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Synthesis of chiral oxacyclic dienes via ruthenium-catalyzed enyne metathesis: useful building blocks for chiral tricyclic oxygen derivatives

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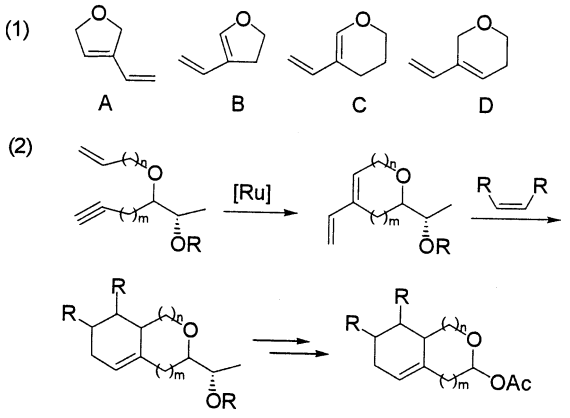
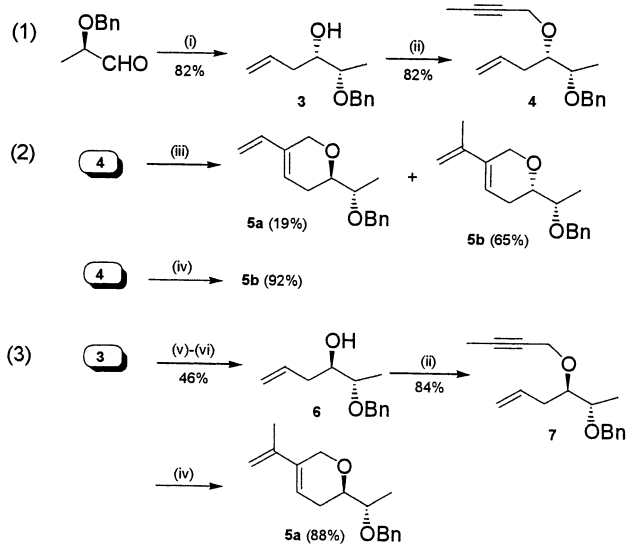
Abstract—Various chiral oxacyclic dienes were synthesized via enyne metathesis using Grubbs catalyst $(PCy_3)_2Cl_2Ru{=}CHPh$. A series of substrates bearing a 1,2-diol skeleton was prepared from (2*S*)-(benzyloxy)-propanal. The enyne metathesis proceeds smoothly in CH_2Cl_2 at 23°C with a low loading of catalyst (2.0 mol%) under ethylene gas (1–2.5 atm), giving good yields of products without epimerization at any stereogenic carbon. Heating compound **5** comprising a disubstituted alkyne in benzene (80°C) under nitrogen resulted in formation of two diastereomers via epimerization of the primary product. The epimerization occurs at the oxacyclic carbon rather than the benzyl carbon. Diels–Alder reactions of chiral oxacyclic dienes **19** and **22** with maleic anhydride, maleimide and benzoquinone proceeded with high diastereoselectivities, yielding a single cycloadduct efficiently at ambient conditions. The structures of Diels–Alder adducts were determined by ^{1}H NOE NMR spectra. The cycloadducts were formed via the approach of dienophiles to the diene in endo mode and opposite the substituent of the stereogenic center. The cycloadducts **29** and **31** were transformed into enantiopure tricyclic furans **35** and **38** after transformation of the (2*S*)-(silyloxy)ethyl group into an acetate group.

1. Introduction

Oxacyclic dienes (A)–(D) are useful building blocks for complex oxygen heterocycles. Cycloaddition of these dienes with electron-deficient olefins normally proceeds with high diastereoselectivities.[1–4] This methodology provides a short entry to framework of naturally occurring compounds. One major problem with the use of these dienes is the diversity of synthetic methods that often requires a long procedure.[1–4] Few of them aim toward the enantiospecific synthesis of oxygen heterocyclic compounds via Diels–Alder reaction.[3a,4] A short and general synthesis of



Scheme 1.



Scheme 2. *Condition*: (i) $allylSiMe_3$, $SnCl_4$; (ii) NaH, 1-bromo-but-2-yne; (iii) $(Pcy_3)_2Cl_2Ru{=}CHPh$ (2.0 mol%), benzene, N_2, 80°C, 8 h; (iv) 2.0 mol% catalyst, CH_2Cl_2, 23°C, 6 h, $CH_2{=}CH_2$ (1.0 atm); (v) DEAD, PPh_3, *p*-nitrobenzoic acid; (iv) Na_2CO_3, EtOH.

Keywords: chiral oxacyclic dienes; enyne metathesis; diastereoselectivity; tricyclic furan.

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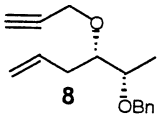
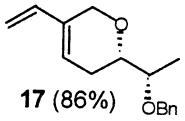
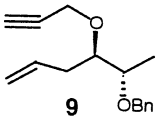
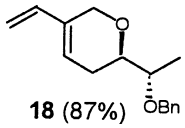
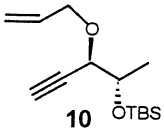
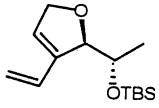
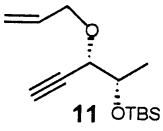
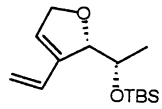
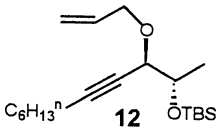
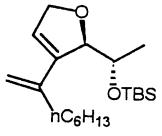
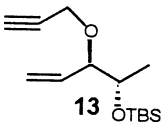
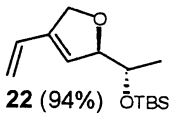
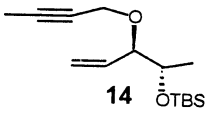
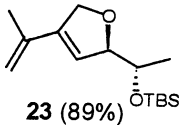
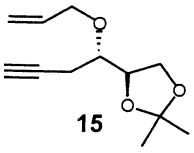
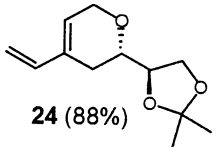
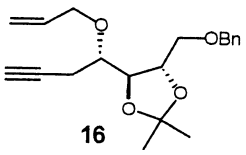
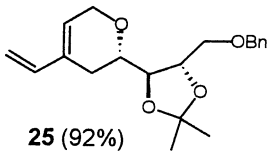
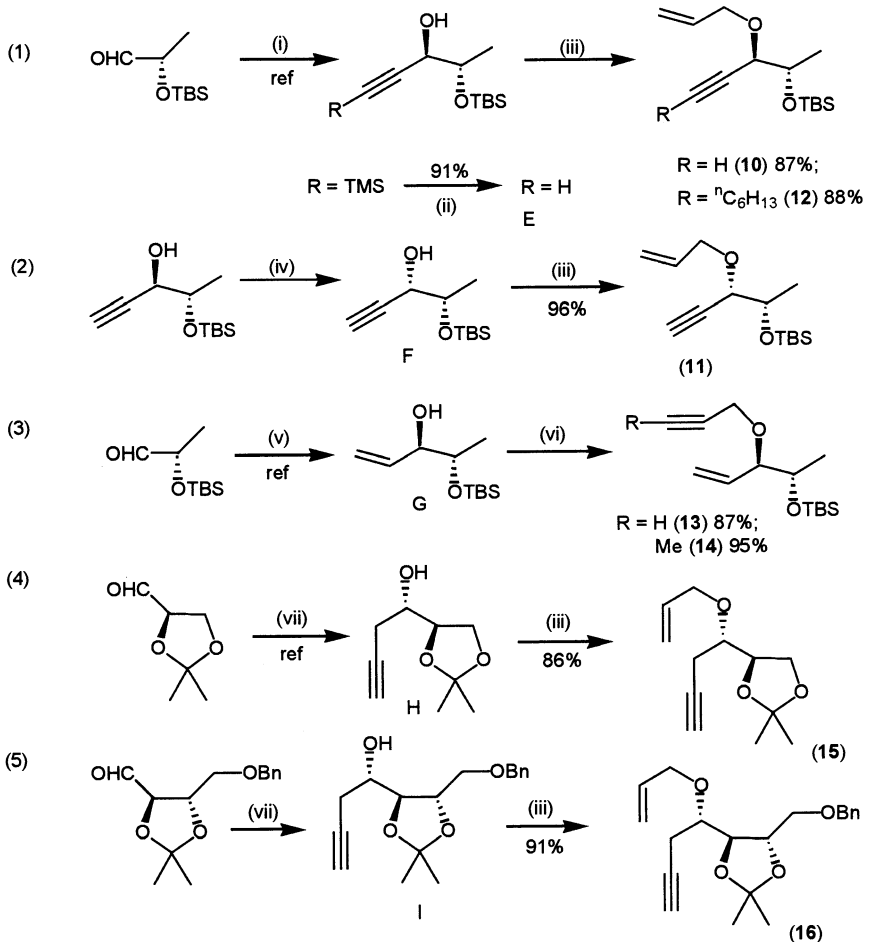
PII: S0040-4020(02)00548-3

Table 1. Synthesis of chiral dienes from enyne metathesis

Entry	Enyne	Conditions[a]	Diene (yields)[b]
1	 **8**	23°C, 6 h	 **17** (86%)
2	 **9**	23°C, 6 h	 **18** (87%)
3	 **10**	23°C, 5 h	 **19** (92%)
4	 **11**	23°C, 6 h	 **20** (86%)
5	 **12**	23°C, 10 h[a,c]	 **21** (67%[a], 81%[b])
6	 **13**	23°C, 6 h[c]	 **22** (94%)
7	 **14**	40°C, 8 h[c]	 **23** (89%)
8	 **15**	23°C, 40 h	 **24** (88%)
9	 **16**	23°C, 40 h	 **25** (92%)

[a] Condition: [enyne]=0.10 M, 2.0 mol% catalyst, 1.0 atm ethylene, CH_2Cl_2, 23°C.
[b] Yields were given after purification from SiO_2 column.
[c] Condition: Ethylene, 2.5 atm.

chiral oxacyclic dienes will be valuable in synthetic organic chemistry. Metal-catalyzed enyne metathesis seems to be a convenient and general approach to achieve the synthesis (Eq. 1).[5–8] In this study, we report synthesis of various chiral oxacyclic dienes via enyne metathesis using Grubbs catalyst $(PCy_3)_2Cl_2Ru{=}CHPh$. Scheme 1 shows our strategy for enantiospecific synthesis of complex oxygen heterocycles. These oxacyclic dienes are designed to bear a (2*S*)-(alkoxy)-ethyl group derived from natural (2*S*)-ethyl lactate. The role of this substituent are twofold in synthetic application:



Scheme 3. *Conditions*: (1) RCCLi (1.0 equiv.), THF, −78°C, 4 h; (2) Bu_4NF (1.0 equiv.); (3) NAH (1.1 equiv.), allylbromide; (4) DEAD, PPh_3, *p*-nitrobenzoic acid, Na_2CO_3; (5) CH_2=CHMgBr, THF, −78°C; (6) NaH, $RCCCH_2Br$; (7) propargylzinc bromide, rt.

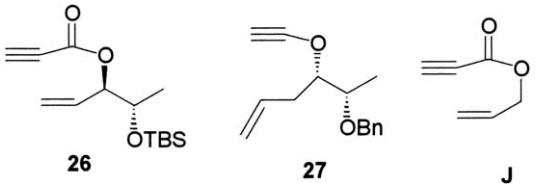
(1) control of diastereoselective Diels–Alder reaction; and (2) easy degradation into a common functionality after cycloadditon reaction.

Synthesis of oxygenated molecules via enyne metathesis using Grubbs catalyst might encounter difficulties according to literature reports.[9] Functional groups such as alcohols, ether and silyl ethers do not react or perform very poorly in enyne cross metathesis. Chelation of oxygen atom to ruthenium carbene catalyst will impede catalytic reactivity. In contrast with diene metathesis,[10] we found that enyne metathesis with Grubbs catalyst might result in epimerization of stereogenic carbon of an oxacyclic molecule, and this problem might be avoided under more mild condition.

2. Results and discussion

As shown in Scheme 2, (4*S*,5*S*)-5-(phenylmethoxy)hex-1-en-4-ol (**3**) was prepared according to the procedure in literature.[11] Treatment of compound **3** with NaH and 1-bromo-but-2-yne gave enyne **4** in 82% yield. Metathesis of compound **4** with Grubbs catalyst was performed in benzene (0.15 M) at elevated temperatures (80°C, 8 h) under nitrogen to afford two diastereomers **5a** and **b** which were separable on silica column. The isolated yields of **5a** and **b** were 19 and 65%, respectively. This result indicates that enyne metathesis with Grubbs catalyst at 80°C can lead to epimerization of a chiral molecule; a phenomenon has not been previously observed. The epimerization can be circumvented by the use of ethylene gas[6a,b,9] (1.0 atm) to effect the metathesis at 23°C (0.1 M, CH_2Cl_2, 8 h). This condition afforded only diene **5b** in 92% yield. To determine the relative configuration of **5a**, we prepared compound **7** via Mitsonobu reaction[12a] of the alcohol **4**, followed by a similar propargylation of the resulting alcohol **6**. Metathesis of compound **7** (0.1 M) at 23°C gave only compound **5a** (88%) of which the NMR spectra and the [α_D value [−59.2 (*c* 2.6, $CHCl_3$)] matched well with those of the one [−58.7 (*c* 2.6, $CHCl_3$)] given in Eq. (2). This information suggests that the epimerization occurred at the pyranyl carbon rather than the benzylic carbon. The mechanism for this epimerization is unclear at this stage.

We extended this ruthenium-catalyzed metathesis to the synthesis of various chiral oxacyclic dienes; the examples are provided in Table 1. Synthesis of the substrates **8** and **9** follows the same procedures as those of enynes **4** and **7**. Scheme 3 shows the synthetic protocol for the substrates **8**–**16** that were prepared from propargylation or allylation of their parent alcohols, **E**–**I**. The synthesis of these alcohol derivatives **E**,[13] **G**, [14] **H**,[15] **I**[15] are well documented in literature. The alcohol **F** used for synthesis of enyne **11**

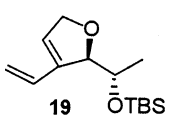
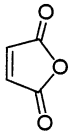
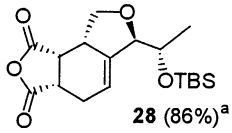
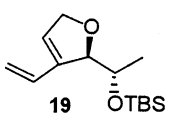
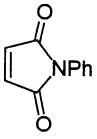
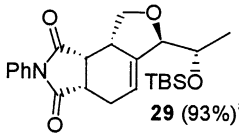
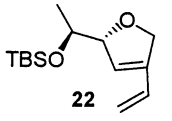
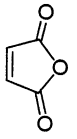
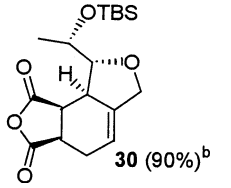
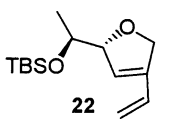
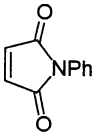
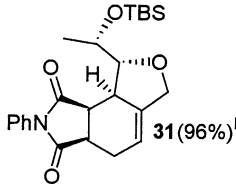
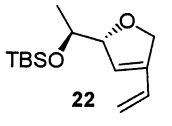
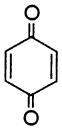
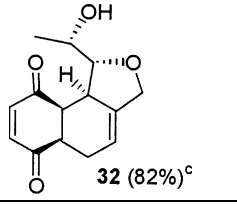


Scheme 4.

was obtained by Mitsonobu reaction[12] of its epimer **E** (R=H, Eq. (2)). These substrates comprise a vinyl group because the Grubbs catalyst do not work for 1,2- or 1,1-disubstituted olefins in enyne metathesis.[6a,b] Similar to the preceding cases, the enynes **10**–**16** were treated with ruthenium catalyst (2.0 mol%) in CH_2Cl_2 (0.10–0.12 M) at 23°C under ethylene gas (1.0–2.5 atm). The Grubbs catalyst effected enyne metathesis of the substrate **8** and **9** (entries 1 and 2) tethered with a terminal alkyne, affording the pyranyl dienes **17** and **18** in 86 and 87% isolated yields, respectively.

This approach is also applicable to a synthesis of furyl dienes **19** and **20** for which the yields were 92 and 86%, respectively. A similar furyl diene **21** (entry 5) was formed in 67% yield from the enyne **12** bearing a long alkynyl chain. The yield of compound **21** was increased to 81% under a pressurised ethylene (2.5 atm) at 23°C for 10 h. Similarly, a pressurised ethylene (2.5 atm) is required to facilitate metathesis of enynes **13** and **14** (entries 6 and 7) to the corresponding dienes **22** and **23** in good yields. The highly oxygenated functionalities enynes **15** and **16** did not inhibit catalytic activity. The reaction is complete over a prolong period (40 h) to give the pyranyl dienes **24** and **25** in good yields (>88%).

Table 2. Asymmetric Diels–Alder reaction with dienophiles

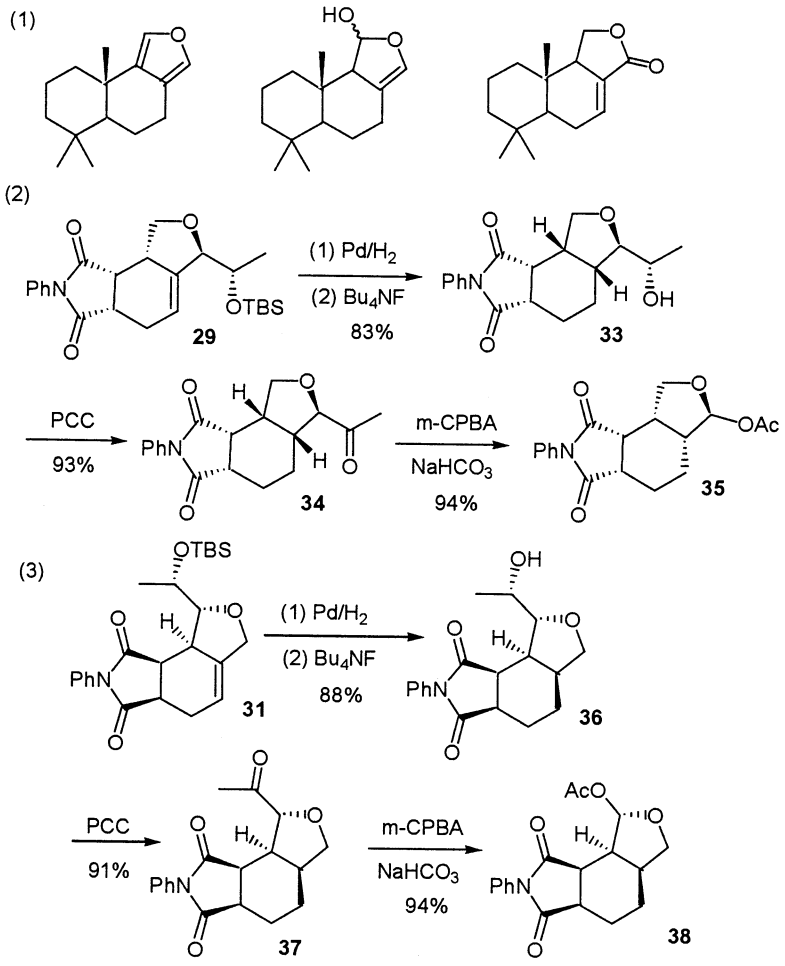
Entry	Oxacyclic dienes	Dienophiles	Cycloadduct (yields)
1			
2			
3			
4			
5			

Conditions: (a) toluene, 90°C, 2 h; (b) toluene 110°C, 6 h; (c) $SnCl_4$ (5.0 equiv.) CH_2Cl_2, 23°C.

Grubbs catalyst is not applicable to the two enynes **26** and **27** (Scheme 4). For compound **26** bearing a propiolate group, no product was formed over a long period (40 h) even under pressurised ethylene gas (2.5 atm). The starting material **26** was recovered in 86% yield in this case. Enyne metathesis with Grubbs catalyst with terminal electron-deficient alkynes proceeds with difficulty. Hoye reported[7e] that very slow addition (37 h) of Grubbs catalyst (10 mol%) to the enyne **J** (0.1 M, CH_2Cl_2, 23°C) afforded the corresponding diene in 30–40% yield.[7e] The turnover number was 2 if the catalyst was added in one-pot operation. Metathesis on alkynyl ether **27** led to the formation of a mixture of products even at 23°C (3 h). The two major components of products were not separable on silica column for further characterization.

We examined diastereoselective Diels–Alder reactions of dienes **19** and **22** with electron-deficient olefins; the results are shown in Table 2. The yields of cycloadducts are given after purification either from a preparative silica plate (entries 1–4) or from crystallization from diethyl ether/hexane (entry 5). Heating diene **19** with equimolar amount of maleic anhydride and phenyl maleimide in toluene (90°C, 2 h) afforded the cycloadducts **28** and **29** (entries 1 and 2) as a single diastereomer; the yields were 86 and 93%, respectively. Cycloaddition of compound **22** with maleic anhydride and phenyl maleimide proceeded with high diastereoselectivities in hot toluene (110°C, 6 h), yielding the products **30** and **31** in 90 and 96% yields, respectively. With the use of excess $SnCl_4$ (5.0 equiv.), reaction of the diene **22** with benzoquinone (1.2 equiv.) in CH_2Cl_2 (23°C, 12 h) led to formation of a single stereoisomer **32** (82%) from which the silyloxy group was removed. The stereochemistry of compounds **29**, **30** and **32** was determined according to ^1H NMR NOE spectra (see Section 3).

This information suggests that the dienophiles approached the diene in *endo* mode and opposite the chiral (2*S*)-(silyloxy)ethyl substituent. Scheme 5 shows several examples of naturally occurring compounds which represent families of drimane sesquiterpenes.[16,17] The cycloadducts from preceding reactions appear to be useful building blocks if the 2*S*-(silyloxy)ethyl substituent is to be degraded. Treatment of cycloadduct **29** with Pd/H_2 (1.0 atm) resulted in selective hydrogenation of the internal double bond, followed by the removal of the silyloxy group, yielding the alcohol **33** in 83% yield. Oxidation of alcohol **33** with PCC afforded the ketone **34** of which the structure was confirmed by X-ray diffraction study.[18] Compound **34** was transformed into the lactol **35** by *m*-CPBA oxidation, and the alkoxyalky group of compound **34** is more prone to migration than an alkyl group in Baeyer–Villager oxidation.[19] This transformation was shown to proceed exclusively via retention of stereochemistry. A similar transformation was performed on the



Scheme 5.

tricyclic adduct **31** to give compounds **36** and **37** respectively. Oxidation of ketone **37** with *m*-CPBA gave the lactol **38** which has an acetate group on the furanyl C_2-carbon.

In summary, Grubbs catalyst in enyne metathesis is effective in the synthesis of chiral oxacyclic dienes. We observed that Grubbs catalyst might result in epimerization of a stereogenic carbon of an oxacyclic molecule at high reaction temperatures. We demonstrate that the 2-(silyloxy)ethyl group of oxacyclic dienes **19** and **22** effects diastereoselective Diels–Alder reactions with electron-deficient olefins. The cycloadducts **29** and **31** were transformed into enantiopure tricyclic furans **35** and **38** after transformation of this silyloxy group into an acetate group. This proves that oxacyclic dienes in this study are useful building block for the framework of naturally occurring compounds.

3. Experimental

3.1. General

Unless otherwise noted, all reactions were carried out under a nitrogen atmosphere in oven-dried glassware using standard syringe, cannula and septa apparatus. Benzene, diethyl ether, tetrahydrofuran and hexane were dried with sodium benzophenone and distilled before use. Dichloromethane was dried over CaH_2 and distilled before use. $(PCy_3)_2Cl_2$-Ru=CHPh, (*S*)-ethyl lactate, allyltrimethylsilane, propargyl bromide, 1-bromo-but-2-yne, allylbromide, $SnCl_4$, maleic anhydride, phenyl maleimide, benzoquinone, ethylene gas and sodium hydride were obtained commercially and used without purification. The chiral alcohol **3**,[11] **E**,[13] **G**,[14] **H**[15] and **I**[15] was prepared according to the procedure in literature. Spectral data of compounds **33**–**35** were reported previously in our preceding paper.[4]

3.1.1. Synthesis of 1-{[(1*S*,2*S*)-1-methyl-2-(2-butynyloxy)-4-pentenyl]oxy-methyl}benzene (4). To a THF solution (20 mL) of chiral alcohol **3** (0.41 g, 2.00 mmol) was added NaH (48 mg, 2.1 mmol), and the mixtures were stirred for 4 h at 23°C before treatment of 1-bromo-but-2-yne (0.33 g, 2.0 mmol). The solution was stirred for 8 h, and quenched with a saturated NH_4Cl solution. The solution was concentrated, extracted with diethyl ether and eluted through silica column (diethyl ether/hexane=1/1) to give the enyne **4** as a colorless oil (0.42 g, 1.64 mmol, 82%). $[\alpha_D{}^{25}=-4.0$ (*c* 0.55, $CHCl_3$); IR (neat, cm^{-1}): 2241 (w), 1645 (w), 1600 (w); ^1H NMR (400 MHz, $CDCl_3$): δ (m, 5H), 5.80–5.86 (m, 1H), 5.05 (d, 1H, J=16.0 Hz), 5.02 (d, 1H, J=11.0 Hz), 4.56 (ABq, J=4.8 Hz, 2H), 4.20 (s, 2H), 3.60–3.66 (m, 1H), 3.48–3.53 (m, 1H), 2.35–2.42 (m, 1H),

2.21–2.26 (m, 1H), 1.83 (s, 3H), 1.18 (d, J=4.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 3.5, 15.2, 34.5, 58.5, 71.3, 75.7, 76.7, 80.6, 81.9, 116.6, 127.4, 127.7, 128.3, 135.4, 138.8; HRMS calcd for $C_{17}H_{22}O_2$: 258.1620, found 258.1617.

3.2. Enyne metathesis of compound 4

Method A. To a benzene solution (20 mL) was added compound **4** (0.24 g, 0.93 mmol) and $(PCy_3)_2Cl_2Ru$=CHPh (16.0 mg, 1.9×10^{-2} mmol) under nitrogen, and the mixtures were heated at 80°C for 8 h. The solution was filtered over a short silica bed and chromatographed over a preparative silica plate (diethyl ether/hexane=1/1) to afford the diene **5a** (46 mg, 0.17 mmol, 19%) and **5b** (159 mg, 0.61 mmol, 65%) as colorless oil.

Method B. To a CH_2Cl_2 solution (20 mL) was added compound **4** (0.24 g, 0.93 mmol), $(PCy_3)_2Cl_2Ru$=CHPh (16.0 mg, 1.9×10^{-2} mmol) under ethylene gas (1.0 atm), and the mixtures were stirred at 23°C for 8 h. Workup of this mixture in a similar fashion afforded the diene **5b** in 92% yield.

3.2.1. Spectral data for (2*R*)-2-[(1*S*)-1-(benzyloxy)ethyl]-5-isopropenyl-3,6-dihydro-2*H*-pyran (5a). $[\alpha]_D^{23}=-58.7$ (c 3.6, $CHCl_3$); IR (neat, cm^{-1}): 1645 (w), 1600 (w); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25–7.37 (m, 5H), 5.91 (d, J=6.0 Hz, 1H), 4.82 (s, 1H), 4.72 (s, 1H), 4.64 (d, J=3.6 Hz, 2H), 4.42 (ABq, J=2.5 Hz, 2H), 3.57 (m, 1H), 3.51 (m, 1H), 2.26 (m, 1H), 2.03 (m, 1H), 1.87 (s, 3H), 1.20 (d, J=6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 16.0, 20.8, 27.1, 66.8, 72.0, 76.9, 77.3, 110.5, 121.7, 127.0, 127.9, 128.0, 136.2, 139.5, 140.7; HRMS calcd for $C_{17}H_{22}O_2$: 258.1620, found 258.1614.

3.2.2. Spectral data for (2*S*)-2-[(1*S*)-1-(benzyloxy)ethyl]-5-isopropenyl-3,6-dihydro-2*H*-pyran (5b). $[\alpha]_D^{23}=+52.9$ (c 1.8, $CHCl_3$); IR (neat, cm^{-1}): 1641 (w), 1604 (w); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.15–7.25 (m, 5H), 5.85 (s, 1H), 4.73 (s, 1H), 4.62 (s, 1H), 4.50 (ABq, J=12.4 Hz, 2H), 4.31 (ABq, J=2.0 Hz, 2H), 3.45 (m, 1H), 3.33 (m, 1H), 2.01–2.15 (m, 2H), 1.77 (s, 3H), 1.15 (d, J=6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 15.4, 20.3, 26.7, 66.6, 71.6, 76.4, 76.6, 109.6, 121.4, 127.3, 127.7, 128.3, 135.8, 139.0, 140.0; HRMS calcd for $C_{17}H_{22}O_2$: 258.1620, found 258.1614.

3.2.3. Synthesis of (4*R*,5*S*)-5-(phenylmethoxy)hex-1-en-4-ol (6). To a toluene solution (25 mL) of DEAD (1.81 g, 10.4 mmol) and PPh_3 (2.73 g, 10.4 mmol) added the alcohol **3** (2.00 g, 9.70 mmol), and the solution was stirred for 1 h before *p*-nitrobenzoic acid (1.74 g, 10.4 mmol) was added at 23°C. The mixture was stirred for 8 h, and filtered to remove white precipitates. To the toluene filtrate was added water (10 mL), and the organic layer was separated, concentrated and eluted through a short silica column to afford the ester product (2.60 g, 7.31 mmol). To a methanol solution (10.0 mL) of this ester (2.60 g, 7.31 mmol) was added K_2CO_3 (1.72 g) solution, and the mixture was stirred for 6 h before quenched with a NH_4Cl solution. The solution was concentrated dried over $MgSO_4$, and the organic layer was extracted with diethyl ether (20 mL). The etherate solution was concentrated and eluted through a silica column to afford the chiral alcohol as a colorless oil (0.92 g, 4.47 mmol, 46%). $[\alpha]_D^{25}=+89.1$ (c 5.0, $CHCl_3$); IR (neat, cm^{-1}): 3403 (br s), 1645 (w), 1598 (w); ^{1}H NMR (400 MHz, $CDCl_3$): δ 726–7.35 (m, 5H), 5.83 (m, 1H), 5.14 (d, J=18.8 Hz, 1H), 5.06 (d, J=11.2 Hz, 1H), 4.57 (ABq, J=2.0 Hz, 2H), 3.75 (m, 1H), 3.56 (m, 1H), 2.24 (m, 2H), 2.05 (br s, 1H), 1.19 (d, J=6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.8, 36.9, 70.7, 72.6, 77.3, 117.5, 127.6, 127.7, 128.4, 134.9, 138.3; HRMS calcd for $C_{13}H_{18}O_2$: 206.1307, found 206.1303.

3.2.4. Synthesis of 1-{[(1*S*,2*R*)-2-(2-butynyloxy)-1-methyl-4-pentenyl]oxy-methyl}benzene (7). This compound was prepared similarly from the chiral alcohol **6**, NaH and 1-bromo-but-2-yne; the yield of the enyne **7** was (90%). $[\alpha]_D^{25}=-61.2$ (c 3.6, $CHCl_3$); IR (neat, cm^{-1}): 2235 (w), 1643 (w); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.26–7.35 (m, 5H), 5.83 (m, 1H), 5.07 (d, J=16.0 Hz, 1H), 5.02 (d, J=11.0 Hz, 1H), 4.58 (ABq, J=10.8 Hz, 2H), 4.19 (d, J=1.6 Hz, 2H), 3.64 (m, 1H), 3.52 (m, 1H), 2.39 (m, 1H), 2.24 (m, 1H), 1.83 (s, 3H), 1.20 (d, J=6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 3.8, 15.5, 34.7, 58.7, 71.2, 71.5, 77.6, 80.8, 82.1, 116.9, 127.7, 127.9, 128.5, 135.6, 139.1; HRMS calcd for $C_{17}H_{22}O_2$: 258.16.20, found 258.1613.

3.2.5. Enyne metathesis of compound 7. To a CH_2Cl_2 solution (20 mL) of compound **7** (0.24 g, 0.93 mmol) was added $(PCy_3)_2Cl_2Ru$=CHPh (16.0 mg, 1.9×10^{-2} mmol) under ethylene gas (1.0 atm), and the mixtures were stirred at 23°C for 8 h. Work up of this mixture afforded the diene **5a** (0.22 g, 0.82 mmol) in 88% yield. The $[\alpha]_D$ value [−59.2 (c 2.6, $CHCl_3$)] and ^{1}H NMR spectral data of this compound matched with that of **5a** $[\alpha]_D$ value [−58.7 (c 2.6, $CHCl_3$)] in the preceding reaction.

3.2.6. Synthesis and spectral data of 1-{[(1*S*,2*S*)-1-methyl-2-(2-propynyloxy)-4-pentenyl]oxy-methyl}benzene (8). The reaction of the alcohol **3** with NaH and benzyl bromide gave the enyne **8** in 87% yield. $[\alpha]_D^{23}=+30.3$ (c 2.5, $CHCl_3$); IR (neat, cm^{-1}): 2223 (w), 1642 (w), 1603 (w); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25–7.35 (m, 5H), 5.85 (m, 1H), 5.09 (1H, d, J=17.2 Hz), 5.02 (1H, d, J=10.6 Hz), 4.57 (2H, ABq, J=8.0 Hz), 4.24 (s, 2H), 3.63 (1H, m), 3.53 (1H, m), 2.38 (1H, m), 2.37 (1H, s), 2.23 (1H, m), 1.20 (d, J=2.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 15.3, 34.5, 57.9, 71.3, 73.9, 75.9, 80.4, 80.9, 116.9, 127.5, 127.7, 128.3, 135.0, 138.7; HRMS calcd for $C_{16}H_{20}O_2$: 244.1463, found 244.1461.

3.2.7. Spectral data of 1-{[(1*S*,2*R*)-1-methyl-2-(2-propynyloxy)-4-pentenyl]oxy-methyl}benzene (9). Enyne **9** was prepared from the alcohol **6**, NaH and benzyl bromide; the yield was 87%. $[\alpha]_D^{23}=+47.0$ (c 1.5, $CHCl_3$); IR (neat, cm^{-1}): 2223 (w), 1651 (w), 1599 (w); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25–7.35 (m, 5H), 5.82 (m, 1H), 5.09 (d, J=17.0 Hz, 1H), 5.04 (d, J=10.5 Hz, 1H), 4.57 (ABq, J=8.0 Hz, 2H), 4.24 (s, 2H), 3.64 (m, 1H), 2.38 (m, 1H), 1.20 (d, J=2.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 15.3, 34.5, 57.9, 71.3, 73.9, 75.9, 80.4, 80.9, 116.9, 127.5, 127.7, 128.3, 135.0, 138.7; HRMS calcd for $C_{16}H_{20}O_2$: 244.1463, found 244.1461.

3.2.8. Spectral data for (3*R*,4*S*)-3-(allyloxy)-4-[dimethyl(*tert*-butyl)siloxy]-1-pentyne (10). Enyne **10**

was prepared similarly from the alcohol **E** (R=H), NaH and allyl bromide, and the yield was 87%. $[\alpha]_D^{23}=-27.0$ (*c* 2.0, $CHCl_3$); IR (neat, cm^{-1}): 2218 (w), 1640 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 5.86 (m, 1H), 5.31 (d, *J*=16.8 Hz, 1H), 5.16 (d, 1H, *J*=10.2 Hz), 4.25 (m, 1H), 3.96 (m, 1H), 3.88 (d, *J*=4.4 Hz, 2H), 2.37 (s, 1H), 1.20 (d, *J*=6.4 Hz, 3H), 0.84 (s, 9H), 0.09 (s, 3H), 0.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −5.0, −4.6, 18.1, 19.7, 25.8, 70.1, 70.6, 73.9, 74.3, 81.5, 117.3, 134.3; HRMS calcd for $C_{14}H_{26}SiO_2$: 254.1702, found 254.1700.

3.2.9. Spectral data for (3*S*,4*S*)-3-(allyloxy)-4-[dimethyl-(*tert*-butyl)siloxy]-1-pentyne (11). This compound was prepared similarly from the alcohol **F**, NaH and allyl bromide; the yield was 96%. $[\alpha]_D^{23}=+33.8$ (*c* 0.65, $CHCl_3$); IR (neat, cm^{-1}): 2230 (w), 1644 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 5.87 (m, 1H), 5.27 (d, *J*=16.8 Hz, 1H), 5.16 (d, *J*=10.2 Hz, 1H), 4.24 (dd, *J*=10.2, 4.5 Hz, 1H), 3.94 (dd, *J*=10.2, 7.0 Hz, 1H), 3.88 (m, 2H), 2.39 (s, 1H), 1.22 (d, *J*=6.4 Hz, 3H), 0.87 (s, 9H), 0.09 (s, 3H), 0.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.4, −4.6, 18.3, 19.8, 26.0, 70.3, 70.4, 74.4, 81.1, 117.5, 134.6; HRMS calcd for $C_{14}H_{26}SiO_2$: 254.1702, found 254.1698.

3.2.10. Spectral data for (2*S*,3*R*)-3-(allyloxy)-2-[*tert*-dimethyl(*tert*-butyl)-siloxy]-4-unde-cyne (12). Enyne **12** was prepared from chiral alcohol **E** (R=C_6H_{13}), NaH and allyl bromide, and the yield was 88%. $[\alpha]_D^{23}=-43.6$ (*c* 4.8, $CHCl_3$); IR (neat, cm^{-1}): 2230 (w), 1643 (w), 1600 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 5.88 (m, 1H), 5.28 (d, *J*=18.2 Hz, 1H), 5.15 (d, *J*=10.4 Hz, 1H), 4.23 (m, 1H), 4.00 (m, 1H), 3.83 (m, 2H), 2.19 (t, *J*=4.0 Hz, 2H), 1.53 (m, 2H), 1.38 (m, 2H), 1.29 (m, 4H), 1.21 (d, *J*=6.4 Hz, 3H), 0.87 (t, *J*=6.2 Hz, 3H), 0.86 (s, 9H), 0.10 (s, 3H), 0.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −5.0, −4.5, 14.3, 18.5, 19.1, 20.0, 22.8, 26.1, 28.8, 28.9, 31.6, 70.1, 71.4, 74.6, 77.9, 87.2, 117.2, 135.1; HRMS calcd for $C_{20}H_{38}SiO_2$: 338.2641, found 338.2644.

3.2.11. Spectral data for (3*S*,4*R*)-3-(2-propynyloxy)-4-(*tert*-butyldimethylsiloxy)-1-pentene (13). Alcohol **G** (R=H), NaH and propargyl bromide yielded enyne **13** as a colorless oil (87%). $[\alpha]_D^{23}=-74.8$ (*c* 1.5, $CHCl_3$); IR (cm^{-1}): 2241 (w), 1631 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 5.66 (m, 1H), 5.29 (d, *J*=10.0 Hz, 1H), 5.28 (d, *J*=17.0 Hz, 1H), 4.19 (dd, *J*=2.4, 2.0 Hz, 1H), 4.03 (dd, *J*=2.4, 2.0 Hz, 1H), 3.78 (m, 1H), 3.70 (m, 1H), 2.34 (t, *J*=2.8 Hz, 1H), 1.13 (d, *J*=5.6 Hz, 2H), 0.85 (s, 9H), 0.03 (s, 3H), 0.02 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.1, 26.0, 55.7, 70.8, 73.9, 80.4, 84.5, 119.6, 135.3; HRMS calcd for $C_{14}H_{26}SiO_2$: 254.4437, found 254.4432.

3.2.12. Spectral data for (3*S*,4*R*)-3-(2-butynyloxy)-4-(*tert*-butyldimethylsiloxy)-1-pentene (14). Alcohol **G** (R=H), NaH and 1-brom-2-butyne yielded enyne **14** as a colorless oil (95%). $[\alpha]_D^{23}=-45.1$ (*c* 1.5, $CHCl_3$); IR (cm^{-1}): 1909 (s), 1654 (m); ^1H NMR (400 MHz, $CDCl_3$): δ 5.68 (m, 1H), 5.25 (d, *J*=10.0 Hz, 1H), 5.22 (d, *J*=16.6 Hz, 1H), 4.06 (ABq, *J*=13.8 Hz, 1H), 3.76 (m, 1H), 3.63 (m, 1H), 1.83 (s, 3H), 1.15 (d, *J*=6.0 Hz, 3H), 0.87 (s, 9H), 0.03 (s, 3H), 0.02 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.3, −4.4, 3.7, 18.3, 20.2, 26.0, 56.4, 70.9, 75.7, 81.9, 84.3, 119.1, 135.8; HRMS calcd for $C_{15}H_{28}SiO_2$: 268.4705, found 268.4708.

3.2.13. Spectral data for (4*R*)-4-[(1*S*)-1-(allyloxy)-3-butynyl]-2,2-dimethyl-1,3-dioxolane (15). Alcohol **H**, NaH and allyl bromide gave enyne **15** as a colorless oil (86% yield). $[\alpha]_D^{23}=+14.8$ (*c* 1.1, $CHCl_3$); IR (cm^{-1}): 2234 (w), 1656 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 5.89 (m, 1H), 5.28 (d, *J*=17.2 Hz, 1H), 5.18 (d, *J*=10.4 Hz, 1H), 4.26–4.21 (m, 1H), 4.19–4.13 (m, 1H), 4.07 (dd, *J*=8.4, 7.6 Hz, 1H), 3.94 (dd, *J*=8.4 Hz, 1H), 3.50–3.46 (m, 1H), 2.60 (dd, *J*=17.2, 5.2 Hz, 1H), 2.60 (dd, *J*=17.2, 4.6 Hz, 1H), 2.01 (t, *J*=2.4 Hz, 1H), 1.40 (s, 3H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.2, 25.4, 26.9, 66.7, 70.4, 71.6, 76.6, 76.9, 80.6, 109.5, 117.6, 134.7; HRMS calcd for $C_{12}H_{18}O_3$: 210.2724, found 210.2715.

3.2.14. Spectral data for (4*R*,5*R*)-4-[(1*R*)-1-(allyloxy)-3-butynyl]-5-[(benzyloxy)methyl]-2,2-dimethyl-1,3-dioxolane (16). Alcohol **I**, NaH and allyl bromide gave enyne **16** as a colorless oil (86% yield). $[\alpha]_D^{23}=+11.2$ (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2234 (w), 1656 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 7.27 (m, 5H), 5.80 (m, 1H), 5.24 (d, *J*=17.2 Hz, 1H), 5.13 (d, *J*=10.8 Hz, 1H), 4.64–4.55 (ABq, *J*=12.0 Hz, 2H), 4.23–4.17 (m, 1H), 4.02 (m, 1H), 3.86 (t, *J*=6.8 Hz, 1H), 3.71 (dd, *J*=10.4, 10.0 Hz, 1H), 3.57 (m, 2H), 2.58 (dd, *J*=17.2, 3.6 Hz, 1H), 2.44 (dd, *J*=17.2, 4.0 Hz, 1H), 1.99 (t, *J*=2.4 Hz, 1H), 1.41 (s, 3H), 1.39 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.2, 27.0, 27.1, 70.2, 71.3, 71.4, 73.3, 77.8, 78.0, 78.8, 80.5, 109.6, 117.4, 127.6, 127.7, 128.2, 134.5, 138.0; HRMS calcd for $C_{20}H_{26}O_4$: 330.4231, found 330.4233.

3.2.15. Spectral data for (2*S*)-2-[(1*S*)-1-(benzyloxy)-ethyl]-5-vinyl-3,6-dihydro-2*H*-pyran (17). Enyne metathesis of compound **8** afforded diene **17** as a colorless oil (86%). $[\alpha]_D^{23}=-56.6$ (*c* 5.0, $CHCl_3$); IR (neat, cm^{-1}): 1641 (w), 1600 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 7.25–7.34 (m, 5H), 6.24 (dd, *J*=18.0, 11.2 Hz, 1H), 5.81 (d, 1H, *J*=4.5 Hz), 4.93 (d, *J*=18.0 Hz, 1H), 4.61 (ABq, *J*=11.2 Hz, 2H), 4.49 (d, *J*=10.4 Hz, 1H), 4.29 (d, *J*=10.4 Hz, 1H), 3.50–3.60 (m, 2H), 2.26 (br t, *J*=8.3 Hz, 1H), 1.99 (m, 1H), 1.09 (d, *J*=2.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 15.4, 26.8, 65.7, 71.6, 76.4, 76.7, 110.8, 125.5, 127.4, 127.7, 128.3, 135.0, 135.8, 138.9; HRMS calcd for $C_{16}H_{20}O_2$: 244.1463, found 244.1457.

3.2.16. Spectral data for (2*R*)-2-[(1*S*)-1-(benzyloxy)-ethyl]-5-vinyl-3,6-dihydro-2*H*-pyran (18). Enyne metathesis of compound **9** afforded diene **18** as a colorless oil (87%). $[\alpha]_D^{23}=+28.4$ (*c* 1.3, $CHCl_3$); IR (neat, cm^{-1}): 1641 (w), 1601 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 7.25–7.32 (m, 5H), 6.24 (dd, *J*=18.0, 10.8 Hz, 1H), 5.83 (br s, 1H), 4.92 (d, *J*=18.0 Hz, 1H), 4.89 (d, *J*=10.8 Hz, 1H), 4.58 (ABq, *J*=12.0 Hz, 2H), 3.55 (m, 1H), 3.44 (m, 1H), 2.39 (m, 1H), 2.13 (m, 1H), 1.23 (d, *J*=6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 16.3, 26.5, 65.7, 71.4, 76.7, 76.9, 111.2, 125.4, 127.5, 127.9, 128.5, 135.4, 136.2, 138.5; HRMS calcd for $C_{16}H_{20}O_2$: 244.1463, found 244.1460.

3.2.17. Spectral data for [dimethyl(*tert*-butyl)siloxy](1*S*)-1-[(2*R*)-3-vinyl-2,5-dihy-dro-2-furanyl]ethyl ether (19). Enyne metathesis of compound **10** afforded diene **19** as a

colorless oil (92%). $[\alpha]_D^{23}=+16.6$ (c 0.8, $CHCl_3$); IR (neat, cm^{-1}): 1641 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 6.39 (dd, J=18.0, 11.6 Hz, 1H), 5.87 (br s, 1H), 5.16 (d, J=18.0 Hz, 1H), 5.07 (d, 1H, J=10.8 Hz, 1H), 4.87 (br s), 4.67 (m, 2H), 4.10 (m, 1H), 1.17 (d, J=6.4 Hz, 3H), 0.85 (s, 9H), 0.07 (s, 3H), 0.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.4, −4.4, 16.6, 18.3, 25.9, 70.3, 75.5, 89.5, 116.0, 126.6, 129.8, 139.1; HRMS calcd for $C_{14}H_{26}SiO_2$: 254.1702, found 254.1699.

3.2.18. Spectral data for [dimethyl(*tert*-butyl)siloxy](1*S*)-1-[(2*S*)-3-vinyl-2,5-dihydro-2-furanyl]ethyl ether (20). Enyne metathesis of compound **11** afforded diene **20** as a colorless oil (86%). $[\alpha]_D^{23}=+8.8$ (c 1.1, $CHCl_3$); IR (neat, cm^{-1}): 1641 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 6.41 (dd, J=18.0, 10.6 Hz, 1H), 5.89 (br, s, 1H), 5.22 (d, J=17.6 Hz, 1H), 5.12 (d, J=7.2 Hz, 1H), 4.77 (s, 1H), 4.65 (m, 1H), 4.56 (m, 1H), 4.03 (m, 1H), 1.17 (d, J=6.4 Hz, 3H), 0.84 (s, 9H), −0.01 (s, 3H), −0.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.4, −4.9, 17.9, 19.8, 25.9, 69.3, 75.2, 88.7, 115.9, 126.7, 130.0, 138.8; HRMS calcd for $C_{14}H_{26}SiO_2$: 254.1702, found 254.1698.

3.2.19. Spectral data for (2*R*)-2-[(2*R*)-3-(1-hexylvinyl)-2,5-dihydro-2-furanyl]ethyl ether (21). Enyne metathesis of compound **12** afforded diene **21** as a colorless oil (81%). $[\alpha]_D^{23}=+8.4$ (c 1.1, $CHCl_3$); IR (neat, cm^{-1}): 1654 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 5.82 (d, J=1.6 Hz, 1H), 5.08 (s, 1H), 4.97 (s, 1H), 4.86 (br s, 1H), 4.65 (d, J=1.6 Hz, 1H), 4.13 (m, 1H), 2.24 (t, J=3.6 Hz, 2H), 1.20–1.45 (m, 11H), 1.05 (d, J=6.4 Hz, 3H), 0.85 (s, 9H), 0.12 (s, 3H), 0.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.4, −4.6, 14.0, 16.2, 18.2, 22.6, 23.2, 25.8, 28.3, 29.1, 36.9, 70.3, 76.2, 90.1, 113.1, 123.5, 140.3, 140.5; HRMS calcd for $C_{20}H_{38}SiO_2$: 338.2641, found 338.2640.

3.2.20. Spectral data for (2*R*)-2-[(1*S*)-1-(*tert*-butyldimethylsiloxy)ethyl]-4-vinyl-2,5-dihydro-furan (22). Enyne metathesis of compound **13** afforded diene **22** as a colorless oil (94%). $[\alpha]_D^{23}=+111.5$ (c 1.5, $CHCl_3$); IR (neat, cm^{-1}): 1654 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 6.49 (dd, J=17.6, 10.8 Hz, 1H), 5.80 (d, J=1.60 Hz, 1H), 5.13 (d, J=11.2 Hz, 1H), 4.95 (d, J=17.6 Hz, 1H), 4.76–4.67 (m, 1H), 4.60–4.59 (m, 1H), 3.72–3.68 (m, 1H), 1.14 (d, J=6.0 Hz, 3H), 0.85 (s, 9H), 0.03 (s, 3H), 0.02 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.63, −4.25, 18.2, 20.3, 26.0, 71.5, 74.5, 91.5, 116.3, 126.4, 129.8, 139.6; HRMS calcd for $C_{14}H_{26}SiO_2$ 254.4705, found 254.4701.

3.2.21. Spectral data for (2*R*)-2-[(1*S*)-1-(*tert*-butyldimethylsiloxy)ethyl]-4-isopropenyl-2,5-dihydrofuran (23). Enyne metathesis of compound **14** afforded diene **23** as a colorless oil (89%). $[\alpha]_D^{23}=-23.6$ (c 0.45, $CHCl_3$); IR (cm^{-1}): 1656 (w), ^1H NMR (400 MHz, $CDCl_3$): δ 5.81 (d, J=2.0 Hz, 1H), 4.95 (s, 1H), 4.73 (m, 1H), 4.62–4.61 (m, 1H), 3.68 (m, 1H), 1.92 (s, 3H), 1.16 (d, J=6.0 Hz, 3H), 0.86 (s, 9H), 0.043 (s, 3H), 0.031 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.9, −4.5, 18.0, 20.2, 20.4, 25.7, 71.4, 75.1, 91.8, 113.7, 123.7, 136.4, 141.1; HRMS calcd for $C_{15}H_{28}SiO_2$ 268.4705, found 268.4708.

3.2.22. Spectral data for (2*S*)-2-[(4*R*)-2,2-dimethyl-1,3-dioxolan-4-yl]-4-vinyl-3,6-dihydro-2*H*-pyran (24). Enyne metathesis of compound **15** afforded diene **24** as a colorless oil (88%). $[\alpha]_D^{23}=-55.3$ (c 1.5, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$): δ 6.33 (dd, J=17.6 Hz, 1H), 5.67 (d, J=2.4 Hz, 1H), 5.16 (d, J=17.2 Hz, 1H), 4.98 (d, J=10.4 Hz, 1H), 4.23 (s, 1H), 4.07 (dd, J=8.4, 7.6 Hz, 1H), 4.04–3.99 (m, 1H), 3.91 (dd, J=8.4, 8.0 Hz, 1H), 3.45–3.39 (m, 1H), 2.36–2.32 (m, 1H), 2.14–2.07 (m, 1H), 1.38 (s, 3H), 1.33 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.1, 26.5, 26.6, 65.7, 67.1, 74.6, 77.9, 109.2, 111.6, 126.0, 133.0, 137.8; HRMS calcd for $C_{12}H_{18}O_3$: 210.2724, found 210.2722.

3.2.23. Spectral data for (2*R*)-2-[(4*R*,5*R*)-5-[(benzyloxy)-methyl]-2,2-dimethyl-1,3-dioxolan-4-yl]-4-vinyl-3,6-dihydro-2*H*-pyran (25). Enyne metathesis of compound **16** afforded diene **25** as a colorless oil (92%). $[\alpha]_D^{23}=-187.5$ (c 1.5, $CHCl_3$); IR (cm^{-1}): 1666 (w), ^1H NMR (400 MHz, $CDCl_3$): δ 7.35–7.25 (m, 5H), 6.36 (dd, J=17.2, 10.8 Hz, 1H), 5.70 (d, J=1.6 Hz, 1H), 5.18 (d, J=17.6 Hz, 1H), 5.01 (d, J=10.8 Hz, 1H), 4.60 (ABq, J=14.4 Hz, 2H), 4.25–4.21 (m, 1H), 4.20–4.17 (m, 1H), 3.82 (t, J=7.2 Hz, 1H), 3.74 (dd, J=10.4 Hz, 1H), 3.61 (dd, J=10.8 Hz, 1H), 3.57–3.53 (m, 1H), 2.37–2.19 (m, 2H), 1.42 (s, 3H), 1.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 26.5, 27.1, 27.1, 65.9, 71.3, 73.4, 75.0, 79.3, 79.6, 109.8, 111.7, 125.9, 127.5, 127.6, 128.3, 133.1, 137.9, 138.1; HRMS calcd for $C_{20}H_{26}O_4$: 330.4231, found 330.4226.

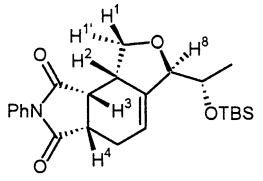
3.2.24. Spectral data for compound 26. $[\alpha]_D^{23}=+18.6$ (c 2.0, $CHCl_3$); IR (cm^{-1}): 2245 (w), 1665 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 5.85 (m, 1H), 5.32 (d, J=16.0 Hz, 1H), 5.28 (d, J=11.6 Hz, 1H), 5.13 (dd, J=7.1, 4.5 Hz, 1H), 3.95 (m 1H), 2.85 (s, 1H), 1.09 (d, J=6.0 Hz, 3H), 0.87 (s, 9H), 0.05 (s, 3H), 0.04 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.8, −4.7, 18.0, 19.5, 25.7, 69.1, 74.5, 74.8, 81.0, 120.0, 131.6, 185.7; HRMS calcd for $C_{14}H_{24}SiO_3$: 268.4273, found 268.4267.

3.2.25. Spectral data for the enyne 27. $[\alpha]_D^{23}=+4.4$ (c 2.0, $CHCl_3$); IR (cm^{-1}): 2251 (w), 1666 (w); ^1H NMR (400 MHz, $CDCl_3$): δ 7.26–7.41 (m, 5H), 5.80 (m, 1H), 5.16 (d, J=10.2 Hz, 1H), 5.10 (d, 1H, J=17.6 Hz), 4.56 (ABq, J=12.0 Hz, 2H), 4.04 (m, 1H), 3.79 (m, 1H), 2.53–2.40 (m, 2H), 2.09 (s, 1H), 1.22 (d, J=6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 15.1, 27.1, 33.5, 71.5, 74.0, 90.2, 90.6, 118.3, 127.6, 127.8, 128.3, 132.8, 138.2; HRMS calcd for $C_{15}H_{18}O_2$: 230.1306, found 230.1300.

3.2.26. Synthesis of (3a*S*,6*R*,8a*R*,8b*R*)-8-[(1*S*)-1-(*tert*-butyldimethylsiloxy)ethyl]-1,3,3a,4,6,8,8a,8b-octahydro-furo[3,4-*e*]isobenzofuran-1,3-dione (28). To a toluene solution (2.0 mL) of the diene **19** (66 mg, 0.26 mmol) was added maleic anhydride (24 mg, 0.25 mmol), and the mixture was heated in toluene (90°C, 2 h). The solution was concentrated, dried over $MgSO_4$, and eluted through a preparative silica plate to afford the cycloadduct 28 (76 mg, 2.2 mmol, 86%) as a colorless oil. $[\alpha]_D=-20.4$ (c 0.95, $CHCl_3$); IR (neat, cm^{-1}): 1846 (s), 1771 (s); ^1H NMR (500 MHz, $CDCl_3$): δ 5.83 (br s, 1H), 4.27 (m, 2H), 4.15 (s, 1H), 3.82 (m, 1H), 3.53 (m, 1H), 3.43 (m, 1H), 2.84 (dd, 1H, J=16.5, 10.0 Hz, 1H), 2.22 (m, 1H), 1.11 (d, J=6.5 Hz, 3H), 0.83 (s, 9H), 0.02 (s, 3H), −0.01 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): δ −4.6, −4.5, 18.0, 19.5, 24.5, 25.8,

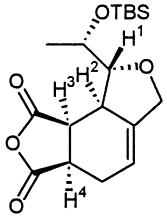
38.4, 40.3, 41.4, 68.7, 70.4, 84.1, 117.1, 136.5, 144.1, 171.0, 173.8; HRMS calcd for $C_{18}H_{28}SiO_5$: 352.1706, found 352.1699.

3.2.27. Synthesis of (3*R*,5a*S*,8a*R*,8b*S*)-3-[(1*S*)-1-(*tert*-butyldimethylsiloxy)ethyl]-3,5,5a,6,7,8,8a,8b-octahydro-1*H*-furo[3,4-*e*]isoindole-6,8-dione (29). Heating a toluene solution of the diene **19** (90°C, 2 h) with phenyl maleimide afforded the cycloadduct **29** in 93% yield after purification from preparative silica plate. $[\alpha]_D=-12.2$ (*c* 1.1, $CHCl_3$); IR (neat, cm^{-1}): 1778 (s), 1711 (s); ^1H NMR (500 MHz, $CDCl_3$): δ 7.41 (t, *J*=8.0 Hz, 2H), 7.35 (t, *J*=8.0 Hz, 1H), 6.98 (d, *J*=8.0 Hz, 2H), 5.82 (br s, 1H), 4.38 (dd, *J*=8.2, 7.6 Hz, 1H), 4.28 (dd, *J*=8.2, 7.1 Hz, 1H), 4.13 (s, 1H), 3.82 (m, 1H), 3.39 (t, *J*=7.5 Hz, 1H), 3.26 (t, *J*=7.5 Hz, 1H), 2.95 (dd, *J*=15.0, 7.5 Hz 1H), 2.83 (m, 1H), 2.19 (m, 1H), 1.12 (d, *J*=6.5 Hz, 3H), 0.85 (s, 9H), 0.06 (s, 3H), 0.03 (s, 3H); ^{13}C NMR (500 MHz, $CDCl_3$): δ −4.6, −4.5, 17.9, 19.5, 24.4, 25.8, 38.9, 39.8, 40.6, 68.9, 70.3, 84.1, 117.0, 126.3, 128.5, 129.0, 131.8, 143.6, 176.2, 178.4; HRMS calcd for $C_{24}H_{33}SiO_4N$: 427.2179, found 427.2177.



Irradiation	Intensity
H^2 (δ 2.83)	H^1 (2.6%), H^3 (3.1%)
H^8 (δ 4.13)	H^1 (0%), $H^{1'}$ (1.5%)

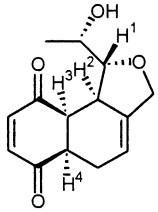
3.2.28. Synthesis of (3a*R*,8*R*,8a*R*,8b*S*)-8-[(1*S*)-1-(*tert*-butyldimethylsiloxy)ethyl]-1,3,3a,4,6,8,8a,8b-octahydro-furo[3,4-*e*]isobenzofuran-1,3-dione (30). Heating a toluene solution (110°C, 6 h) of the diene **22** (70 mg, 0.275 mmol) with maleic anhydride (27.0 mg, 0.275 mmol) afforded the cycloadduct **30** (87 mg, 0.25 mmol) in 90% yield after purification from preparative silica plate. $[\alpha]_D^{25}=-15.7$ (*c*, 1.5 $CHCl_3$); IR (cm^{-1}): 1844 (m), 1788 (m); ^1H NMR (400 MHz, $CDCl_3$): δ 5.70 (m, 1H), 4.45 (dd, *J*=6.8, 6.4 Hz, 1H), 4.39 (dd, *J*=12.6, 2.1 Hz, 1H), 4.25 (dd, *J*=12.6, 3.1 Hz, 1H), 4.0–3.9 (m, 1H), 3.51 (dd, *J*=9.6 Hz, 1H), 3.43 (dt, *J*=8.0, 1.6 Hz, 1H), 2.83–2.77 (m, 2H), 2.26–2.18 (m, 1H), 1.22 (d, *J*=6.4 Hz, 3H), 0.85 (s, 9H), 0.06 (s, 3H), 0.02 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.6, −4.41, 18.0, 20.9, 25.3, 25.7, 39.8, 41.3, 42.8, 69.3, 70.1, 83.6, 114.0, 145.7, 171.5, 174.1; HRMS calcd for $C_{18}H_{28}SiO_5$: 321.1706, found 321.1700.



Irradiation	Intensity
H^2 (δ 2.79)	H^1 (0%), H^3 (2.6%) H^4(1.4%)
H^3(δ 3.51)	H^2 (3.1%), H^4 (4.1%)

3.2.29. Synthesis of (1*R*,5a*R*,8a*S*,8b*R*)-7-phenyl-1-[(1*S*)-1-(*tert*-butyldimethylsiloxy)ethyl]-3,5,5a,6,7,8,8a,8b-octahydro-1*H*-furo[3,4-*e*]isoindole-6,8-dione (31). Heating a toluene solution (110°C, 6 h) of the diene **22** (50.9 mg, 0.196 mmol) with phenyl maleimide (34.0 mg, 0.196 mmol) afforded the cycloadduct **31** (81 mg, 0.189 mmol) in 96% yield after purification from preparative silica plate. $[\alpha]_D^{25}=-48.0$ (*c* 0.6, $CHCl_3$); IR (cm^{-1}): 1770 (m), 1716 (m); ^1H NMR (400 MHz, $CDCl_3$): δ 7.35–7.15 (m, 5H), 5.69 (br, 1H), 4.67 (dd, *J*=6.4 Hz, 1H), 4.40 (dd, *J*=13.2 Hz, 1H), 4.23 (dd, *J*=13.2 Hz, 1H), 4.02–3.98 (m, 1H), 3.39 (dd, *J*=8.8 Hz, 1H), 3.30 (dt, *J*=8.8, 1.2 Hz, 1H), 2.92–2.86 (m, 2H), 2.25–2.19 (m, 1H), 1.25 (d, *J*=6.4 Hz, 3H), 0.09 (s, 9H), 0.07 (s, 9H), 0.04 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.7, −4.4, 18.0, 20.9, 25.7, 26.0, 40.2, 40.9, 41.8, 69.2, 70.0, 83.5, 113.6, 126.3, 129.0, 129.1, 131.8, 134.5, 145.2, 176.5, 178.5; HRMS calcd for $C_{24}H_{33}NO_4Si$: 427.2179, found 427.2176.

3.2.30. Synthesis of (1*R*,5a*R*,9a*S*,9b*R*)-1-[(1*S*)-1-hydroxyethyl]-1,3,5,5a,6,9,9a,9b-octahydro benzo[*e*]isobenzofuran-6,9-dione (32). To a CH_2Cl_2 solution (3.0 mL) of the diene **22** (110 mg, 0.39 mmol) and benzoquinone (425 mg, 3.94 mmol) was added $SnCl_4$ (1.96 mL, 1.96 mmol), and the mixture was stirred at 23°C for 12 h. To this mixture was added $NaHCO_3$ solution, and the organic layer was extracted with diethyl ether, dried over $MgSO_4$ and evaporated to dryness. Recrystallization of the residues in a saturated diethyl ether/hexane solution afforded compound **32** as colorless solid (80.0 mg, 0.32 mmol, 82%). $[\alpha]_D^{25}=-59.0$ (*c* 0.6, $CHCl_3$); IR (cm^{-1}): 3059 (m), 2900 (m), 1687 (s); ^1H NMR (400 MHz, $CDCl_3$): δ 6.60 (d, *J*=7.6 Hz, 1H), 6.56 (d, *J*=7.6 Hz, 1H), 5.4–5.3 (m, 1H), 4.66 (dd, *J*=9.6, 9.2 Hz, 1H), 4.48 (dd, *J*=13.2, 3.2 Hz, 1H), 4.37 (dd, *J*=12.8, 4.4 Hz, 1H), 4.01–3.96 (m, 1H), 3.66 (t, *J*=4.8 Hz, 1H), 3.17 (m, 1H), 2.74 (m, 1H), 2.40 (m, 1H), 2.25 (m, 1H), 2.07 (s, 1H), 1.25 (d, *J*=6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 18.9, 26.7, 41.3, 47.5, 48.9, 68.9, 69.6, 82.3, 112.4, 137.2, 140.6, 140.7, 198.0, 200.7; HRMS calcd for $C_{14}H_{16}O_4$: 248.1049, found 248.1041.



Irradiation	Intensity
H^2 (δ 2.74)	H^1 (0%), H^3 (2.8%) H^4(1.8%)
H^3(δ 3.66)	H^2 (2.4%), H^4 (3.1%)

3.2.31. Synthesis of (1*R*,3a*S*,5a*R*,8a*S*,8b*S*)-1-[hydroxyethyl]-7-phenylperhydrofuro[3,4-*e*]isoindole-6,8-dione (36). To compound **31** (100 mg, 0.247 mmol) in 5 mL MeOH was added Pd/C (52.14 mg, 0.049 mmol) under 1 atm H_2 and the mixtures were stirred for 12 h. The catalyst was filtered off through a small bed of celite. To the filtrate was added excess Bu_4NF and the mixtures were stirred for 4 h. The solution was concentrated and eluted through a silica column (ether/hexane=2/1) to give alcohol **36** (65 mg, 0.203 mmol, 88%, R_f=0.23). $[\alpha]_D^{25}=-47.5$ (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3392 (br), 1607 (s); ^1H NMR (400 MHz, $CDCl_3$): δ 7.23–7.48 (m, 5H), 4.70 (t, *J*=4.0 Hz, 1H), 4.07 (t, *J*=8.0 Hz, 1H), 3.92–3.87 (m, 1H), 3.38 (t, *J*=9.2 Hz, 1H), 3.20 (dt, *J*=2.0, 8.0 Hz, 1H), 3.11

(dd, J=6.4, 9.2 Hz, 1H), 2.68–2.62 (m, 1H), 2.53–2.42 (m, 1H), 2.20–2.13 (m, 2H), 2.03–1.83 (m, 2H), 1.21 (d, J=6.0 Hz, 3H), 1.15–1.04 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 178.7, 178.6, 131.8, 129.1, 128.6, 126.3, 83.7, 74.35, 68.80, 40.02, 39.7, 36.7, 23.7, 21.4, 18.3; HRMS calcd for $C_{18}H_{21}NO_4$: 315.1470, found 315.1481.

3.2.32. Synthesis of (1*R*,3a*S*,5a*R*,8a*S*,8b*S*)-1-acetyl-7-phenylperhydrofuro[3,4-*e*]isoindole-6,8-dione (37). To a dichloromethane solution (5 mL) of compound **36** (25 mg, 0.0793 mmol) was added PCC (34.2 mg, 0.159 mmol) and dry molecular sieves 4 Å (35 mg) and the mixtures were stirred for 3 h under room temperature. The solution was filtered through celite, concentrated and chromatographed on a silica column (ether/hexane=2/1) to give compound **37** (22.8 mg, 0.0726 mmol, 91%, R_f=0.24) as a colorless oil. $[\alpha]_D^{25}$=−16.7 (c 1.0 $CHCl_3$); IR (cm^{-1}): 1782 (m), 1708 (s), 1604 (m); ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.46–7.26 (m, 5H), 4.99 (d, J=4.5 Hz, 1H), 4.16 (t, J=8.5 Hz, 1H), 3.47 (t, J=8.0 Hz, 1H), 3.25–3.17 (m, 2H), 2.91–2.87 (m, 1H), 2.50–2.45 (m, 1H), 2.23 (s, 3H), 2.12–2.08 (m, 1H), 1.89–1.81 (m, 2H), 1.15–1.09 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 209.8, 178.5, 177.8, 131.6, 129.1, 128.6, 126.2, 84.9, 75.1, 39.6, 38.0, 26.2, 22.8, 21.9; HRMS calcd for $C_{18}H_{19}NO_4$: 313.1314, found 313.1324.

3.2.33. Synthesis of (1*S*,3a*S*,5a*R*,8a*S*,8b*S*)-6,8-dioxo-7-phenylperhydrofuro[3,4-*e*]isoindol-1-yl-acetate (38). To a dichloromethane solution (5 mL) of **37** (50.0 mg, 0.16 mmol) were added sodium hydrogen carbonate (20.3 mg, 0.239 mmol) and *m*-chloroperbenzoic acid (88.1 mg, 0.477 mmol) at 0°C. The solution was stirred for 8 h and added with aqueous sodium sulfite solution, and washed with aqueous sodium hydrogen carbonate. The solution was extracted with dichloromethane, dried over $MgSO_4$ and eluted through a short silica bed (diethyl ether) to afford lactol **38** (49.4 mg, 0.150 mmol, 94%, R_f=0.55), $[\alpha]_D^{25}$=+14.5 (c 1.0, CH_2Cl_2); IR (cm^{-1}): 1713 (s), 1597 (m); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.46–7.22 (m, 5H), 6.45 (d, J=2.0 Hz, 1H), 4.26 (t, J=8.0 Hz, 1H), 3.66 (dd, J=8.8, 4.4 Hz, 1H), 3.34 (t, J=7.6 Hz, 1H), 3.15–3.13 (m, 1H), 2.88–2.83 (m, 1H), 2.68–2.65 (m, 1H), 2.04 (s, 3H), 1.95–1.93 (m, 2H), 1.81–1.79 (m, 1H), 1.25–1.22 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 178.2, 176.6, 170.3, 129.7, 129.1, 128.6, 100.1, 76.2, 43.5, 38.9, 37.7, 35.5, 23.9, 21.8, 21.1; HRMS calcd for $C_{18}H_{19}NO_5$: 329.1263, found 329.1282.

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18. Crystal structure of compound **34** and spectral data of compounds **33**–**35** have appeared in our previous study which described the synthesis of chiral dienes based on tungsten-mediated [3+2]-cycloaddition reactions. The latter method is a non-metathesis reaction which used stoichiometric amount of propargyltungsten complexes. See Ref. 4.
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