40.9, 40.4, 37.0, 36.5, 34.0, 29.4, 28.3, 25.9, 22.1, 14.1; IR ($CHCl3$) 3500, 1700 cm^{-1}; LRMS *m*/*z* 340 (M^+); HRMS calcd for $C_{18}H_{28}O_2S_2$ 340.1531, found 340.1502. A suspension of the dithioketal (136 mg, 0.40 mmol) and W-2 Raney Ni in EtOH (3 mL) was heated for 4.5 h under reflux. After filteration through Celite and concentration, the residue was purified with chromatography on silica gel (AcOEt:hexane = 1:9, v/v) and recrystallization from *i*-Pr_2O to give **30** (51 mg, 51%) as colorless plates: mp 143−144 °C; ^{1}H NMR ($CDCl_3$) δ 2.48 (dd, 1H, J = 6.6, 2.2 Hz), 1.95 (d, 1H, J = 4.4 Hz), 1.81 (d, 1H, J = 6.6 Hz), 1.78−1.66 (m, 1H), 1.63−1.52 (m, 1H), 1.50−1.16 (m, 9H), 1.01 (s, 3H), 0.97 (s, 3H), 0.86 (s, 3H), 0.75 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 182.2, 56.9, 53.8, 53.1, 52.2, 44.2, 40.7, 35.4, 33.8, 30.1, 29.8, 29.3, 28.4, 22.0, 21.9, 14.4; IR ($CHCl_3$) 3500, 1695 cm^{-1}; LRMS *m*/*z* 250 (M^+). Anal. Calcd for $C_{16}H_{26}O_2$: C, 76.75; H, 10.47. Found: C, 76.46; H, 10.32.

(±)-Longiborneol (2). To a mixture of HOTT (**27**; 261 mg, 0.70 mmol) and DMAP (5.7 mg, 47 μmol) was added a solution of **30** (59 mg, 0.23 mmol) and NEt_3 (0.19 mL, 1.4 mmol) in 1,4-dioxane (2.4 mL), which was stirred for 14 h at rt under an Ar atmosphere. After the addition of *t*-BuSH (0.24 mL, 2.1 mmol), the mixture was stirred for 12 h at 80 °C under an O_2 current. To this was added $P(OMe)_3$ (0.28 mL, 2.3 mmol) at rt, and the resulting mixture was stirred for a further 2 h at rt. After the addition of saturated NH_4Cl, the mixture was extracted with Et_2O. The organic layer was then dried and concentrated. Column chromatography on silica gel (AcOEt:hexane = 1:9, v/v) afforded **2** (51 mg, 51%) as colorless prisms (from pentane), mp 100−102 °C [lit.[8] mp 100−102 °C], whose spectral data were identical with those reported for (±)-**2**.[8]

Acknowledgment. We thank Dr. Chizuko Kabuto (Instrumental Analysis Center for Chemistry, Faculty of Science, Tohoku University) for doing the X-ray analysis. We are grateful to Emeritus Professor Keiichiro Fukumoto of Tohoku University for the kind discussion. This work was partly supported by a Grant-in Aid for Research on Priority Areas (Nos. 11119206 and 11147202) from the Ministry of Education, Science, Sports and Culture, Japan.

Supporting Information Available: X-ray crystallographic data for compound **29** and copies of ^{1}H NMR spectra (300 MHz) for compounds **1**, **19**, **23**, **26**, and **28**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO000185S