Supporting Information

Highly Enantioselective Catalytic Carbon Dioxide Incorporation Reaction: Nickel-Catalyzed Asymmetric Carboxylative Cyclization of Bis-1,3-dienes

Masanori Takimoto, Yoichi Nakamura, Kaoru Kimura, and Miwako Mori*

Graduate School of Pharmaceutical Sciences, Hokkaido University, Sapporo 060-0812, Japan

General Information. All ^{1}H NMR and ^{13}C NMR were recorded on a JEOL EX-270 (270 MHz for ^{1}H, 67.5 MHz for ^{13}C), or JEOL AL-400 (400 MHz for ^{1}H, 100 MHz for ^{13}C) instrument in $CDCl_3$ with tetramethylsilane as an internal standard otherwise mentioned. Data are reported as follows: chemical shift in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad signal), coupling constant (Hz), integration. Infrared spectra (IR) were obtained on a Perkin Elmer 1605 FTIR spectrometer or a JASCO FT/IR-460Plus spectrometer and absorptions are reported in reciprocal centimeters. Mass spectra were obtained on a JEOL JMS-700TZ (EI), or a JEOL JMS-FABmate (EI). Elemental Analyses were performed at the Center for Instrumental Analysis of Hokkaido University. Melting points were recorded on a Yanagimoto Micro Melting Point Apparatus and those were uncorrected. High performance liquid chromatography (HPLC) analysis was performed on a JASCO model PU-980 HPLC equipped with a JASCO model UV-970 variable wavelength UV detector and JASCO model 807-IT intelligent integrator using a DAICEL Chiralcel OJ, Chiralcel OD, Chiralpac AD, and Chiralpak AS (0.46 cm X 25 cm) as chiral stationary phase columns. Optical rotations were recorded on a JASCO model P-1030 Polarimeter. Silica gel column chromatography was performed with Merck Silica Gel 60 (230-400 mesh ASTM).

Materials or Methods. All reactions were performed under an argon atmosphere using standard Schlenk techniques unless otherwise mentioned. THF (dehydrated, stabilizer-free) was obtained from Kanato Kagaku Co. and used without further purification. Carbon dioxide (CO_2) gas was dried by passing through a column filled with Sicapent® and used without further purification. $Ni(acac)_2$ was dried under high vacuum (<10^{-3} mmHg) at 90 °C overnight and stored under argon atmosphere. All other solvents and reagents were purified when necessary using standard procedures. Bis-1,3-dienes **1a** and **1b** were prepared according to the procedures described in the literature.[1] (*S*)-MeO-MOP was prepared from (*S*)-1,1'-bi-2-naphthol according to the reported procedures.[2]

Preparation of (3*E*,8*E*)-6,6-Bis-benzyloxymethylundeca-1,3,8,10-tetraene (1c). To a cooled (0 °C) suspension of $LiAlH_4$ (537 mg, 14.2 mmol) in Et_2O (20 mL) was added a solution of **1b** (943 mg, 3.54 mmol). The mixture was refluxed for 30 min, then cooled to 0 °C. The cooled mixture was treated by successive dropwise addition of water (0.5 mL), 15% aqueous solution of NaOH (0.5 mL), and water (1.6 mL). The resulting mixture was stirred at 0 °C until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The solvents were evaporated in vacuo and the residue was purified by silica gel column chromatography (hexane/EtOAc = 3/2) to afford diol **I** (652 mg, 88%) as a colorless solid (Scheme S1).

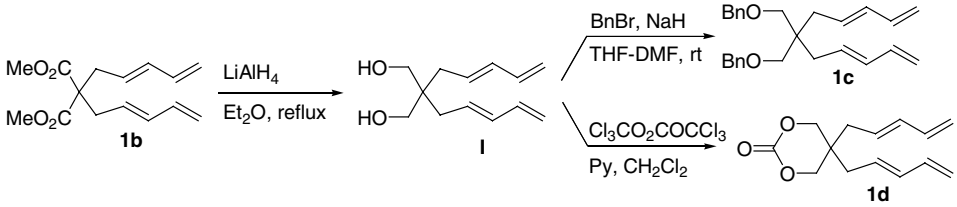
To a solution of **I** (300 mg) in THF-DMF (4/1, 5 mL) was added NaH (60% dispersion in oil, 230 mg, 5.76 mmol) and

benzyl bromide (0.60 mL, 5.0 mmol) at 0 °C. After the mixture was stirred at room temperature for 12 hr, saturated aqueous solution of NH_4Cl was added at 0 °C. The aqueous layer was extracted with Et_2O. The combined organic layers were washed with water and brine, dried over Na_2SO_4, and concentrated in vacuo. The residue was purified by silicagel column chromatography (hexane/EtOAc = 50/1) to afford **1c** (555 mg, 99%) as a colorless oil.

Compound I. IR ($CHCl_3$) 3434, 3088, 2973, 2924, 2881, 1815, 1649, 1601 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 6.32 (ddd, *J* = 16.7, 10.3, 10.0 Hz, 2 H), 6.11 (dd, *J* = 15.0, 10.3 Hz, 2 H), 5.71 (dt, *J* = 15.0, 7.6 Hz, 2 H), 5.13 (d, *J* = 16.7 Hz, 2 H), 5.01 (d, *J* = 10.0 Hz, 2 H), 3.57 (d, *J* = 4.4 Hz, 4 H), 2.44 (brs, 2 H), 2.11 (d, *J* = 7.6 Hz, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 34.97, 43.20, 68.27, 115.64, 129.42, 134.11, 136.53; LR MS (EI, *m/z*) 208 (M^+), 190, 159, 67; Anal. Calcd for $C_{13}H_{20}O_2$: C, 74.96; H, 9.68. Found C, 74.92; H, 9.77.

Substrate 1c. IR (neat) 3081, 3030, 2894, 2857, 1360, 2333, 1652, 1601 cm-1; ^1H NMR (400 MHz, $CDCl_3$) δ 7.21-7.38 (m, 10 H), 6.28 (ddd, *J* = 17.0, 10.5, 10.3 Hz, 2 H), 6.04 (dd, *J* = 15.0, 10.5 Hz, 2 H), 5.64 (dt, *J* = 15.0, 7.6 Hz, 2 H), 5.07 (d, *J* = 17.0 Hz, 2 H), 4.96 (d, *J* = 10.3 Hz, 2 H), 4.46 (s, 4 H), 3.27 (s, 4 H), 2.13 (d, *J* = 7.6 Hz, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 35.57, 43.22, 72.44, 73.19, 114.87, 127.15, 127.21, 128.03, 130.38, 133.71, 136.95, 138.56; LR MS (EI, *m/z*) 297 (M^+-Bn), 279, 91; Anal. Calcd for $C_{27}H_{32}O_2$: C, 83.46; H, 8.30. Found C, 83.65; H, 8.32.

Scheme S1.

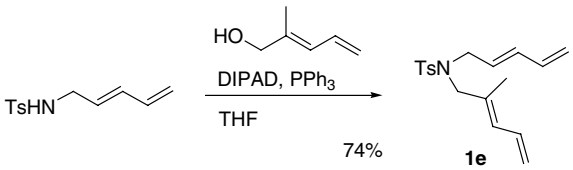


Preparation of 5,5-di[(*1E*)-penta-2,4-dienyl]-1,3-dioxan-2-one (1d). To a solution of **I** (250 mg, 1.20 mmol) and pyridine (0.60 mL, 7.2 mmol) in CH_2Cl_2 (6.0 mL) was added a solution of triphosgene (178 mg, 0.60 mmol) in CH_2Cl_2 (6 mL) at –78 °C. After the mixture was stirred at –78 °C for 15 min, this was allowed to stirred at ambient temperature for 2 hr. To this was added saturated aqueous solution of NH_4Cl at 0 °C. The aqueous layer was extracted with AcOEt. The combined organic layers were washed with 10% HCl, saturated aqueous solution of $NaHCO_3$, and brine, dried over Na_2SO_4. The solvent were evaporated in vacuo and the residue was purified by silicagel column chromatography (hexane/EtOAc = 2/1) to afford **1d** (251 mg, 89%) as a colorless oil: IR (neat) 3085, 2972, 2911, 2855, 1756, 1650, 1601, 1536 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 6.32 (ddd, *J* = 17.0, 10.5, 10.2 Hz, 2 H), 6.17 (dd, *J* = 15.3, 10.5 Hz, 2 H), 5.60 (dt, *J* = 15.3, 7.9 Hz, 2 H), 5.20 (d, *J* = 17.0 Hz, 2 H), 5.10 (d, *J* = 10.2 Hz, 2 H), 2.12 (d, *J* = 7.9 Hz, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 34.33, 35.04, 74.30, 117.35, 125.47, 135.69, 136.08, 147.83; LR MS (EI, *m/z*) 234 (M^+), 205, 180, 67; Anal. Calcd for $C_{14}H_{18}O_3$: C, 71.77; H, 7.74. Found C, 71.77; H, 7.74.

Preparation of 4-Methyl-*N*-[(2*E*)-2-methylpenta-2,4-dienyl]-*N*-[(2*E*)-penta-2,4-dienyl]benzenesulfonamide (1e). To a cooled (0 °C) solution of 4-methyl-*N*-[(2*E*)-2,4-pentadienyl]benzenesulfonamide[3] (350 mg, 1.47 mmol), (2*E*)-2-methyl-2,4-pentadiene-1-ol[4] (145 mg, 1.47 mmol) and PPh_3 (514 mg, 1.96 mmol) in THF (9.8 mL) was added diisopropyl azodicarboxylate (0.36 ml, 1.81 mmol). The mixture was stirred at room temperature for 1 hr, after which concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/EtOAc = 10/1) to afford

bis-diene **1e** (345 mg, 74%) as a colorless oil (Scheme S1): IR (neat) 3084, 3041, 3012, 2972, 2919, 2855, 1654, 1599 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.69 (d, *J* = 8.2 Hz, 2 H), 7.29 (d, *J* = 8.2 Hz, 2 H), 6.53 (ddd, *J* = 16.7, 10.5, 10.5 Hz, 1 H), 6.18 (ddd, *J* = 17.0, 10.2, 10.2 Hz, 1 H), 6.00 (dd, *J* = 15.2, 10.5 Hz, 1 H), 5.97 (d, *J* = 10.2 Hz, 1 H), 5.35 (dt, *J* = 15.2, 6.8 Hz, 1 H), 5.04-5.18 (m, 4 H), 3.77 (d, *J* = 6.8 Hz, 2 H), 3.72 (s, 2 H), 2.42 (s, 3 H), 1.71 (s, 3 H); ^{13}C NMR (100 MHZ, $CDCl_3$) δ 143.18, 137.42, 135.86, 135.03, 132.95, 132.41, 129.61, 129.38, 127.37, 127.26, 117.88, 117.53, 54.66, 48.47, 21.48, 14.55; LR MS (EI, *m/z*) 317 (M^+), 302, 276, 250, 162; Anal. Calcd for $C_{18}H_{23}NO_2S$: C, 68.10; H, 7.30; N, 4.41. Found: C, 68.08; H, 7.48; N, 4.58.

Scheme S1.



General Procedure for Asymmetric Ring-Closing Carboxylation. To a solution of $Ni(acac)_2$ (10 mol %) and a chiral phosphine ligand (10 mol % or 20 mol %) in THF in a Schlenk-type flask was added a solution of bisdiene (1.0 eq) in THF. The mixture was frozen in a liquid nitrogen bath and the flask was evacuated (<0.01 mmHg). A balloon filled with CO_2 was attached to the reaction flask to introduce CO_2, and then the frozen mixture was allowed to stand ambient temperature until it thawed. To the resulting solution was added a solution of diorganozinc reagent in hexane or xylene (4.5 eq) at 0 °C. After the mixture was stirred at indicated temperature for indicated time, the reaction mixture was hydrolyzed with 10 % aqueous solution of HCl at 0 °C, and the aqueous layer was extracted with EtOAc. The combined organic layers were washed with brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was treated with diazomethane in Et_2O at 0 °C according to standard procedures. The obtained crude material was purified by silica gel column chromatography (hexane/EtOAc) to afford analytically pure product.

-Experimental Details for Screening of Chiral Phosphine Ligands (Table 1)-

Entry 1 (BINAP): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.1 mg, 0.020 mmol)/(*R*)-BINAP (12.5 mg, 0.020 mmol) in THF (0.5 mL), bis-diene **1a** (60.4 mg, 0.20 mmol) in THF (3.5 mL), and Me_2Zn (1.0 M in hexane, 0.89 mL, 0.89 mmol) at room temperature for 23 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 7/1) to afford **2a** (37.8 mg, 52%) as colorless oil. The spectral data of this material were identical with those reported previously.[1c] The enantiomeric excess was determined by HPLC analysis with DAICEL Chiralpak AS column (hexane/2-propanol=9/1, 0.5 ml/min, UV detection at 254 nm, minor: 46.7 min, major: 70.1 min, 12% ee).

Entry 2 (BPPFA): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.1 mg, 0.020 mmol)/(*S*)-(*R*)-BPPFA (12.5 mg, 0.020 mmol) in THF (0.5 mL), bis-diene **1a** (60.0 mg, 0.20 mmol) in THF (3.5 mL), and Me_2Zn (1.0 M in hexane, 0.89 mL, 0.89 mmol) at room temperature for 24 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 7/1) to afford **2a** (45.9 mg, 62%) as colorless oil. The enantiomeric excess was determined by the same method described above (minor: 46.7 min, major: 70.1 min, 11% ee).

Entry 3 (DIOP): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.1 mg, 0.020 mmol)/(*R,R*)-DIOP (10.0 mg, 0.020 mmol) in THF (0.5 mL), bis-diene **1a** (58.8 mg, 0.19 mmol) in THF (3.5 mL), and Me_2Zn (1.0 M in hexane, 0.89 mL, 0.89 mmol) at room temperature for 13 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 7/1) to afford **2a** (54.8 mg, 75%) as colorless oil. The enantiomeric excess was determined by the same method described above (major: 46.7 min, minor: 70.1 min, 55% ee).

Entry 4 (NMDPP): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.3 mg, 0.021 mmol)/(*S*)-NMDPP (12.6 mg, 0.039 mmol) in THF (0.5 mL), bis-diene **1a** (59.5 mg, 0.20 mmol) in THF (3.5 mL), and Me_2Zn (1.0 M in hexane, 0.89 mL, 0.89 mmol) at room temperature for 15 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 7/1) to afford **2a** (49.8 mg, 67%) as colorless oil. The enantiomeric excess was determined by the same method described above (minor: 46.7 min, major: 70.1 min, 3% ee).

Entry 5 (PHOX): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.1 mg, 0.020 mmol)/(*S*)-PHOX (13.7 mg, 0.037 mmol) in THF (0.5 mL), bis-diene **1a** (60.1 mg, 0.20 mmol) in THF (3.5 mL), and Me_2Zn (1.0 M in hexane, 0.89 mL, 0.89 mmol) at room temperature for 33 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 7/1) to afford **2a** (43.0 mg, 58%) as colorless oil. The enantiomeric excess was determined by the same method described above (major: 46.7 min, minor: 70.1 min, 15% ee).

Entry 6 (PPFA): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.2 mg, 0.020 mmol)/(*S*)-(*R*)-PPFA (17.1 mg, 0.039 mmol) in THF (0.5 mL), bis-diene **1a** (60.9 mg, 0.20 mmol) in THF (3.5 mL), and Me_2Zn (1.0 M in hexane, 0.89 mL, 0.89 mmol) at room temperature for 15 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 7/1) to afford **2a** (50.2 mg, 66%) as colorless oil. The enantiomeric excess was determined by the same method described above (minor: 46.7 min, major: 70.1 min, 43%ee).

Entry 7 (MeO-MOP at rt): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.1 mg, 0.020 mmol)/(*S*)-MeO-MOP (18.5 mg, 0.039 mmol) in THF (0.5 mL), bis-diene **1a** (60.1 mg, 0.20 mmol) in THF (3.5 mL), and Me_2Zn (1.0 M in hexane, 0.89 mL, 0.89 mmol) at room temperature for 4 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 7/1) to afford **2a** (62.5 mg, 83%) as colorless oil. The enantiomeric excess was determined by the same method described above (minor: 46.7 min, major: 70.1 min, 91% ee).

Entry 8 (MeO-MOP at 0 °C): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.1 mg, 0.020 mmol)/(*S*)-MeO-MOP (18.5 mg, 0.039 mmol) in THF (0.5 mL), bis-diene **1a** (60.7 mg, 0.20 mmol) in THF (3.5 mL), and Me_2Zn (1.0 M in hexane, 0.89 mL, 0.89 mmol) at 0 °C for 24 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 7/1) to afford **2a** (54.1 mg, 71%) as colorless oil. The enantiomeric excess was determined by the same method described above (minor: 46.7 min, major: 70.1 min, 93% ee) .

Methyl (2*S*)-2-{(3*S*,4*R*)-4-[(1*E*)-But-1-enyl]-1-(4-methylbenzenesulfonyl)pyrrolidin-3-yl}but-3-enoate (2a). $[\alpha]_D^{28}$ = +7.5 ° (*c* 1.00, $CHCl_3$, 93%ee, entry 8 in Table 1).

-Experimental Details for Asymmetric Carboxylation Using (*S*)-MeO-MOP (Table 2)-

Entry 1 (1a with Ph_2Zn): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.1 mg, 0.020 mmol)/(*S*)-MeO-MOP (18.4 mg, 0.039 mmol) in THF (0.5 mL), bis-diene **1a** (60.6 mg, 0.20 mmol) in THF (3.5 mL), and Ph_2Zn (0.5 M in xylene, 1.78 mL, 0.89 mmol) at 0 °C for 26 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 12/1~7/1) to afford **3a** (70.2 mg, 81%) as colorless oil. The spectral data of this

material were identical with those reported previously;[1c] HPLC Analysis – DAICEL Chiralpak AS column (hexane/2-propanol=9/1, 0.75 ml/min, UV detection at 254 nm, Minor: 57.4 min, major: 72.5 min, 95% ee).

Methyl (2*S*)-2-{(3*S*,4*R*)-4-[(1*E*)-3-phenylpropenyl]-1-(4-methylbenzenesulfonyl)pyrrolidin-3-yl}-but-3-enoate (3a). $[\alpha]_D^{22}$ = +7.3 ° (*c* 0.97, $CHCl_3$, 95% ee).

Entry 2 (1a with Et_2Zn): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.2 mg, 0.020 mmol)/(*S*)-MeO-MOP (18.6 mg, 0.040 mmol) in THF (0.5 mL), bis-diene **1a** (59.8 mg, 0.20 mmol) in THF (3.5 mL), and Et_2Zn (1.0 M in hexane, 0.89 mL, 0.89 mmol) at 0 °C for 8 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 9/1~7/1) to afford **4a** (44.0 mg, 57%) and **5** (9.8 mg, 13%) as colorless oils. The spectral data of **5** were identical with those reported previously;[1c] HPLC Analysis for **4a** – DAICEL Chiralpak AS column (hexane/2-propanol=9/1, 0.5 ml/min, UV detection at 254 nm, minor: 39.1 min, major: 67.4 min, 94% ee); HPLC Analysis for **5** – DAICEL Chiralcel OJ column (hexane/2-propanol=9/1, 0.5 ml/min, UV detection at 254 nm, minor: 31.3 min, major: 41.9 min, 95% ee).

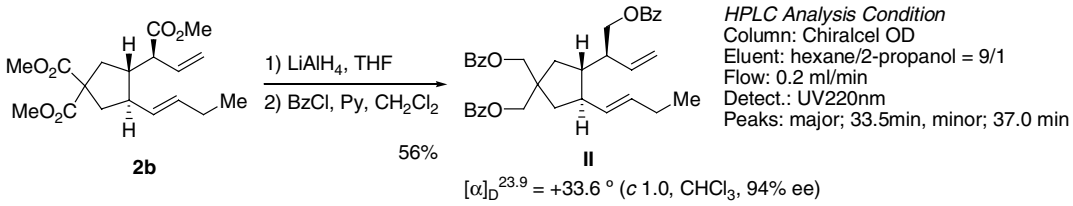
Methyl (2*S*)-2-{(3*S*,4*R*) -1-(4-methylbenzenesulfonyl)-4-[(1*E*)-pent-1-enyl]pyrrolidin-3-yl}but-3-enoate (4a). $[\alpha]_D^{20}$ = + 8.10 ° (*c* 0.99, $CHCl_3$, 94% ee); IR (neat) 2956, 2873, 1732, 1638, 1597, 1347, 1162 cm^{-1}; ^1H NMR δ (400 MHz, $CDCl_3$) δ 7.70 (d, *J* = 8.4 Hz, 2 H), 7.33 (d, *J* = 8.4 Hz, 2 H), 5.71 (ddd, *J* = 17.2, 9.0, 8.0 Hz, 1 H), 5.36 (dt, *J* = 15.2, 6.9 Hz, 1 H), 5.14 (d, *J* = 9.0 Hz, 1 H), 5.09 (d, *J* = 17.2 Hz, 1 H), 5.03 (dd, *J* = 15.2, 10.0 Hz, 1 H), 3.64 (s, 3 H), 3.42 (dd, *J* = 8.8, 6.8 Hz, 1 H), 3.38 (dd, *J* = 8.8, 6.8 Hz, 1 H), 3.10 (dd, *J* = 10.0, 6.8 Hz, 1 H), 2.97 (dd, *J* = 8.0, 8.0 Hz, 1 H), 2.87 (dd, *J* = 10.0, 8.0 Hz, 1 H), 2.45 (s, 3 H), 2.43-2.51 (m, 1 H), 2.20 (dddd, *J* = 8.0, 8.0, 8.0, 8.0 Hz, 1 H), 1.88 (td, *J* = 6.9, 6.9 Hz, 2 H), 1.26-1.85 (m, 2 H), 0.84 (t, *J* = 7.2 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.4, 143.4, 133.5, 133.4, 133.1, 129.5, 128.5, 127.5, 119.0, 53.0, 52.0, 51.8, 50.7, 45.7, 44.6, 34.5, 22.3, 21.6, 13.6; LR MS (EI, *m/z*) 391 (M^+), 360, 236; Anal. Calcd for $C_{21}H_{29}NO_4S$: C, 64.42; H, 7.47; N, 3.58. Found: C, 64.52; H, 7.50; N, 3.33.

Methyl (2*S*)-2-[(3*S*,4*R*)-4-(prop-2-ennyl)-1-(4-methylbenzenesulfonyl)pyrrolidin-3-yl]but-3-enoate (5). $[\alpha]_D^{26}$ = -30.9 ° (*c* 0.98, $CHCl_3$, 95% ee).

Entry 3 (1b with Me_2Zn): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (4.8 mg, 0.019 mmol)/(*S*)-MeO-MOP (17.7 mg, 0.038 mmol) in THF (0.5 mL), bis-diene **1b** (50.0 mg, 0.19 mmol) in THF (2.0 mL), and Me_2Zn (1.0 M in hexane, 0.85 mL, 0.85 mmol) at room temperature for 32 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 8/1) to afford **2b** (66.9 mg, 100%, 94% ee) as a colorless oil. The spectral data of this material were identical with those reported previously.[1c] This material was transformed into tribenzoate **II** according to the procedure described below (Scheme S3), and the enantiomeric excess of **II** was determined by HPLC analysis with DAICEL Chiralcel OD column (hexane/2-propanol=9/1, 0.2 ml/min, UV detection at 220 nm, major: 33.5 min, minor: 37.0 min, 94% ee).

Dimethyl (3*R*,4*S*)-3-[(1*E*)-But-1-enyl]-4-[(1*S*)-1-methoxycarbonylprop-2-enyl]cyclopentane-1,1-dicarboxylate (2b). $[\alpha]_D^{26}$ = +3.90 ° (*c* 1.21, $CHCl_3$, 94% ee).

Scheme S3.



$[\alpha]_D^{23.9}$ = +33.6 ° (*c* 1.0, $CHCl_3$, 94% ee)

(2*S*)-2-{(1*S*,2*R*)-4,4-bis-acetoxymethyl-2-[(1*E*)-but-1-enyl]cyclopentyl}but-3-enyl benzoate (II). To a cooled solution (0 °C) of **2b** (9.5 mg, 0.028 mmol) in THF (3 mL) was added $LiAlH_4$ (10.7 mg, 0.28 mmol). After the mixture was refluxed for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added at 0 °C. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The solvents were evaporated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in CH_2Cl_2 (2 mL) was added pyridine (0.2 ml), and benzoyl chloride (0.04 mL, 0.34 mmol) at 0 °C. After the resulting mixture was stirred at room temperature for 1 hr, saturated aqueous solution of $NaHCO_3$ was added at 0 °C. The aqueous layer was extracted with Et_2O. The combined organic layers were washed with brine, dried over Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/ether=4/1) to afford compound **II** (8.6 mg, 56% from **2b**): $[\alpha]_D^{23.9}$ + 33.6 ° (*c* 1.0, $CHCl_3$, 94% ee); IR (neat) 3068, 2965, 2926, 2854, 1720, 1601, 1584 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.98-8.06 (m, 6 H), 7.51-7.59 (m, 3 H), 7.37-7.46 (m, 6 H), 5.80 (ddd, *J* = 16.7, 10.3, 8.8 Hz, 1 H), 5.52 (ddd, *J* = 15.2, 6.2 Hz, 1 H), 5.27 (dd, *J* = 15.2, 8.5 Hz, 1 H), 5.15 (d, *J* = 10.3 Hz, 1 H), 5.14 (d, *J* = 16.7 Hz, 1 H), 4.30-4.37 (m, 6 H), 2.62-2.70 (m, 1 H), 2.50-2.61 (m, 1 H), 1.93-2.13 (m, 5 H), 1.60 (dd, *J* = 13.5, 11.7 Hz, 1 H), 1.49 (dd, *J* = 13.5, 10.8 Hz, 1 H), 0.95 (t, *J* = 7.3 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.85, 25.71, 36.45, 40.49, 43.90, 45.20, 45.58, 46.18, 66.02, 68.45, 68.59, 117.65, 128.11, 128.19, 129.26, 129.34, 129.74, 130.07, 131.42, 132.61, 132.81, 133.14, 136.77, 166.02, 166.13, 166.15; LR MS (EI, *m/z*) 566 (M^+), 444, 402, 105; Anal. Calcd for $C_{36}H_{38}O_6$: C, 76.30; H, 6.76. Found C, 76.35; H, 6.69.

Entry 4 (1b with Ph_2Zn): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (4.8 mg, 0.019 mmol)/(*S*)-MeO-MOP (17.7 mg, 0.038 mmol) in THF (0.5 mL), bis-diene **1b** (50.0 mg, 0.19 mmol) in THF (2 mL), and Ph_2Zn (0.5 M in xylene, 1.70 mL, 0.85 mmol) at room temperature for 28 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 8/1~6/1) to afford **3b** (67.7 mg, 89%) as a colorless oil. The spectral data of this material were identical with those reported previously.[1c] The enantiomeric excess was determined by HPLC analysis with DAICEL Chiralcel OD column (hexane/2-propanol=9/1, 0.2 ml/min, UV detection at 220 nm, minor: 13.3 min, major: 15.7 min, 92% ee).

(3*S*,4*R*)-3-[(1*S*)-1-Methoxycarbonylprop-2-enyl]-4-[(1*E*)-3-phenylpropenyl]cyclopentane-1,1-dicarboxylate (3b). $[\alpha]_D^{27.1}$ = +11.43 ° (*c* 1.49, $CHCl_3$, 93% ee)

Entry 5 (1c with Me_2Zn): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (4.0 mg, 0.015 mmol)/(*S*)-MeO-MOP (14.5 mg, 0.031 mmol) in THF (0.5 mL), bis-diene **1c** (60.0 mg, 0.15 mmol) in THF (2.5 mL), and Me_2Zn (1.0 M in hexane, 0.70 mL, 0.70 mmol) at room temperature for 36 hr. The crude material was by purified by

silica gel column chromatography (hexane/Et_2O = 10/1) to afford **2c** (68.2 mg, 95%) as a colorless oil. The enantiomeric excess was determined by HPLC analysis with DAICEL Chiralcel OD column (hexane/2-propanol=95/5, 0.1 ml/min, UV detection at 220 nm, minor: 43.1 min, major: 46.6 min, 95% ee).

Methyl (1*S*)-2-{(1*S*,2*R*)-4,4-bis[(benzyloxy)methyl]-2-[(*E*)-but-1-enyl]cyclopentyl}but-3-enoate (2c). $[\alpha]_D^{21.7}$ = +24.00 ° (*c* 1.45, $CHCl_3$, 95% ee); IR (neat) 3064, 3032, 2962, 2930, 2854, 1735, 1640, 1609, 1589 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.20-7.35 (m, 10 H), 5.87 (ddd, *J* = 17.3, 10.2, 10.2 Hz, 1 H), 5.40 (dt, *J* = 15.2, 6.2 Hz, 1 H), 5.17 (dd, *J* = 15.2, 8.2 Hz, 1 H), 5.08 (d, *J* = 10.2 Hz, 1 H), 5.03 (d, *J* = 17.3 Hz, 1 H), 4.49 (s, 2 H), 4.48 (s, 2 H), 3.60 (s, 3 H), 3.27-3.37 (m, 4 H), 3.04 (dd, *J* = 9.1, 5.9 Hz, 1 H), 2.20-2.32 (m, 1 H), 1.92-2.10 (m, 3 H), 1.72-1.84 (m, 2 H), 1.24-1.44 (m, 2 H), 0.94 (t, *J* = 7.3 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.98, 25.73, 36.15, 40.20, 45.34, 45.91, 47.36, 51.48, 52.67, 73.08, 73.14, 74.71, 74.97, 117.11, 127.06, 127.11, 127.99, 131.47, 132.45, 134.97, 138.58, 173.12; LR MS (EI, *m/z*) 462 (M^+), 431, 371, 363, 255, 91; Anal. Calcd for $C_{30}H_{38}O_4$: C, 77.89; H, 8.28. Found C, 77.61; H, 8.49.

Entry 6 (1c with Ph_2Zn): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (3.3 mg, 0.013 mmol)/(*S*)-MeO-MOP (12.1 mg, 0.026 mmol) in THF (0.5 mL), bis-diene **1c** (50.0 mg, 0.13 mmol) in THF (1.2 mL), and Ph_2Zn (1.0 M in THF, 0.58 mL, 0.58 mmol) at 4 °C for 93 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 8/1~6/1) to afford **3c** (54.4 mg, 80%) as a colorless oil. The enantiomeric excess was determined by HPLC analysis with DAICEL Chiralcel OD column (hexane/2-propanol=9/1, 0.2 ml/min, UV detection at 220 nm, minor: 27.2 min, major: 31.5 min, 90% ee).

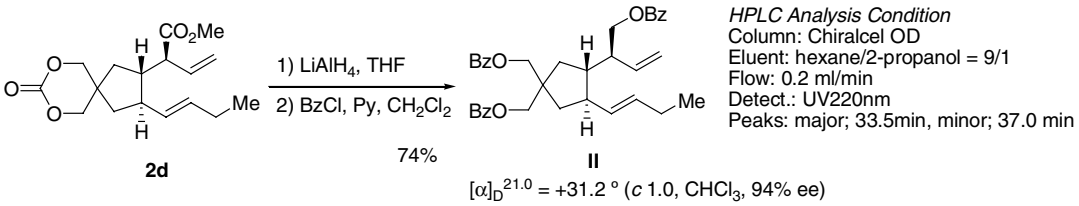
Methyl (*S*)-2-{(1*S*,2*R*)-4,4-bis[(benzyloxy)methyl]-2-[(*E*)-3-phenylprop-1-enyl]cyclopentyl}but-3-enoate (3c). $[\alpha]_D^{23.9}$ = +28.0 ° (*c* 1.39, $CHCl_3$, 90% ee); IR (neat) 3068, 3027, 2930, 2854, 1734, 1635, 1604 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.18-7.33 (m, 15 H), 5.85 (ddd, *J* = 17.0, 9.4, 8.8 Hz, 1 H), 5.52 (dt, *J* = 15.3, 6.8 Hz, 1 H), 529 (dd, *J* = 15.3, 8.5 Hz, 1 H), 5.03 (d, *J* = 8.8 Hz, 1 H), 5.02 (d, *J* = 17.0 Hz, 1 H), 4.48 (s, 4 H), 3.58 (s, 3 H), 3.33 (s, 2 H), 3.31 (d, *J* = 6.8 Hz, 2 H), 3.30 (s, 2 H), 3.05 (dd, *J* = 9.1, 6.5 Hz, 1 H), 2.26-2.37 (m, 1 H), 2.01-2.12 (m, 1 H), 1.72-1.85 (m, 2 H), 1.23-1.42 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 36.26, 39.11, 40.18, 45.47, 46.03, 47.39, 51.54, 53.00, 73.15, 73.17, 74.69, 74.91, 117.12, 125.65, 127.11, 127.13, 127.17, 128.02, 128.06, 128.23, 129.18, 134.29, 135.06, 138.55, 140.48, 173.09; LR MS (EI, *m/z*) 524 (M^+), 493, 425, 317, 91; Anal. Calcd for $C_{35}H_{40}O_4$: C, 80.12; H, 7.68. Found C, 80.30; H, 7.67.

Entry 7 (1d with Me_2Zn): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (5.5 mg, 0.021 mmol)/(*S*)-MeO-MOP (20.0 mg, 0.043 mmol) in THF (1 mL), bis-diene **1d** (50.0 mg, 0.21 mmol) in THF (3 mL), and Me_2Zn (1.0 M in hexane, 0.96 mL, 0.96 mmol) at room temperature for 17 hr. The crude material was by purified by silica gel column chromatography (hexane/EtOAc = 3/2) to afford **2d** (59.3 mg, 90%) as a colorless oil. This material was transformed into tribenzoate **II** according to the procedure described below (Scheme S4), and the enantiomeric excess of **II** was determined by HPLC analysis with DAICEL Chiralcel OD column (hexane/2-propanol=9/1, 0.2 ml/min, UV detection at 220 nm, major: 33.5 min, minor: 37.0 min, 94% ee).

Methyl (*S*)-2-{(2*S*,3*R*)-3-[(*E*)-propenyl]-7,9-dioxaspiro[4,5]decan-8-on-2-yl}but-3-enoate (2d). $[\alpha]_D^{23.7}$ = +22.62 ° (*c* 1.16, $CHCl_3$, 94% ee); IR (neat) 3080, 2959, 2880, 1756, 1733, 1637 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.85 (ddd, *J* = 17.0, 11.4, 10.0 Hz, 1 H), 5.49 (dt, *J* = 15.2, 6.2 Hz, 1 H), 5.19 (dd, *J* = 15.2, 8.4 Hz, 1 H), 5.17 (d, *J* = 11.4 Hz, 1 H), 5.11 (d, *J* = 17.0 Hz, 1 H), 4.10-4.21 (m, 4 H), 3.67 (s, 3 H), 3.12 (dd, *J* = 9.1, 5.6 Hz, 1 H), 2.33-2.44 (m, 1 H), 2.09-2.20 (m, 1

H), 1.95-206 (m, 2 H), 1.90 (dd, *J* = 13.5, 7.3 Hz, 1 H), 1.84 (dd, *J* = 13.5, 8.2 Hz, 1 H), 1.60 (dd, *J* = 13.5, 10.6 Hz, 1 H), 1.42 (dd, *J* = 13.5, 10.6 Hz, 1H), 0.96 (t, *J* = 7.6 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.78, 25.64, 34.96, 37.52, 39.27, 45.39, 46.92, 51.51, 51.78, 76.36, 76.59, 118.17, 129.34, 133.87, 134.14, 147.84, 172.48; LR MS (EI, *m/z*) 308 (M^+), 277, 249, 209, 147, 100; Anal. Calcd for $C_{17}H_{24}O_5$: C, 66.21; H, 7.84. Found C, 66.09; H, 7.89.

Scheme S4.



$[\alpha]_D^{21.0}$ = +31.2 ° (*c* 1.0, $CHCl_3$, 94% ee)

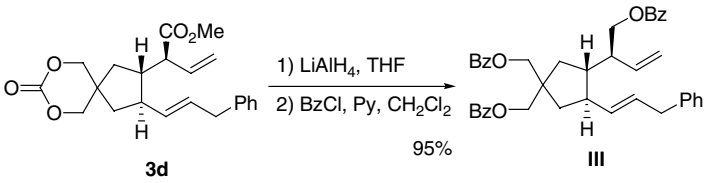
Conversion to Compound II. To a solution of **2d** (10.0 mg, 0.032 mmol) in Et_2O (1.5 mL) was added $LiAlH_4$ (12.0 mg, 0.32 mmol) at 0 °C. After the mixture was refluxed for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added at 0 °C. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The solvents were evaporated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in CH_2Cl_2 (1.5 mL) was added pyridine (0.039 ml, 0.48 mmol), and benzoyl chloride (0.031 mL, 0.32 mmol) at 0 °C. After the resulting mixture was stirred at room temperature for 1 hr, a few drops of 3-[(dimethylamino)propyl]amine was added at 0 °C. After 5 min of standing at ambient temperature, the solvent was evaporated in vacuo. The residue was purified by silica gel column chromatography (hexane/ether=4/1) to afford compound **II** (13.7 mg, 74% from **2d**). The spectral data of this material were identical with those of the material that is independently derived from **2b** (see, Page S5): $[\alpha]_D^{23.9}$ + 33.6 ° (*c* 1.0, $CHCl_3$).

Entry 8 (1d with Ph_2Zn): According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (6.6 mg, 0.025 mmol)/(*S*)-MeO-MOP (24.0 mg, 0.051 mmol) in THF (1 mL), bis-diene **1d** (60.0 mg, 0.26 mmol) in THF (4.1 mL), and Ph_2Zn (0.5 M in xylene, 2.3 mL, 1.15 mmol) at 0 °C for 17 hr. The crude material was by purified by silica gel column chromatography (hexane/EtOAc = 4/3) to afford **3d** (78.8 mg, 83%) as a colorless oil. This material was transformed into tribenzoate **III** according to the procedure described below (Scheme S5), and the enantiomeric excess of **III** was determined by HPLC analysis with DAICEL Chiralcel OD column (hexane/2-propanol=9/1, 0.2 ml/min, UV detection at 220 nm, major: 51.9 min, minor: 63.8 min, 95% ee).

Methyl (*S*)-2-{(2*S*,3*R*)-3-[(*E*)-3-phenylpropenyl]-7,9-dioxaspiro[4,5]decan-8-on-2-yl}but-3-enoate (3d). $[\alpha]_D^{23.8}$ = +17.2 ° (*c* 1.13, $CHCl_3$, 95% ee); IR (neat) 3084, 3054, 3025, 2949, 1755, 1735, 1637, 1602, 1541 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25-7.36 (m, 2 H), 7.12-7.23 (m, 3 H), 5.83 (ddd, *J* = 17.0, 10.0, 10.0 Hz, 1 H), 5.62 (dt, *J* = 15.2, 6.8 Hz, 1 H), 5.29 (dd, *J* = 15.2, 8.2 Hz, 1 H), 5.12 (d, *J* = 10.0 Hz, 1 H), 5.09 (d, *J* = 17.0 Hz, 1 H), 4.08-4.19 (m, 4 H), 3.63 (s, 3 H), 3.33 (d, *J* = 6.8 Hz, 2 H), 3.12 (dd, *J* = 8.8, 5.8 Hz, 1 H), 2.38-2.50 (m, 1 H), 2.09-2.20 (m, 1 H), 1.91 (dd, *J* =13.7, 7.6 Hz, 1 H), 1.84 (dd, *J* = 13.7, 8.2 Hz, 1 H), 1.60 (dd, *J* = 13.7, 10.8 Hz, 1 H), 1.43 (dd, *J* = 13.7, 11.1 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 34.98, 37.56, 38.90, 39.25, 45.44, 46.91, 51.76, 51.80, 118.13, 125.83, 128.15, 130.98, 131.94, 133.92, 139.79, 147.77, 172.39; LR MS (EI, *m/z*) 370 (M^+), 339, 271, 209, 117, 100, 91; Anal. Calcd for $C_{22}H_{26}O_5$: C, 71.33; H, 7.07. Found C, 70.98; H, 7.07.

Scheme S5.



HPLC Analysis Condition
Column: Chiralcel OD
Eluent: hexane/2-propanol = 9/1
Flow: 0.2 ml/min
Detect.: UV220nm
Peaks: major; 57.9min, minor; 63.8 min

Conversion to Compound III. To a solution of **3d** (14.2 mg, 0.038 mmol) in Et_2O (1.5 mL) was added $LiAlH_4$ (14.5 mg, 0.38 mmol) at 0 °C. After the mixture was refluxed for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added at 0 °C. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The solvents were evaporated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in CH_2Cl_2 (1.5 mL) was added pyridine (0.046 ml, 0.57 mmol), and benzoyl chloride (0.044 mL, 0.38 mmol) at 0 °C. After the resulting mixture was stirred at room temperature for 1 hr, a few drops of 3-[(dimethylamino)propyl]amine was added at 0 °C. After 5 min of standing at ambient temperature, the solvent was evaporated in vacuo. The residue was purified by silica gel column chromatography (hexane/ether=4/1) to afford compound **III** (22.9 mg, 95% from **3d**): $[\alpha]_D^{20.0}$ = +31.48 ° (*c* 1.44, $CHCl_3$, 95% ee); IR (neat) 3063, 3029, 2926, 2893, 2862, 1719, 1601, 1584 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.97-8.04 (m, 6 H), 7.50-7.58 (m, 3 H), 7.38-7.47 (m, 6 H), 7.22-7.28 (m, 2 H), 7.14-7.19 (m, 3 H), 5.77 (ddd, *J* = 17.0, 11.0, 9.4 Hz, 1 H), 5.64 (dt, *J* = 15.2, 6.7 hz, 1 H), 5.38 (dd, *J* = 15.2, 8.5 Hz, 1 H), 5.12 (d, *J* = 11.0 Hz, 1 H), 5.11 (d, *J* = 17.0 hz, 1 H), 4.2904.39 (m, 6 H), 3.32 (d, *J* = 6.7 Hz, 2 H), 2.55-2.70 (m, 2 H), 2.05-2.15 (m, 1 H), 1.94-.04 (m, 2 H), 1.49-1.66 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 36.53, 39.09, 40.39, 43.99, 45.29, 45.79, 46.18, 65.87, 68.40, 68.55, 117.65, 125.74, 128.13, 128.15, 128.20, 128.30, 129.29, 129.35, 129.72, 130.05, 130.08, 132.63, 132.83, 133.91, 136.79, 140.05, 166.01, 166.12, 166.13; LR MS (EI, *m/z*) 628 (M^+), 507, 105; Anal. Calcd for $C_{41}H_{40}O_6$: C, 78.32; H, 6.41. Found C, 78.45; H, 6.38.

-Experimental Details for Asymmetric Carboxylation of 1e Using (*S*)-MeO-MOP (Scheme 2)-

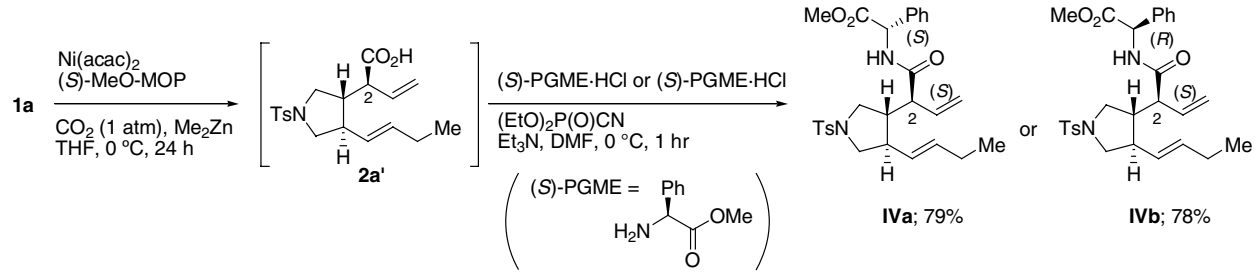
Methyl (2*S*)-2-{(3*R*,4*R*)-4-[(1*E*)-but-1-enyl]-4-methyl-1-(4-methylbenzenesulfonyl)pyrrolidin-3-yl}but-3-enoate (2e). According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (4.0 mg, 0.015 mmol)/(*S*)-MeO-MOP (14.8 mg, 0.031 mmol) in THF (0.4 mL), bis-diene **1e** (50.0 mg, 0.16 mmol) in THF (2 mL), and Me_2Zn (1.0 M in hexane, 0.71 mL, 0.71 mmol) at 4 °C for 62 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 6/1) to afford **2e** (54.4 mg, 88%) as a colorless oil. The enantiomeric excess was determined by HPLC analysis with DAICEL Chiralcel OD column (hexane/2-propanol=9/1, 0.2 ml/min, UV detection at 220 nm, major: 38.5 min, minor: 42.8 min, 92% ee). $[\alpha]_D^{28.2}$ = - 4.57 ° (*c* 1.03, $CHCl_3$, 96% ee); IR (neat) 2960, 2875, 1735, 1636, 1597 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.69 (d, *J* = 8.2 Hz, 2 H), 7.33 (d, *J* = 8.2 Hz, 2 H), 5.58 (ddd, *J* = 17.0, 10.0, 9.4 Hz, 1 H), 5.35 (dt, *J* = 15.8, 6.4 Hz, 1 H), 5.18 (d, *J* = 15.8 Hz, 1 H), 5.08 (d, *J* = 17.0 Hz, 1 H), 5.01 (d, *J* = 10.0 Hz, 1 H), 3.65 (s, 3 H), 3.43 (dd, *J* = 10.0, 8.5 Hz, 1 H), 2.95-3.14 (m, 4 H), 2.44 (s, 3 H), 2.22-2.31 (m, 1 H), 1.95 (qd, *J* = 7.6, 6.4 Hz, 2 H), 0.91 (t, *J* = 7.6 Hz, 3 H), 0.91 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.43, 143.28, 134.27, 133.68, 133.33, 132.01, 129.54, 127.24, 117.94, 60.77, 52.08, 50.74, 50.24, 47.90, 44.93, 25.68, 21.52, 17.27, 13.48; LR MS (EI, *m/z*) 391 (M^+), 376, 360, 332, 292, 236; Anal. Calcd for $C_{21}H_{29}NO_4S$: C, 64.42; H, 7.47; N, 3.58. Found: C, 64.14; H, 7.34; N, 3.40.

Methyl (2*S*)-2-{(3*R*,4*R*)-4-methyl-1-4-[(1*E*)-3-phenylprop-1-enyl]- (4-methylbenzenesulfonyl)pyrrolidin-3-yl}but-3-enoate (3e). According to the general procedure, the reaction was carried out by using $Ni(acac)_2$ (4.8 mg, 0.019 mmol)/(*S*)-MeO-MOP (17.7 mg, 0.038 mmol) in THF (0.2 mL), bis-diene **1e** (60.0 mg, 0.19 mmol) in THF (1.5 mL), and Ph_2Zn (0.5 M in xylene, 1.70 mL, 0.85 mmol) at 4 °C for 90 hr. The crude material was by purified by silica gel column chromatography (hexane/ethyl acetate, 5/1) to afford **3e** (75.0 mg, 87%) as a colorless oil. The enantiomeric excess was determined by HPLC analysis with DAICEL Chiralpak AD column (hexane/2-propanol=9/1, 0.5 ml/min, UV detection at 220 nm, major: 38.5 min, minor: 42.8 min, 91% ee). $[\alpha]_D^{24.0}$ = - 5.22 ° (*c* 1.15, $CHCl_3$, 91% ee); IR (neat) 3026, 2950, 2872, 1732, 1636, 1598 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.69 (d, *J* = 8.2 Hz, 2 H), 7.32 (d, *J* = 8.2 Hz, 2 H), 7.26 (dd, *J* = 7.0, 7.0 Hz, 2 H), 7.18 (t, *J* = 7.0 Hz, 1 H), 7.09 (d, *J* = 7.0 Hz, 2 H), 5.53 (ddd, *J* = 17.0, 10.0, 9.4 Hz, 1 H), 5.47 (dt, *J* = 15.6, 6.7 Hz, 1 H), 5.28 (d, *J* = 15.6 Hz, 1 H), 5.03 (d, *J* = 17.0 Hz, 1 H), 4.88 (d, *J* = 10.0 Hz, 1 H), 3.64 (s, 3 H), 3.44 (dd, *J* = 10.0, 8.8 Hz, 1 H), 3.28 (d, *J* = 6.7 Hz, 2 H), 3.12 (d, *J* = 9.6 Hz, 1 H), 3.05 (d, *J* = 9.6 Hz, 1 H), 3.04 (dd, *J* = 10.0, 10.2 Hz, 1 H), 2.96 (dd, *J* = 10.0, 9.4 Hz, 1 H), 2.43 (s, 3 H), 2.25-2.34 (m, 1 H), 0.91 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.13, 143.16, 139.59, 135.48, 133.98, 133.52, 129.44, 129.03, 128.19, 128.10, 127.11, 125.83, 117.99, 60.73, 52.18, 50.84, 50.32, 48.01, 45.15, 39.14, 21.67, 17.25; LR MS (EI, *m/z*) 453 (M^+), 422, 394, 354, 298; Anal. Calcd for $C_{26}H_{31}NO_4S$: C, 68.85; H, 6.89; N, 3.09. Found: C, 68.83; H, 6.92; N, 3.11.

-Determination of Relative and Absolute Configuration of Asymmetric Ring-Closing Carboxylation Products-

Absolute Configuration of 2a. Carboxylic acid **2a'**, which was obtained by methylative carboxylation of **1a** according to the general procedure by using (*S*)-MeOMOP, was condensed with (*S*)-phenylglycine methyl ester [(*S*)-PGME] or (*R*)-phenylglycine methyl ester [(*R*)-PGME] to afford amide **IVa** or **IVb** (Scheme S6). Absolute configurations of C2-position of these diastereomers were established according to the Kusumi's method using an anisotropic effect of the chiral auxiliary on ^1H NMR chemical shift.[5] The ^1H NMR spectrum of **IVa** and **IVb** were compared in detail and the differences of the chemical shifts were calculated. The calculated Δδ values ($\Delta\delta = \delta_{IVa} - \delta_{IVb}$, see Figure S1) for compound **IVa** indicated that the configuration of C2 in compound **IVa** was (*S*). These results indicated that the absolute configuration of **2a** obtained from the reaction using (*S*)-MeO-MOP was as shown in our manuscript.

Scheme S6.



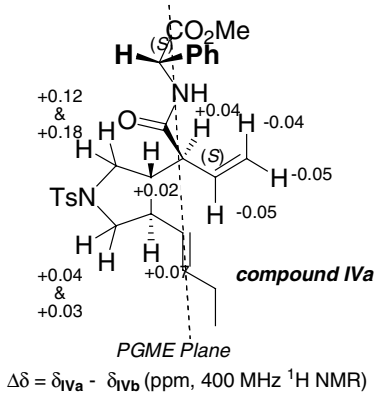


Figure S1. Δδ values for **IVa**

Preparation of Compound IVa and IVb. According to the typical procedure, methylative carboxylation of **1a** (50 mg, 0.164 mmol) was carried out in THF (2.5 mL) at 0 °C for 24 hr by using $Ni(acac)_2$ (4.2 mg, 0.016 mmol), (*S*)-MeO-MOP (15.4 mg, 0.032 mmol), and Me_2Zn (1.0 M in hexane, 0.74 mL, 0.74 mmol). After the usual workup procedure (without diazomethane treatment), the obtained material was passed through a short column of silica gel (eluent; $CHCl_3$/MeOH=30/1) to afford crude carboxylic acid **2a'** (60.5 mg, major impurities were triphenylphosphine oxide). This material was used for the next reaction without further purification.

To a cooled solution (0 °C) of the crude **2a'** (30.0 mg) in DMF (0.5 ml), was added (*S*)-phenylglycine methyl ester hydrochloride (33 mg, 0.165 mmol), diethyl cyanophosphonate (0.037 mL, 0.247 mmol), and Et_3N (0.070 mL, 0.495 mmol). The mixture was stirred at 0 °C for 1hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=3/1) to afford compound **IVa** (33.7 mg, 79% from **1a**, colorless crystal). The compound **IVb** was prepare as follows.

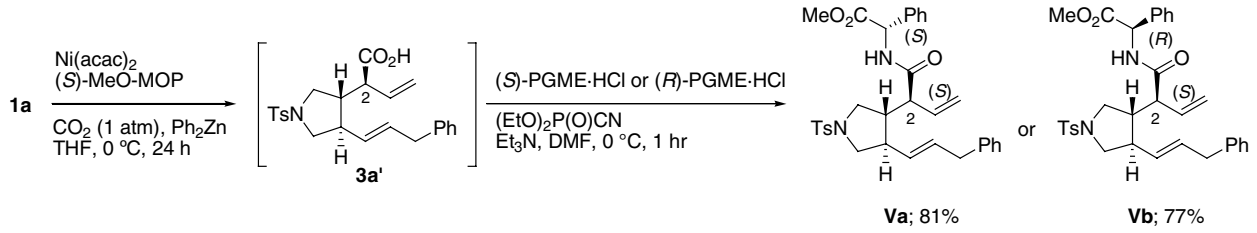
To a cooled solution (0 °C) of the crude **2a'** (30.5 mg) in DMF (0.5 ml), was added (*R*)-phenylglycine methyl ester hydrochloride (33 mg, 0.165 mmol), diethyl cyanophosphonate (0.037 mL, 0.247 mmol), and Et_3N (0.070 mL, 0.495 mmol). The mixture was stirred at 0 °C for 1hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=3/1) to afford compound **IVb** (33.2 mg, 78% from **1a**, colorless crystal).

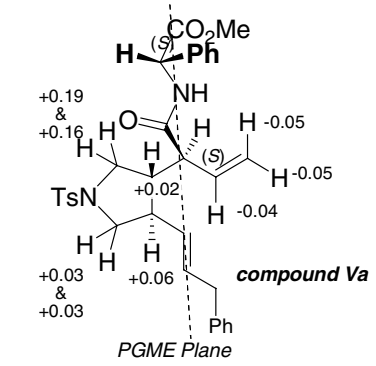
Compound IVa. $[\alpha]_D^{24}$ = +57.1 ° (*c* 1.01, $CHCl_3$); IR (nujol) 3333, 1741, 1649, 1634, 1456, 1376, 1159 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.71 (d, *J* = 8.0 Hz, 2 H), 7.29-7.39 (m, 7 H), 6.48 (d, *J* = 7.2 Hz, 1 H), 5.71 (ddd, *J* = 17.2, 9.7, 8.8 Hz, 1 H), 5.44 (d, *J* = 7.2 Hz, 1 H), 5.41 (dt, *J* = 15.6, 6.4 Hz, 1 H), 5.17 (d, *J* = 9.7 Hz, 1 H), 5.13 (d, *J* = 17.2 Hz, 1 H), 5.01 (dd, *J* = 15.6, 7.6 Hz, 1 H), 3.74 (s, 3 H), 3.44 (dd, *J* = 10.0, 7.6 Hz, 1 H), 3.35 (dd, *J* = 10.4, 7.4 Hz, 1 H), 3.27 (dd, *J* = 10.4, 7.4 Hz, 1 H), 2.84 (dd, *J* = 10.0, 7.6 Hz, 1 H), 2.79 (dd, *J* = 8.8, 7.4 Hz, 1 H), 2.57 (dddd, *J* = 7.6, 7.6, 7.6, 7.6 Hz, 1 H), 2.43 (s, 3 H), 2.26 (dddd, *J* = 7.6, 7.4, 7.4, 7.4 Hz, 1 H), 1.87 (qd, *J* = 7.2, 6.4 Hz, 2 H), 0.86 (t, *J* = 7.2 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.8, 170.7, 143.3, 135.9, 134.8, 134.6, 133.3, 129.5, 128.9, 128.6, 127.9, 127.6, 127.1, 119.4, 56.6, 53.6, 52.9, 52.8, 50.9, 45.3, 44.3, 25.4, 21.6, 13.5; LR MS (EI, *m/z*) 511 (M^++1), 479, 451, 355; Anal. Calcd for $C_{28}H_{34}N_2O_5S$: C, 65.86; H, 6.71; N, 5.49. Found: C, 65.89; H, 6.77; N, 5.37.

Compound IVb. $[\alpha]_D^{24}$ = -69.2 ° (*c* 0.97, $CHCl_3$); IR (nujol) 3332, 1742, 1642, 1634, 1457, 1376, 1154 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.64 (d, *J* = 8.4 Hz, 2 H), 7.26-7.41 (m, 7 H), 6.54 (d, *J* = 6.8 Hz, 1 H), 5.76 (ddd, *J* = 17.6, 10.4, 8.8 Hz, 1 H), 5.48 (d, *J* = 6.8 Hz, 1 H), 5.28 (dt, *J* = 15.2, 7.6 Hz, 1 H), 5.22 (d, *J* = 10.4 Hz, 1 H), 5.17 (d, *J* = 17.6 Hz, 1 H), 4.99 (dd, *J* = 15.2, 7.5 Hz, 1 H), 3.71 (s, 3 H), 3.40 (dd, *J* = 10.0, 7.5 Hz, 1 H), 3.23 (dd, *J* = 10.2, 7.4 Hz, 1 H), 3.09 (dd, *J* = 10.4, 7.4 Hz, 1 H), 2.81 (dd, *J* = 9.6, 7.5 Hz, 1 H), 2.75 (dd, *J* = 8.8, 7.4 Hz, 1 H), 2.50 (dddd, *J* = 7.5, 7.5, 7.5, 7.5 Hz, 1 H), 2.42 (s, 3 H), 2.24 (dddd, *J* = 7.5, 7.4, 7.4, 7.4 Hz, 1 H), 1.87 (qd, *J* = 7.6, 7.6 Hz, 2 H), 0.85 (t, *J* = 7.6 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.9, 170.6, 143.4, 136.2, 134.7, 134.3, 133.1, 129.5, 129.0, 128.6, 127.9, 127.6, 127.1, 119.6, 56.4, 53.6, 52.9, 52.8, 50.9, 45.3, 44.2, 25.4, 21.6, 13.5; LR MS (EI, *m/z*) 511 (M^++1), 479, 451, 355; Anal. Calcd for $C_{28}H_{34}N_2O_5S$: C, 65.86; H, 6.71; N, 5.49. Found: C, 65.69; H, 6.74; N, 5.34.

Absolute Configuration of 3a. Carboxylic acid **3a'**, which was obtained by phenylative carboxylation of **1a** according to the general procedure by using (*S*)-MeOMOP, was condensed with (*S*)-PGME or (*R*)-PGME to afford amide **Va** or **Vb** (Scheme S7). Absolute configurations of C2-position of **Va** were established according to the Kusumi's method as mentioned above by calculated Δδ values for compound **Va** (Figure S2). These results indicated that the absolute configuration of **3a** obtained from the reaction using (*S*)-MeO-MOP was as shown in our manuscript.

Scheme S7.





$\Delta\delta = \delta_{Va} - \delta_{Vb}$ (ppm, 400 MHz ^1H NMR)

Figure S2. Δδ values for **Va**

Preparation of Compound Va and Vb. According to the typical procedure, phenyative carboxylation of **1a** (55 mg, 0.181 mmol) was carried out in THF (2.8 mL) at 0 °C for 24 hr by using $Ni(acac)_2$ (4.6 mg, 0.018 mmol), (*S*)-MeO-MOP (17.0 mg, 0.036 mmol), and Ph_2Zn (0.5 M in xylene, 1.63 mL, 0.82 mmol). After the usual workup procedure (without diazomethane treatment), the obtained crude material was used for the next reaction without further purification.

To a cooled solution (0 °C) of the crude **3a'** (a half amount of the material obtained in the above-mentioned reaction) in DMF (1.0 ml), was added (*S*)-phenylglycine methyl ester hydrochloride (36 mg, 0.18 mmol), diethyl cyanophosphonate (0.080 mL, 0.53 mmol), and Et_3N (0.12 mL, 0.86 mmol). The mixture was stirred at 0 °C for 1hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=3/1) to afford compound **Va** (47.3 mg, 81% from **1a**, colorless crystal). The compound **Vb** was prepare as follows.

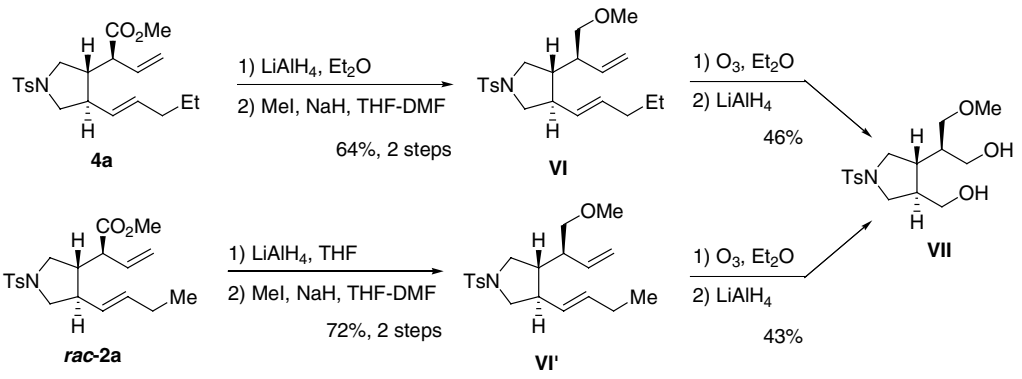
To a cooled solution (0 °C) of the crude **3a'** (a half amount of the material obtained in the above-mentioned reaction) in DMF (1.0 ml), was added (*R*)-phenylglycine methyl ester hydrochloride (36 mg, 0.18 mmol), diethyl cyanophosphonate (0.080 mL, 0.53 mmol), and Et_3N (0.12 mL, 0.86 mmol). The mixture was stirred at 0 °C for 1hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=3/1) to afford compound **Vb** (40.4 mg, 77% from **1a**, colorless crystal).

Compound Va. mp 141-142 °C (recryst from hexane/ether); $[\alpha]_D^{26}$ = +52.5 ° (*c* 0.80, $CHCl_3$); IR ($CHCl_3$) 3419, 3028, 3009, 2954, 1743, 1676, 1636, 1599 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, *J* = 8.2 Hz, 2 H), 7.15-7.37 (m, 10 H), 7.06 (d, *J* = 7.0 Hz, 2 H), 6.44 (d, *J* = 6.8 Hz, 1 H), 5.68 (ddd, *J* = 17.0, 10.2, 10.2 Hz, 1 H), 5.52 (dt, *J* = 15.2, 6.7 Hz, 1 H), 5.43 (d, *J* = 6.8 Hz, 1 H), 5.15 (dd, *J* = 15.2, 8.5 Hz, 1 H), 5.09 (d, *J* = 10.2 Hz, 1 H), 5.12 (d, *J* = 17.0 Hz, 1 H), 3.73 (s, 3 H), 3.46 (dd, *J* = 10.0, 7.6 Hz, 1 H), 3.36 (dd, *J* = 10.3, 7.6 Hz, 1 H), 3.26 (dd, *J* = 10.3, 6.2 Hz, 1 H), 3.19 (d, *J* = 6.8 Hz, 2 H), 2.89 (dd, *J* = 10.0, 7.4 Hz, 1 H), 2.77 (dd, *J* = 10.2, 9.0 Hz, 1 H), 2.57-2.66 (m, 1 H), 2.42 (s, 3 H), 2.24-2.33 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.56, 170.37, 143.21, 139.66, 135.71, 134.43, 133.17, 131.55, 130.34, 129.43, 128.80, 128.42, 128.19, 128.16, 127.44, 126.93, 125.89, 119.31, 56.65, 53.90, 52.93, 52.74, 51.05, 45.41, 44.42, 38.90, 21.75; LR MS (EI, *m/z*) 573 (M^++1), 513, 417; Anal. Calcd for $C_{33}H_{36}N_2O_5S$: C, 69.21; H, 6.34; N, 4.89. Found: C, 69.29; H, 6.44; N, 4.87.

Compound Vb. mp 132-134 °C (recryst from hexane/ether); $[\alpha]_D^{26}$ = -81.0 ° (*c* 0.90, $CHCl_3$); IR ($CHCl_3$) 3417, 3005, 2934, 1873, 1741, 1676, 1636, 1598 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.63 (d, *J* = 8.2 Hz, 2 H), 7.16-7.40 (m, 10 H), 7.05 (d, *J* = 8.2 Hz, 2 H), 6.50 (d, *J* = 7.0 Hz, 1 H), 5.73 (ddd, *J* = 17.0, 10.0, 10.0 Hz, 1 H), 5.46 (d, *J* = 7.0 Hz, 1 H), 5.40 (dt, *J* = 15.3, 6.7 Hz, 1 H), 5.17 (d, *J* = 10.0 Hz, 1 H), 5.16 (d, *J* = 17.0 Hz, 1 H), 5.13 (dd, *J* = 15.2, 8.2 Hz, 1 H), 3.71 (s, 3 H), 3.42 (dd, *J* = 10.0, 7.6 Hz, 1H), 3.24 (dd, *J* = 10.2, 7.6 Hz, 1 H), 3.20 (d, *J* = 6.7 Hz, 2 H), 3.08 (dd, *J* = 10.2, 6.2 Hz, 1 H), 2.84 (dd, *J* = 10.0, 7.6 Hz, 1 H), 2.73 (dd, *J* = 10.0, 9.1 Hz, 1 H), 2.51-2.60 (m, 1 H), 2.41 (s, 3 H), 2.23-2.32 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.62, 170.32, 143.23, 139.64, 136.03, 134.26, 132.99, 131.46, 130.31, 129.41, 128.86, 128.46, 128.20, 128.16, 127.45, 127.03, 12.91, 119.55, 56.51, 53.99, 52.94, 52.73, 51.07, 45.37, 44.36, 38.93, 21.75; LR MS (EI, *m/z*) 572 (M^+), 540, 513, 417; Anal. Calcd for $C_{33}H_{36}N_2O_5S$: C, 69.21; H, 6.34; N, 4.89. Found: C, 69.32; H, 6.47; N, 4.84.

Relative Configuration of 4a. According to the procedures shown in Scheme S8, compound **4a** was converted to compound **VII**, whose ^1H NMR spectrum was identical with that of the material independently derived from racemic **2a**.[1c]

Scheme S8.



Preparation of Compound VI. To a cooled solution (0 °C) of **4a** (27 mg, 0.07 mmL) in Et_2O (2 mL) was added $LiAlH_4$ (6.6 mg, 0.18 mmol). After the mixture was stirred at 0 °C for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added to this. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The filtrate was concentrated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in THF/DMF (3/1, 2 mL) was added NaH (60% dispersion in oil, 14 mg, 0.35 mmol) and MeI (0.043 mL, 0.70 mmol) at 0 °C. After the resulting mixture was stirred at room temperature for 2 hr, saturated aqueous solution of NH_4Cl was added at 0 °C. The aqueous layer was extracted with Et_2O. The combined organic layers were washed with brine, dried over Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/EtOAc=4/1) to afford compound **VI** (17.1 mg, 64% from **4a**) as a colorless oil.

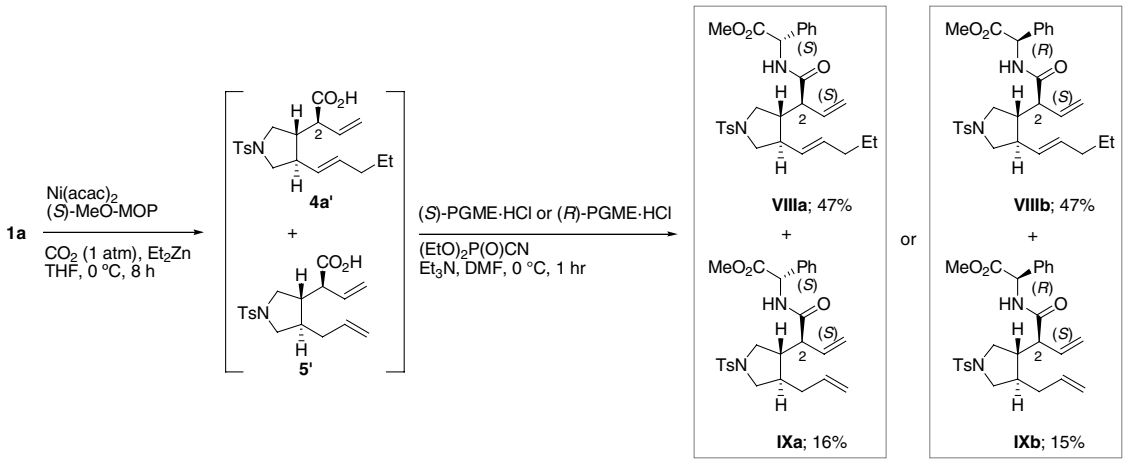
Compound VI. IR (neat) 2957, 2926, 2872, 1638, 1597 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.71 (d, *J* = 8.2 Hz, 2 H), 7.34 (d, *J* = 8.2 Hz, 2 H), 5.59 (ddd, *J* = 17.3, 10.3, 9.1 Hz, 1 H), 5.37 (dt, *J* = 15.6, 6.8 Hz, 1 H), 5.07 (dd, *J* = 15.6, 8.5 Hz, 1 H), 5.06 (d, *J* = 10.3 Hz, 1 H), 5.01 (d, *J* = 17.3 Hz, 1 H), 3.34-3.42 (m, 2 H), 3.28 (d, *J* = 5.6 Hz, 2 H), 3.25 (s, 3 H), 3.06 (dd, *J* = 10.0, 8.8 Hz, 1 H), 2.86 (dd, *J* = 10.0, 8.5 Hz, 1 H), 2.45-2.55 (m, 1 H), 2.44 (s, 3 H), 2.21-2.99 (m, 1 H), 1.92-2.02 (m, 1 H), 1.90 (td, *J* = 7.3, 6.8 Hz, 2 H), 1.32 (qt, *J* = 7.3, 7.3 Hz, 2 H), 0.82 (t, *J* = 7.3 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.09, 136.90, 133.22, 132.72, 129.38, 127.42, 127.36, 117.17, 74.17, 58.86, 53.41, 51.01, 45.39, 44.90, 44.45, 34.64, 22.47, 21.77, 13.87; LR MS (EI, *m/z*) 377 (M^+), 362, 332, 222; Anal. Calcd for $C_{21}H_{31}NO_3S$: C, 66.81; H, 8.28; N, 3.71. Found C, 66.88; H, 8.33; N, 3.65.

Conversion of Compound VI to VII. A solution of **VI** (15.0 mg, 0.040 mmol) in Et_2O (3 mL) was cooled to -78 °C and treated with a stream of O_3 at -78 °C for 15 min. Then, the mixture was treated with a stream of dry O_2 at –78 °C for 10 min to purge an excess amount of O_3. To the reaction mixture was added $LiAlH_4$ (15 mg, 0.40 mmol) at -78 °C and the resulting mixture was slowly wormed to room temperature and stirred at for additional 30 min at the same temperature. To this was added Na_2SO_4•$10H_2O$ at 0 °C and the mixture was stirred at room temperature until excess $LiAlH_4$ was decomposed. The solids were removed by filtration, and then the filtrate was concentrated in vacuo. The residue was purified by silica gel column chromatography ($CHCl_3$/MeOH=10/1) to afford compound **VII** (6.3 mg, 46%) as colorless viscous oil.[1c]

Absolute Configuration of 4a and 5. Carboxylic acid **4a'** and **5'**, which were obtained by carboxylation of **1a** using (*S*)-MeO-MOP and Et_2Zn according to the general procedure, were condensed with (*S*)-phenylglycine methyl ester [(*S*)-PGME] or (*R*)- phenylglycine methyl ester [(*R*)-PGME] to afford a pair of amide **VIIIa** and **IXa** or **VIIIb** and **IXb**

(Scheme S9). Absolute configurations of C2-position of **VIIIa** and **IXa** were established according to the Kusumi's method as mentioned above by calculated Δδ values for **VIIIa** and **IXa** (Figures S3 and S4). These results indicated that the absolute configuration of **4a** and **5** obtained from the reaction using (*S*)-MeO-MOP was as shown in our manuscript.

Scheme S9.



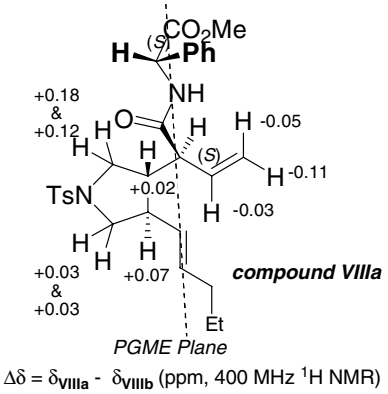


Figure S3.

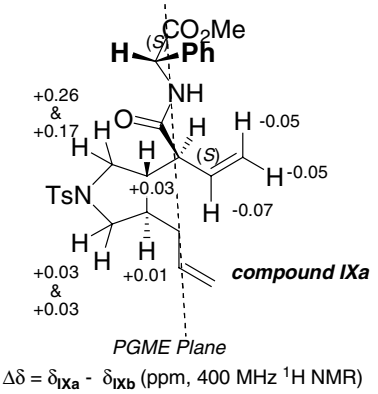


Figure S4.

Preparation of Compound VIIIa and VIIIb. According to the typical procedure, carboxylation of **1a** (60 mg, 0.20 mmol) was carried out in THF (3 mL) at 0 °C for 8 hr by using $Ni(acac)_2$ (5.0 mg, 0.020 mmol), (*S*)-MeO-MOP (18.5 mg, 0.039 mmol), and Et_2Zn (1.0 M in xylene, 0.89 mL, 0.89 mmol). After the usual workup procedure (without diazomethane treatment), the obtained crude material was used for the next reaction without further purification.

To a cooled solution (0 °C) of the crude mixture of **4a'** and **5'** (a half amount of the material obtained in the above-mentioned reaction) in DMF (1.0 ml), was added (*S*)-phenylglycine methyl ester hydrochloride (40 mg, 0.20 mmol), diethyl cyanophosphonate (0.090 mL, 0.60 mmol), and Et_3N (0.12 mL, 0.80 mmol). The mixture was stirred at 0 °C for 1hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=3/1) to afford compounds **VIIIa** (24.5 mg, 47% from **1a**, colorless crystal) and **IXa** (8.0 mg, 16%, colorless crystal). The compound **VIIIb** and **IXb** was prepare as follows.

To a cooled solution (0 °C) of the crude mixture of **4a'** and **5'** (a half amount of the material obtained in the above-mentioned reaction) in DMF (1.0 ml), was added (*R*)-phenylglycine methyl ester hydrochloride (40 mg, 0.20 mmol),

diethyl cyanophosphonate (0.090 mL, 0.60 mmol), and Et_3N (0.12 mL, 0.80 mmol). The mixture was stirred at 0 °C for 1hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=3/1) to afford compounds **VIIIb** (24.8 mg, 47% from **1a**, colorless crystal) and **IXb** (7.8 mg, 15%, colorless crystal).

Compound VIIIa. mp 125-127 °C (recryst from hexane/AcOEt); $[\alpha]_D^{26.6}$ = +53.8 ° (*c* 1.08, $CHCl_3$); IR ($CHCl_3$) 3420, 3026, 3008, 2957, 2927, 2855, 1741, 1676, 1636, 1598, 1494 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, *J* = 8.2 Hz, 2 H), 7.28-7.38 (m, 7 H), 6.49 (d, *J* = 7.0 Hz, 1 H), 5.70 (ddd, *J* = 17.0, 10.2, 10.0 Hz, 1 H), 5.44 (d, *J* = 7.0 Hz, 1 H), 5.35 (dt, *J* = 15.2, 6.8 Hz, 1 H), 5.10 (d, *J* = 10.2 Hz, 1 H), 5.13 (d, *J* = 17.0 Hz, 1 H), 5.03 (dd, *J* = 15.2, 8.6 Hz, 1 H), 3.74 (s, 3 H), 3.44 (dd, *J* = 10.0, 7.4 Hz, 1 H), 3.35 (dd, *J* = 10.2, 7.3 Hz, 1 H), 3.27 (dd, *J* = 10.2, 7.3 Hz, 1 H), 2.84 (dd, *J* = 10.0, 7.6 Hz, 1 H), 2.79 (dd, *J* = 10.0, 8.8 Hz, 1 H), 2.53-2.62 (m, 1 H), 2.43 (s, 3 H), 2.20-2.30 (m, 1 H), 1.83 (dt, *J* = 8.2, 7.0 Hz, 2 H), 1.26 (qt, *J* = 7.3, 7.0 Hz, 2 H), 0.82 (t, *J* = 7.3 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.56, 170.43, 143.16, 135.74, 134.46, 133.21, 132.94, 129.40, 128.98, 128.79, 128.41, 127.49, 126.93, 119.23, 56.68, 53.64, 52.91, 52.86, 52.79, 45.43, 44.45, 34.55, 22.44, 21.71, 13.83; LR MS (EI, *m/z*) 525 (M^++1), 493, 465, 369; Anal. Calcd for $C_{29}H_{36}N_2O_5S$: C, 66.39; H, 6.92; N, 5.34. Found: C, 66.39; H, 6.95; N, 5.51.

Compound VIIIb. mp 107-108 °C (recryst from hexane/AcOEt); $[\alpha]_D^{27}$ = - 81.0 ° (*c* 1.04, $CHCl_3$); IR ($CHCl_3$) 3418, 3026, 3009, 2957, 2927, 2872, 1741, 1676, 1636, 1598 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.64 (d, *J* = 8.5 Hz, 2 H), 7.32-7.41 (m, 5 H), 7.27 (d, *J* = 8.5 Hz, 2 H), 6.56 (d, *J* = 7.0 Hz, 1 H), 5.77 (ddd, *J* = 17.0, 10.2, 10.0 Hz, 1 H), 5.48 (d, *J* = 7.0 Hz, 1 H), 5.23 (dt, *J* = 15.3, 7.0 Hz, 1 H), 5.22 (d, *J* = 10.2 Hz, 1 H), 5.18 (d, *J* = 17.0 Hz, 1 H), 5.01 (dd, *J* = 15.3, 8.2 Hz, 1 H), 3.71 (s, 3 H), 3.40 (dd, *J* = 10.0, 7.3 Hz, 1 H), 3.23 (dd, *J* = 10.2, 7.6 Hz, 1 H), 3.08 (dd, *J* = 10.2, 6.4 Hz, 1 H), 2.81 (dd, *J* = 10.0, 7.6 Hz, 1 H), 2.75 (dd, J = 10.0, 9.1 Hz, 1 H), 2.46-2.56 (m, 1 H), 2.42 (s, 3 H), 2.19-2.28 (m, 1 H), 1.82 (dt, J = 7.0, 6.8 Hz, 2 H), 1.24 (qt, *J* = 7.4, 6.8 Hz, 2 H), 0.81 (t, *J* = 7.4 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.62, 170.35, 143.15, 136.05, 134.21, 133.04, 132.83, 129.36, 128.91, 128.83, 128.42, 127.42, 126.99, 119.48, 56.45, 53.68, 52.90, 52.82, 50.96, 45.39, 44.37, 34.53, 22.41, 21.71, 13.79; LR MS (EI, *m/z*) 525 (M^++1), 493, 465, 369; Anal. Calcd for $C_{29}H_{36}N_2O_5S$: C, 66.39; H, 6.92; N, 5.34. Found: C, 66.41; H, 6.91; N, 5.29.

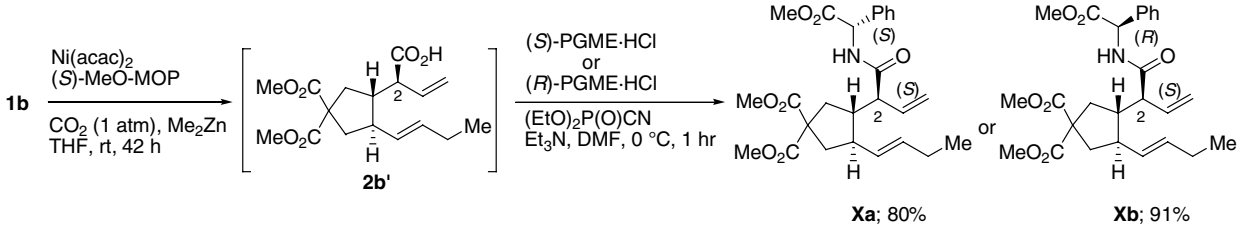
Compound IXa. mp 149-150 °C (recryst from hexane/ether); $[\alpha]_D^{25}$ = +25.6 ° (*c* 0.62, $CHCl_3$); IR ($CHCl_3$) 3419, 3004, 2977, 2933, 2873, 1743, 1676, 1636, 1598 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.78 (d, *J* = 8.2 Hz, 2 H), 7.30-7.39 (m, 7 H), 6.49 (d, J = 7.0 Hz, 1 H), 5.67 (ddd, *J* = 17.0, 10.3, 9.7 Hz, 1 H), 5.49-5.61 (m, 1 H), 5.45 (d, *J* = 7.0 Hz, 1 H), 5.19 (d, *J* = 10.3 Hz, 1 H), 5.13 (d, *J* = 17.0 Hz, 1 H), 4.95 (d, *J* = 10.3 Hz, 1 H), 4.88 (d, *J* = 17.0 Hz, 1 H), 3.75 (s, 3 H), 3.37 (dd, *J* = 10.0, 7.0 Hz, 1 H), 3.27 (dd, *J* = 10.6, 4.7 Hz, 1 H), 3.24 (dd, v = 10.7, 6.4 Hz, 1 H), 2.80 (dd, *J* = 10.5, 5.0 Hz, 1 H), 2.68 (dd, *J* = 9.7, 9.4 Hz, 1 H), 2.43 (s, 3 H), 2.23-2.32 (m, 1 H), 1.97-2.09 (m, 2 H), 1.72-1.87 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.74, 170.51, 143.27, 135.71, 135.13, 134.45, 132.90, 129.40, 128.80, 128.45, 127.58, 126.98, 119.59, 116.84, 56.80, 54.86, 52.97, 52.01, 51.14, 44.20, 40.13, 37.90, 21.74; LR MS (EI, *m/z*) 497 (M^++1), 465, 437, 341; Anal. Calcd for $C_{27}H_{32}N_2O_5S$: C, 65.30; H, 6.49; N, 5.64. Found: C, 65.07; H, 6.52; N, 5.54.

Compound IXb. mp 123-124 °C (recryst from hexane/ether); $[\alpha]_D^{26}$ = -121.1 ° (*c* 0.57, $CHCl_3$); IR ($CHCl_3$) 3420, 3003, 2977, 2933, 2873, 1741, 1676, 1636, 1598 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.62 (d, *J* = 8.2 Hz, 2 H), 7.63-7.42 (m, 5 H), 7.26 (d, *J* = 8.2 Hz, 2 H), 6.55 (d, *J* =7.0 Hz, 1 H), 5.74 (ddd, *J* = 17.0, 10.2, 9.7 Hz, 1 H), 5.50-5.59 (m, 1 H), 4.99 (d, *J* = 7.0 Hz, 1 H), 5.24 (d, *J* = 10.2 Hz, 1 H), 5.17 (d, *J* = 17.0 Hz, 1 H), 4.94 (d, *J* = 10.3 Hz, 1 H), 4.87 (d, *J* = 16.7 Hz, 1 H),

3.72 (s, 3 H), 3.34 (dd, *J* = 10.0, 7.0 Hz, 1 H), 3.11 (dd, *J* = 10.6, 7.3 Hz, 1 H), 2.98 (d, *J* = 10.6, 3.8 Hz, 1 H), 2.78 (dd, *J* = 10.0, 5.7 Hz, 1 H), 2.65 (dd, *J* = 9.7, 9.7 Hz, 1 H), 2.42 (s, 3 H), 2.21-2.29 (m, 1 H), 1.95-2.09 (m, 2 H), 1.72-1.82 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.69, 170.61, 143.26, 136.03, 135.11, 134.32, 132.67, 129.35, 128.89, 128.47, 127.50, 127.05, 119.73, 116.83, 56.61, 54.89, 52.95, 51.98, 51.09, 44.24, 40.05, 37.93, 21.74; LR MS (EI, *m/z*) 497 (M^++1), 465, 437, 341; Anal. Calcd for $C_{27}H_{32}N_2O_5S$: C, 65.30; H, 6.49; N, 5.64. Found: C, 65.11; H, 6.54; N, 5.83.

Absolute Configuration of 2b. Carboxylic acid **2b'**, which was obtained by carboxylation of **1b** using (*S*)-MeO-MOP and Me_2Zn according to the general procedure, were condensed with (*S*)-PGME or (*R*)-PGME to afford an amide **Xa** or **Xb** (Scheme S10). Absolute configuration of C2-position of **Xa** was established according to the Kusumi's method as mentioned above by calculated Δδ values for **Xa** (Figures S5). These results indicated that the absolute configuration of **2b** obtained from the reaction using (*S*)-MeO-MOP was as shown in our manuscript.

Scheme S10.



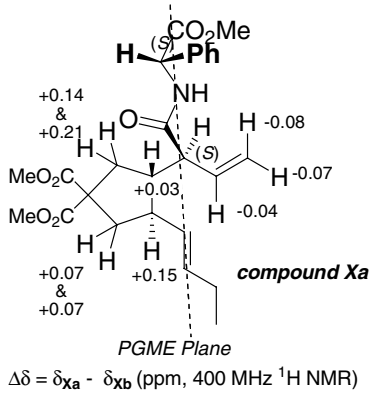


Figure S5.

Preparation of Compound Xa and Xb. According to the typical procedure, methylative carboxylation of **1b** (60 mg, 0.227 mmol) was carried out in THF (3 mL) at room temperature for 42 hr by using $Ni(acac)_2$ (5.8 mg, 0.023 mmol), (*S*)-MeO-MOP (21.3 mg, 0.045 mmol), and Me_2Zn (1.0 M in hexane, 1.0 mL, 1.0 mmol). After the usual workup procedure (without diazomethane treatment), the obtained crude material was used for the next reaction without further purification.

To a cooled solution (0 °C) of the crude **2b'** (a half amount of the material obtained in the above-mentioned reaction) in DMF (1.2 ml), was added (*S*)-phenylglycine methyl ester hydrochloride (45.5 mg, 0.23 mmol), diethyl cyanophosphonate (0.10 mL, 0.68 mmol), and Et_3N (0.16 mL, 1.1 mmol). The mixture was stirred at 0 °C for 1 hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=2/1) to afford

compound **Xa** (42.9 mg, 80% from **1b**) as a colorless viscous oil. The compound **Xb** was prepare as follows.

To a cooled solution (0 °C) of the crude **2b'** (a half amount of the material obtained in the above-mentioned reaction) in DMF (1.2 ml), was added (*S*)-phenylglycine methyl ester hydrochloride (45.5 mg, 0.23 mmol), diethyl cyanophosphonate (0.10 mL, 0.68 mmol), and Et_3N (0.16 mL, 1.1 mmol). The mixture was stirred at 0 °C for 1 hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=2/1) to afford compound **Xb** (49.1 mg, 91% from **1b**) as a colorless viscous oil.

Compound Xa. $[\alpha]_D^{20.1}$ = +61.97 ° (*c* 0.88, $CHCl_3$); IR (neat) 3372, 3318, 1956, 1872, 1750, 1733, 1678, 1661, 1636, 1603, 1587 cm^{-1}; ^1H NMR (400 MHz, C_6D_6) δ 7.32-7.37 (m, 2 H), 7.00-7.13 (m, 3 H), 6.55 (d, *J* = 7.0 Hz, 1 H), 5.96 (ddd, *J* = 17.0, 10.0, 9.4 Hz, 1 H), 5.74 (d, *J* = 7.0 Hz, 1 H), 5.61 (dt, *J* = 15.5, 6.6 Hz, 1 H), 5.27 (dd, *J* = 15.8, 8.2 Hz, 1 H), 4.97 (d, *J* = 17.0 Hz, 1 H), 4.93 (d, *J* = 10.0 Hz, 1 H), 3.38 (s, 3 H), 3.35 (s, 3 H), 3.21 (s, 3 H), 2.91 (dd, *J* = 11.4, 8.2 Hz, 1 H), 2.89 (dd, *J* = 9.4, 5.8 Hz, 1 H), 2.81 (dd, *J* = 12.9, 7.6 Hz, 1 H), 2.71-2.77 (m, 1 H), 2.72 (dd, *J* = 11.4, 9.1 Hz, 1 H), 2.36-2.47 (m, 1 H), 2.24 (dd, *J* = 12.9, 9.1 Hz, 1 H), 2.36-2.47 (m, 1 H), 2.24 (dd, *J* = 12.9, 9.4 Hz, 1 H), 1.94 (qd, *J* = 7.3, 6.2 Hz, 2 H), 0.93 (t, *J* = 7.3 Hz, 1 H) ; ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.93, 25.64, 37.16, 41.00, 46.04, 46.88, 52.79, 52.80, 56.49, 58.14, 118.05, 126.95, 128.26, 128.71, 130.50, 133.53, 135.42, 136.03, 170.76, 171.02, 172.33, 172.60; LR LR MS (EI, *m/z*) 471 (M^+), 440, 412, 325, 233; Anal. Calcd for $C_{26}H_{33}NO_7$: C, 66.22; H, 7.05; N, 2.97. Found C, 65.84; H, 7.06; N, 3.28.

Compound Xb. $[\alpha]_D^{20.3}$ = -82.32 ° (*c* 0.85, $CHCl_3$); IR (neat) 3374, 3317, 2956, 2928, 2870, 1749, 1734, 1676, 1660, 1636, 1602, 1586 $cm^{-1;}$ ^1H NMR (400 MHz, C_6D_6) δ 7.39-7.44 (m, 2 H), 7.01-7.16 (m, 3 H), 6.62 (d, *J* = 7.0 Hz, 1 H), 6.00 (ddd, *J* = 17.3, 10.0, 9.1 Hz, 1 H), 5.79 (d, *J* = 7.0 Hz, 1 H), 5.36 (dt, *J* = 15.2, 6.2 Hz, 1 H), 5.22 (dd, *J* = 15.2, 8.2 Hz, 1 H), 5.05 (d, *J* = 17.3 Hz, 1 H), 5.01 (d, *J* = 10.0 Hz, 1 H), 3.36 (s, 3 H), 3.33 (s, 3 H), 3.18 (s, 3 H), 2.86 (dd, *J* = 9.1, 7.0 Hz, 1 H), 2.77 (dd, *J* = 13.5, 7.9 Hz, 1 H), 2.74 (dd, *J* = 13.2, 7.4 Hz, 1 H), 2.55-2.64 (m, 1 H), 2.51 (dd, *J* = 13.5, 9.1 Hz, 1 H), 2.35-2.43 (m, 1 H), 2.17 (dd, *J* = 13.2, 10.0 Hz, 1 H), 1.90 (qd, *J* = 7.3, 6.2 Hz, 2 H), 0.90 (t, *J* = 7.3 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.87, 25.61, 37.16, 40.98, 46.08, 46.78, 52.71, 52.76, 53.89, 56.32, 58.01, 118.30, 127.02, 128.25, 128.68, 130.36, 133.51, 135.12, 136.25, 170.80, 170.89, 172.23, 172.47; LR MS (EI, *m/z*) 471 (M^+), 440, 412, 233; Anal. Calcd for $C_{26}H_{33}NO_7$: C, 66.22; H, 7.05; N, 2.97. Found C, 66.20; H, 7.18; N, 3.00.

Absolute Configuration of 3b. Carboxylic acid **3b'**, which was obtained by carboxylation of **1b** using (*S*)-MeO-MOP and Ph_2Zn according to the general procedure, were condensed with (*S*)-PGME or (*R*)-PGME to afford an amide **XIa** or **XIb** (Scheme S11). Absolute configuration of C2-position of **XIa** was established according to the Kusumi's method as mentioned above by calculated Δδ values for **XIa** (Figures S6). These results indicated that the absolute configuration of **3b** obtained from the reaction using (*S*)-MeO-MOP was as shown in our manuscript.

Scheme S11.

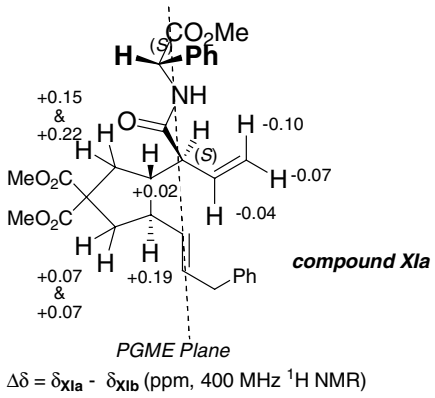


Figure S6.

Preparation of Compound XIa and XIb. According to the typical procedure, phenylative carboxylation of **1b** (60 mg, 0.227 mmol) was carried out in THF (3 mL) at room temperature for 36 hr by using $Ni(acac)_2$ (5.8 mg, 0.023 mmol), (*S*)-MeO-MOP (21.3 mg, 0.045 mmol), and Ph_2Zn (0.5 M in xylene, 2.0 mL, 1.0 mmol). After the usual workup procedure (without diazomethane treatment), the obtained crude material was used for the next reaction without further purification.

To a cooled solution (0 °) of the crude **3b'** (a half amount of the material obtained in the above-mentioned reaction) in DMF (1.2 ml), was added (*S*)-phenylglycine methyl ester hydrochloride (45.5 mg, 0.23 mmol), diethyl cyanophosphonate (0.10 mL, 0.68 mmol), and Et_3N (0.16 mL, 1.1 mmol). The mixture was stirred at 0 °C for 1 hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=2/1) to afford compound **XIa** (40.7 mg, 69% from **1b**) as a colorless viscous oil. The compound **XIb** was prepare as follows.

To a cooled solution (0 °C) of the crude **3b'** (a half amount of the material obtained in the above-mentioned reaction) in DMF (1.2 ml), was added (*S*)-phenylglycine methyl ester hydrochloride (45.5 mg, 0.23 mmol), diethyl cyanophosphonate (0.10 mL, 0.68 mmol), and Et_3N (0.16 mL, 1.1 mmol). The mixture was stirred at 0 °C for 1 hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=2/1) to afford compound **XIb** (49.2 mg, 83% from **1b**) as a colorless viscous oil.

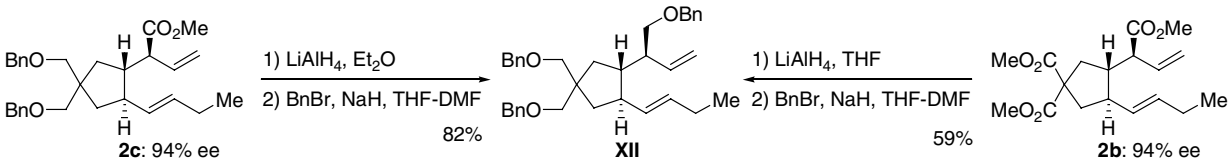
Compound XIa. $[\alpha]_D^{20.5}$ = +61.6 ° (*c* 0.83, $CHCl_3$); IR (neat) 3375, 3317, 3063, 3026, 2952, 2926, 2848, 1750, 1731, 1676, 1661, 1602, 1587 cm^{-1}; ^1H NMR (400 MHz, C_6D_6) δ 7.28-7.32 (m, 2 H), 7.00-7.20 (m, 8 H), 6.49 (d, *J* = 7.0 Hz, 1 H), 5.93 (ddd, *J* = 17.0, 10.0, 9.2 Hz, 1 H), 5.73 (d, *J* = 7.0 Hz, 1 H), 5.71 (dt, *J* = 15.0, 6.7 Hz, 1 H), 5.30 (dd, *J* = 15.0, 7.9 Hz, 1 H), 4.93 (d, *J* = 17.0 Hz, 1 H), 4.89 (d, *J* = 10.0 Hz, 1 H), 3.37 (s, 3 H), 3.35 (s, 3 H), 3.21 (d, *J* = 6.7 Hz, 2 H), 3.19 (s, 3 H),

2.91 (dd, *J* = 13.8, 7.9 Hz, 1 H), 2.85 (dd, *J* = 9.2, 7.6 Hz, 1 H), 2.77 (dd, *J* = 12.6, 7.3 Hz, 1 H), 2.70-2.78 (m, 1 H), 2.72 (dd, *J* = 13.8, 9.1 Hz, 1 H), 2.37-2.48 (m, 1 H), 2.25 (dd, *J* = 12.6, 9.0 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 37.29, 39.04, 40.92, 45.98, 46.79, 52.79, 52.83, 54.41, 56.45, 58.27, 118.08, 125.71, 126.95, 128.11, 128.19, 128.26, 128.72, 130.36, 133.09, 135.43, 135.98, 140.22, 170.74, 171.01, 172.21, 172.55; LR MS (EI, *m/z*) 533 (M^+), 502, 474, 442, 233; Anal. Calcd for $C_{31}H_{35}NO_7$: C, 69.78; H, 6.61; N, 2.62. Found C, 69.65; H, 6.45; N, 2.79.

Compound XIb. $[\alpha]_D^{20.8}$ = -64.9 ° (*c* 1.07, $CHCl_3$); IR (neat) 3374, 3321, 3062, 3027, 3001, 2952, 2847, 1747, 1732, 1676, 1660, 1636, 1602, 1586 cm^{-1}; ^{1}H NMR (400 MHz, C_6D_6) δ 7.35-7.39 (m, 2 H), 7.00-7.24 (m, 8 H), 6.58 (d, *J* = 7.3 Hz, 1 H), 5.96 (ddd, *J* = 17.0, 10.0, 9.1 Hz, 1 H), 5.78 (d, *J* = 7.3 Hz, 1 H), 5.44 (d, *J* = 15.2, 6.7 Hz, 1 H), 5.27 (dd, *J* = 15.2, 8.2 Hz, 1 H), 5.04 (d, *J* = 17.0 Hz, 1 H), 4.97 (d, *J* = 10.0 Hz, 1 H), 3.35 (s, 3 H), 3.32 (s, 3 H), 3.18 (d, *J* = 6.7 Hz, 2 H), 3.17 (s, 3 H), 2.82 (dd, *J* =9.1, 7.3 Hz, 1 H), 2.76 (dd, *J* = 13.5, 7.9 Hz, 1 H), 2.70 (dd, *J* = 13.2, 7.3 Hz, 1 H), 2.53-2.63 (m, 1 H), 2.50 (dd, *J* = 13.5, 9.7 Hz, 1 H), 2.34-2.44 (m, 1 H), 2.18 (dd, *J* = 13.2, 9.6 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 37.34, 39.02, 40.93, 46.02, 46.61, 52.74, 52.80, 54.41, 56.36, 58.17, 118.33, 125.73, 127.01, 128.11, 128.19, 128.25, 128.70, 130.30, 132.98, 135.19, 136.21, 140.14, 170.76, 170.92, 172.13, 172.44; LR MS (EI, *m/z*) 533 (M^+), 502, 474, 442, 233; Anal. Calcd for $C_{31}H_{35}NO_7$: C, 69.78; H, 6.61; N, 2.62. Found C, 69.80; H, 6.71; N, 2.63.

Determination of Stereochemistry of 2c. Product **2c** was transformed into compound **XII** according to the procedure shown in Scheme S12. The spectral data and the optical rotation of this material were identical with those of a material, which was independently derived from **2b** whose relative and absolute stereochemistry was already determined. These results indicated that the relative and absolute configuration of **2c** was as shown in our manuscript.

Scheme S12.



Conversion of 2c to XII. To a solution of **2c** (25 mg, 0.054 mmol) in Et_2O (1.5 mL) was added $LiAlH_4$ (5.1 mg, 0.14 mmol) at 0 °C. After the mixture was stirred at room temperature for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added at 0 °C. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The solvents were evaporated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in THF-DMF (4/1, 1.25 mL) was added NaH (60% dispersion in oil, 22 mg, 0.54 mmol), and benzyl bromide (0.039 mL, 0.32 mmol) at 0 °C. After the mixture was stirred at room temperature for 3 hr, saturated aqueous solution of NH_4Cl was added at 0 °C. The water layer was extracted with Et_2O and combined organic layers were washed with H_2O and brine, and dried over Na_2SO_4. After the solvent was evaporated, the residue was purified by silica gel column chromatography (hexane/EtOAc = 20/1) to afford compound **XII** (23.5 mg, 82% from **2c**): $[\alpha]_D^{23.9}$ = +27.0 ° (*c* 0.98, $CHCl_3$, 94% ee); IR (neat) 3064, 3029, 2958, 2927, 2854, 1786, 1950, 1869, 1809, 1724, 1636, 1604 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.23-7.34 (m, 15 H), 5.73 (ddd, *J* = 17.0, 10.5, 8.8 Hz, 1 H), 5.35 (dd, *J* = 15.3, 6.2 Hz, 1 H), 5.26 (dd, *J* = 15.3, 8.9 Hz, 1 H), 5.06 (d, *J* = 8.8 Hz, 1 H), 5.03 (d, *J* = 17.0 Hz, 1 H), 4.49 (s, 2 H), 4.48 (s, 2 H), 4.45 (s, 2 H), 3.40-3.49

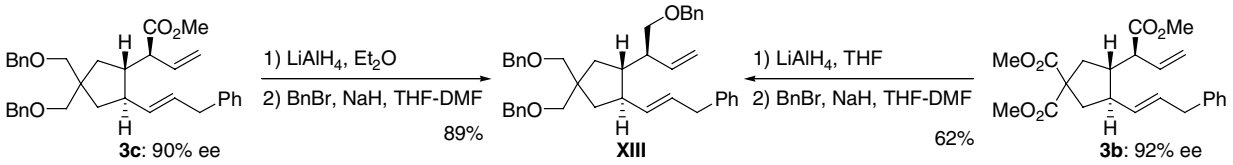
(m, 2 H), 3.33 (s, 2 H), 3.30 (s, 2 H), 2.37-2.48 (m, 1 H), 2.21-2.33 (m, 1 H), 2.27 (qd, *J* = 7.6, 6.2 Hz, 2 H), 1.77-1.88 (m, 1 H), 1.64-1.74 (m, 2 H), 1.18-1.33 (m, 2 H), 0.91 (t, *J* = 7.6 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.08, 25.73, 36.40, 40.72, 45.08, 45.28, 46.08, 46.16, 71.84, 72.86, 73.11, 73.13, 74.83, 75.03, 76.88, 77.00, 77.31, 115.90, 127.05, 127.12, 127.18, 127.33, 128.00, 128.04, 131.60, 132.81, 138.38, 138.67, 138.77; LR MS (EI, *m/z*) 524 (M^+), 433, 416, 403, 91; Anal. Calcd for $C_{36}H_{44}O_3$: C, 82.40; H, 8.45. Found C, 82.27; H, 8.48.

Conversion of 2b to XII. To a solution of **2b** (35 mg, 0.10 mmol, 94% ee) in THF (2.0 mL) was added $LiAlH_4$ (40 mg, 1.0 mmol) at 0 °C. After the mixture was refluxed for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added at 0 °C. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The solvents were evaporated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in THF-DMF (4/1, 1.25 mL) was added NaH (60% dispersion in oil, 40 mg, 1.0 mmol), and benzyl bromide (0.072 mL, 0.60 mmol) at 0 °C. After the mixture was stirred at room temperature for 3 hr, saturated aqueous solution of NH_4Cl was added at 0 °C. The water layer was extracted with Et_2O and combined organic layers were washed with H_2O and brine, and dried over Na_2SO_4. After the solvent was evaporated, the residue was purified by silica gel column chromatography (hexane/EtOAc = 20/1) to afford compound **XII** (32.0 mg, 59% from **2b**): $[\alpha]_D^{21.2}$ = +27.9 ° (*c* 0.87, $CHCl_3$, 94% ee).

Determination of Stereochemistry of 3c. Product **3c** was transformed into compound **XIII** according to the procedure shown in Scheme S13. The spectral data and the optical rotation of this material were identical with those of a material, which was independently derived from **3b** whose relative and absolute stereochemistry was already determined. These results indicated that the relative and absolute configuration of **3c** was as shown in our manuscript.

Scheme S13.



Conversion of 3c to XIII. To a solution of **3c** (25 mg, 0.047 mmol, 90% ee) in Et_2O (1.5 mL) was added $LiAlH_4$ (3.6 mg, 0.095 mmol) at 0 °C. After the mixture was stirred at room temperature for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added at 0 °C. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The solvents were evaporated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in THF-DMF (4/1, 1.25 mL) was added NaH (60% dispersion in oil, 6.8 mg, 0.17 mmol), and benzyl bromide (0.020 mL, 0.17 mmol) at 0 °C. After the mixture was stirred at room temperature for 5 hr, saturated aqueous solution of NH_4Cl was added at 0 °C. The water layer was extracted with Et_2O and combined organic layers were washed with H_2O and brine, and dried over Na_2SO_4. After the solvent was evaporated, the residue was purified by silica gel column chromatography (hexane/EtOAc = 15/1) to afford compound **XIII** (25.1 mg, 89% from **3c**): $[\alpha]_D^{21.4}$ = +27.7 °(*c* 1.10, $CHCl_3$, 90% ee); IR (neat) 3063, 3027, 2921, 2855, 2785, 1949, 1867, 1807, 1736, 1640, 1602, 1584 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.11-7.33 (m, 20 H), 5.70 (ddd, *J* = 17.0, 10.5, 8.8 Hz, 1 H), 5.47 (dt, *J* = 15.0, 7.0 Hz, 1 H), 5.28 (dd, *J* = 15.0, 8.5 Hz, 1 H), 5.03 (d, *J* = 8.8 Hz, 1 H), 5.02 (d, *J* = 17.0 Hz, 1 H), 4.48 (s, 2 H), 4.47 (s, 2 H), 4.41 (s, 2 H),

3.38-3.47 (m, 2 H), 3.32 (s, 2 H), 3.29 (s, 2 H), 3.26 (d, *J* = 7.0 Hz, 2 H), 2.27-2.46 (m, 2 H), 1.79-1.90 (m, 1 H), 1.74 (dd, *J* = 13.5, 7.6 Hz, 1 H), 1.69 (dd, *J* = 13.5, 7.6 Hz, 1 H), 1.21-1.32 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 36.45, 39.12, 40.65, 45.14, 45.37, 46.17, 46.26, 71.84, 72.83, 73.11, 73.13, 74.78, 74.95, 115.93, 125.64, 127.07, 127.13, 127.17, 127.30, 127.98, 128.04, 128.07, 128.25, 128.40, 135.45, 138.35, 138.61, 138.74, 140.58; LR MS (EI, *m/z*) 586 (M^+), 495, 478, 465, 91; Anal. Calcd for $C_{41}H_{46}O_3$: C, 83.92; H, 7.90. Found C, 83.92; H, 8.18.

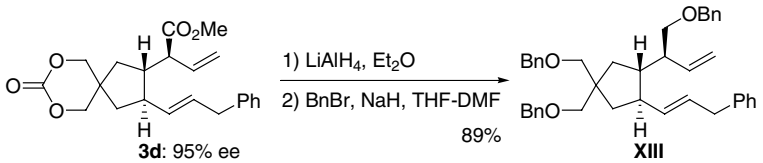
Conversion of 3b to XIII. To a solution of **3b** (35 mg, 0.087 mmol, 92% ee) in THF (2.5 mL) was added $LiAlH_4$ (40 mg, 1.0 mmol) at 0 °C. After the mixture was refluxed for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added at 0 °C. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The solvents were evaporated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in THF-DMF (4/1, 1.25 mL) was added NaH (60% dispersion in oil, 35 mg, 0.87 mmol), and benzyl bromide (0.063 mL, 0.52 mmol) at 0 °C. After the mixture was stirred at room temperature for 5 hr, saturated aqueous solution of NH_4Cl was added at 0 °C. The water layer was extracted with Et_2O and combined organic layers were washed with H_2O and brine, and dried over Na_2SO_4. After the solvent was evaporated, the residue was purified by silica gel column chromatography (hexane/EtOAc = 15/1) to afford compound **XIII** (31.9 mg, 62% from **3b**): $[\alpha]_D^{21.3}$ = +26.8 ° (*c* 1.00, $CHCl_3$, 92% ee).

Determination of Stereochemistry of 2d. Product **2d** was transformed into compound **II** according to the procedure shown in Scheme S4 (see, Page S8). The spectral data and the optical rotation of this material were identical with those of a material, which was independently derived from **2b** (see, Page S6) whose relative and absolute stereochemistry was already determined (see, page S9). These results indicated that the relative and absolute configuration of **2d** was as shown in our manuscript.

Relative and Absolute Configuration of 3d. Product **3d** was transformed into compound **XII** according to the procedure shown in Scheme S14. The spectral data and the optical rotation of this material were identical with those of a material, which was independently derived from **3b** (see, Page S21) whose relative and absolute stereochemistry was already determined. These results indicated that the relative and absolute configuration of **3d** was as shown in our manuscript.

Scheme S14.



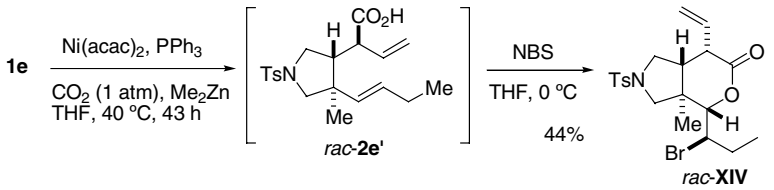
Conversion of 3d to XIII. To a solution of **3d** (20 mg, 0.054 mmol, 90% ee) in Et_2O (2 mL) was added $LiAlH_4$ (20 mg, 0.54 mmol) at 0 °C. After the mixture was stirred at room temperature for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added at 0 °C. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The solvents were evaporated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in THF-DMF (4/1, 1.25 mL) was added NaH (60% dispersion in oil, 22 mg, 0.17 mmol), and benzyl bromide (0.040 mL, 0.32 mmol) at 0 °C. After the mixture was stirred at room temperature for 12 hr, saturated

aqueous solution of NH_4Cl was added at 0 °C. The water layer was extracted with Et_2O and combined organic layers were washed with H_2O and brine, and dried over Na_2SO_4. After the solvent was evaporated, the residue was purified by silica gel column chromatography (hexane/EtOAc = 15/1) to afford compound **XIII** (26.2 mg, 82% from **3d**): $[\alpha]_D^{21.3}$ = +27.1 ° (*c* 1.22, $CHCl_3$, 95% ee).

Relative Configuration of 2e. The relative configuration of **2e** was determined by the results of NOE experiments for compound *rac*-**XIV** (summarized in Figure S7), which was prepared from carboxylic acid **2e'** according to the procedure shown in Scheme S15 and the following text. Carboxylic acid **2e'** was obtained by methylative carboxylation of **1e** according to the general procedure using PPh_3 except that the product was isolated without diazomethane treatment.

Scheme S15.



Preparation of Compound *rac*-XIV. According to the typical procedure, methylative carboxylation of **1e** (65 mg, 0.21 mmol) was carried out in THF (3 mL) at 40 °C for 43 hr by using $Ni(acac)_2$ (7.9 mg, 0.030 mmol), PPh_3 (16.1 mg, 0.060 mmol), and Me_2Zn (1.0 M in hexane, 0.92 mL, 0.92 mmol). After the usual workup procedure (without diazomethane treatment), the obtained material was passed through a short column of silica gel (eluent; $CHCl_3$/MeOH=30/1) to afford crude carboxylic acid *rac*-**2e'** (84 mg, major impurities were triphenylphosphine oxide). This material was used for the next reaction without further purification.

To a cooled (0 °C) solution of carboxylic acid *rac*-**2e'** (84 mg) in THF (4 mL) was added *N*-bromosuccinimide (50.0 mg. 0.28 mmol). After 1 hr at 0 °C in dark, the mixture was diluted with Et_2O and an aqueous solution of $Na_2S_2O_3$ was added to the mixture. The aqueous layer was extracted with Et_2O and the combined organic layers were washed with brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/EtOAc=3/1) to afford bromolactone *rac*-**XIV** (colorless crystal, 41 mg, 44%).

Compound XIV. mp 136-137 °C (recryst from hexane/AcOEt); IR ($CHCl_3$) 3020, 2975, 2911, 1734, 1634, 1598 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.82 (d, *J* = 8.2 Hz, 2 H), 6.85 (d, *J* = 8.2 Hz, 2 H), 5.29 (ddd, *J* = 17.0, 10.0, 8.5 Hz, 1 H), 5.00 (d, *J* = 17.0 Hz, 1 H), 5.07 (d, *J* = 10.0 Hz, 1 H), 3.81 (d, *J* = 10.2 Hz, 1 H), 3.57 (d, *J* = 10.3 Hz, 1 H), 3.42-3.48 (m, 1 H), 3.18 (dd, *J* = 9.4, 7.9 Hz, 1 H), 3.13 (d, *J* = 10.3 Hz, 1 H), 3.01 (dd, *J* = 11.7, 9.4 Hz, 1 H), 2.85 (dd, *J* = 8.5, 8.0 Hz, 1 H), 2.05-2.17 (m, 1 H), 1.93 (s, 3 H), 1.59-1.69 (m, 1 H), 1.33 (ddd, *J* = 11.7, 8.0, 7.9 Hz, 1 H), 0.92 (dd, *J* = 7.0, 7.0 Hz, 3 H), 0.40 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 10.80, 12.24, 21.64, 27.71, 41.89, 45.05, 45.95, 46.26, 53.16, 59.75, 88.47, 122.10, 127.15, 129.82, 130.53, 134.05, 143.69, 168.71; LR MS (EI, *m/z*) 455 (M^+), 334, 376, 300; Anal. Calcd for $C_{20}H_{26}BrNO_4S$: C, 52.63; H, 5.74; N, 3.07. Found: C, 52.86; H, 5.79; N, 2.82.

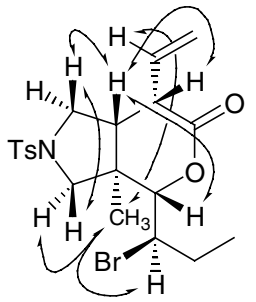
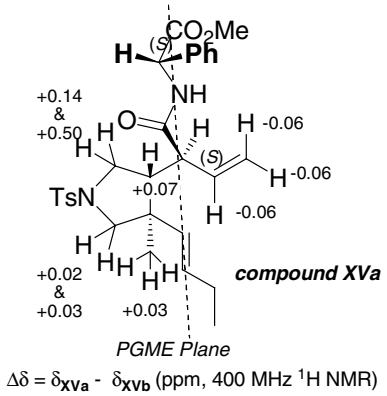


Figure S7. Summary of NOE Experiments for **XIV**

Absolute Configuration of 2e. Optically active carboxylic acid **2e'**, which was obtained by methylative carboxylation of **1e** according to the general procedure by using (*S*)-MeO-MOP, was condensed with (*S*)-PGME or (*R*)-PGME to afford amide **XVa** or **XVb** (Scheme S16). Absolute configurations of C2-position of **XVa** were established according to the Kusumi's method as mentioned above by calculated Δδ values for compound **XVa** (Figure S8). These results indicated that the absolute configuration of **2e** obtained from the reaction using (*S*)-MeO-MOP was as shown in our manuscript.

Scheme S16.



Δδ = $\delta_{\mathbf{XVa}}$ - $\delta_{\mathbf{XVb}}$ (ppm, 400 MHz ^{1}H NMR)

Figure S8.

Preparation of XVa and XVb. According to the typical procedure, methylative carboxylation of **1e** (50 mg, 0.157 mmol) was carried out in THF (2.4 mL) at 4 °C for 68 hr by using $Ni(acac)_2$ (4.0 mg, 0.016 mmol), (*S*)-MeO-MOP (14.8 mg, 0.031 mmol), and Me_2Zn (1.0 M in hexane, 0.71 mL, 0.71 mmol). After the usual workup procedure (without diazomethane treatment), the obtained material was passed through a short column of silica gel (eluent; $CHCl_3$/MeOH=20/1) to afford crude carboxylic acid **2e'** (59.2 mg, major impurities were triphenylphosphine oxide). This material was used for the next reaction without further purification.

To a cooled solution (0 °C) of the crude **2e'** (29.6 mg) in DMF (0.5 ml), was added (*S*)-phenylglycine methyl ester hydrochloride (31.5 mg, 0.16 mmol), diethyl cyanophosphonate (0.036 mL, 0.24 mmol), and Et_3N (0.066 mL, 0.47 mmol). The mixture was stirred at 0 °C for 1hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=3/1) to afford compound **XVa** (35.6 mg, 86% from **1e**, colorless crystal).

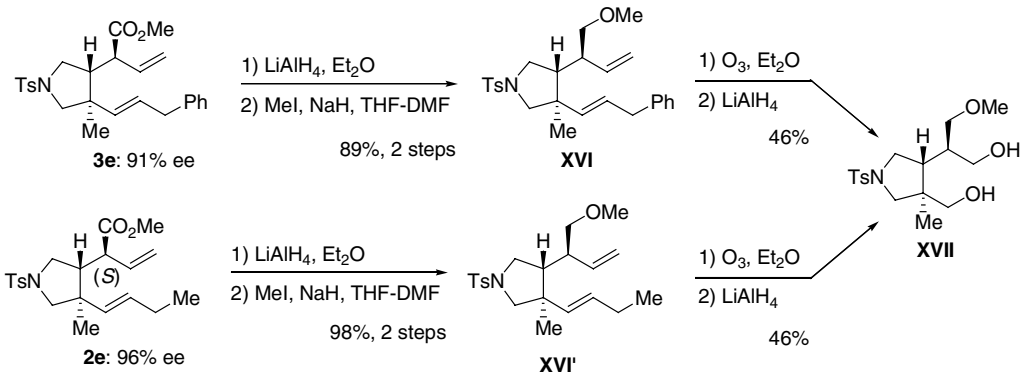
The compound **XVb** was prepare as follows. To a cooled solution (0 °C) of the crude **2e'** (29.6 mg) in DMF (0.5 ml), was added (*R*)-phenylglycine methyl ester hydrochloride (31.5 mg, 0.16 mmol), diethyl cyanophosphonate (0.036 mL, 0.24 mmol), and Et_3N (0.066 mL, 0.47 mmol). The mixture was stirred at 0 °C for 1hr, and then diluted with AcOEt. The organic layer was washed with saturated aqueous solution of $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/AcOEt=3/1) to afford compound **XVb** (35.8 mg, 87% from **1e**, amorphous solid).

Compound XVa. mp 154-155 °C (recryst from hexane/AcOEt); $[\alpha]_D^{24}$ = +50.7 ° (*c* 0.55, $CHCl_3$); IR ($CHCl_3$) 3421, 2961, 2929, 2872, 1740, 1677, 1635, 1598, 1495 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.68 (d, *J* = 8.5 Hz, 2 H), 7.28-7.37 (m, 7 H), 6.63 (d, *J* = 6.8 Hz, 1 H), 5.58 (ddd, *J* = 17.3, 10.2, 9.7 Hz, 1 H), 5.44 (d, *J* = 6.8 Hz, 1 H), 5.34 (dt, *J* = 15.8, 6.8 Hz, 1 H), 5.14 (d, *J* = 15.8 Hz, 1 H), 5.07 (d, *J* = 17.3 Hz, 1 H), 4.98 (d, *J* = 10.2 Hz, 1 H), 3.76 (s, 3 H), 3.57 (dd, *J* = 10.2, 8.8 Hz, 1 H), 3.14 (dd, *J* = 10.2, 10.2 Hz, 1 H), 3.11 (d, *J* = 9.4 Hz, 1 H), 2.89 (dd, *J* = 9.7, 9.1 Hz, 1 H), 2.88 (d, *J* = 9.4 Hz, 1 H), 2.43 (s, 3 H), 2.22-2.30 (m, 1 H), 1.89-1.99 (m, 2 H), 1.04 (s, 3 H), 0.89 (t, *J* = 7.3 Hz, 3 H); ^{13}C NMR (100 MHz,$CDCl_3$) δ 170.80, 170.70, 143.22, 135.90, 135.67, 133.57, 133.50, 131.99, 129.57, 128.82, 128.45, 127.40, 127.00, 117.62, 60.82, 56.46, 52.88, 52.80, 50.70, 47.59, 44.93, 25.74, 21.59, 17.39, 13.53; LR MS (EI, *m/z*) 525 (M^++1), 493, 465, 369; Anal. Calcd for $C_{29}H_{36}N_2O_5S$: C, 66.39; H, 6.92; N, 5.34. Found: C, 66.33; H, 6.89; N, 5.28.

Compound XVb. $[\alpha]_D^{27}$ = -77.6 ° (*c* 1.38, $CHCl_3$); IR (in $CHCl_3$) 3419, 2963, 2933, 2874, 1739, 1677, 1636, 1598, 1494 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.56 (d, *J* = 8.2 Hz, 2 H), 7.32-7.46 (m, 5 H), 7.26 (d, *J* = 8.2 Hz, 2 H), 6.63 (d, *J* = 6.8 Hz, 1 H), 5.63 (ddd, *J* = 17.0, 10.8, 9.7 Hz, 1 H), 5.44 (d, *J* = 6.8 Hz, 1 H), 5.32 (dt, *J* = 15.8, 6.5 Hz, 1 H), 5.14 (d, *J* = 17.0 Hz, 1 H), 5.14 (d, *J* = 15.8 Hz, 1 H), 5.04 (d, *J* = 10.8 Hz, 1 H), 3.71 (s, 3 H), 3.24 (dd, *J* = 10.0, 8.8 Hz, 1 H), 3.09 (d, *J* = 9.3 Hz, 1 H), 2.99 (dd, *J* = 10.2, 10.0 Hz, 1 H), 2.83 (dd, *J* = 10.2, 9.7 Hz, 1 H), 2.84 (d, *J* = 9.3 Hz, 1 H), 2.42 (s, 3 H), 2.14-2.24 (m, 1 H), 1.89-1.98 (m, 2 H), 1.01 (s, 3 H), 0.88 (t, *J* = 7.4 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.90, 170.81, 143.18, 136.07, 135.46, 133.47, 133.45, 132.01, 129.52, 128.96, 128.55, 127.31, 127.17, 117.75, 60.74, 56.49, 52.86, 52.81, 50.53, 47.85, 44.95, 25.74, 21.55, 17.31, 13.53; LR MS (EI, *m/z*) 525 (M^++1), 493, 465, 369; Anal. Calcd for $C_{29}H_{36}N_2O_5S$: C, 66.39; H, 6.92; N, 5.34. Found: C, 66.41; H, 6.93; N, 5.22.

Relative and Absolute configuration of 3e. According to the procedures shown in Scheme S17, compound **3e** was converted to compound **XVII**, whose ^1H NMR spectrum and optical rotation were identical with those of the material independently derived from optically active (2*S*)-**2e**.

Scheme S17.



Preparation of Compound XVI. To a cooled solution (0 °C) of **3e** (91% ee, 72 mg, 0.16 mmL) in Et_2O (3 mL) was added $LiAlH_4$ (15.0 mg, 0.40 mmol). After the mixture was stirred at 0 °C for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added to this. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The filtrate was concentrated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in THF/DMF (3/1, 2 mL) was added NaH (60% dispersion in oil, 32 mg, 0.50 mmol) and MeI (0.098 mL, 1.6 mmol) at 0 °C. After the resulting mixture was stirred at room temperature for 2 hr, saturated aqueous solution of NH_4Cl was added at 0 °C. The aqueous layer was extracted with Et_2O. The combined organic layers were washed with brine, dried over Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/EtOAc=4/1) to afford compound **XVI** (62 mg, 89% from **3e**) as a colorless oil.

Compound XVI. $[\alpha]_D^{22.1}$ = +23.4 ° (*c* 2.06, $CHCl_3$); IR (neat) 3062, 3026, 2975, 2924, 2978, 1636, 1598 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.71 (d, *J* = 8.2 Hz, 2 H), 7.31 (d, *J* = 8.2 Hz, 2 H), 7.25 (dd, *J* = 7.3, 6.6 Hz, 2 H), 7.17 (t, *J* = 7.3 Hz, 1 H), 7.09 (d, *J* = 6.7 Hz, 2 H), 5.51 (ddd, *J* = 17.3, 10.0, 9.6 Hz, 1 H), 5.42 (dt, *J* = 15.8, 6.8 Hz, 1 H), 5.26 (d, *J* = 15.8 Hz, 1 H), 4.90 (d, *J* = 17.3 Hz, 1 H), 4.81 (d, *J* = 10.0 Hz, 1 H), 3.56 (dd, *J* = 10.0, 8.2 Hz, 1 H), 3.26 (d, *J* = 5.6 Hz, 2 H), 3.25 (s, 3 H), 3.19 (d, *J* = 4.7 Hz, 2 H), 3.02-3.12 (m, 3 H), 2.42 (s, 3 H), 2.11-2.21 (m, 1 H), 1.92-2.04 (m, 1 H), 0.86 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.99, 139.86, 138.75, 136.32, 133.95, 129.36, 128.36, 128.23, 128.07, 127.11, 125.76, 115.56, 76.16, 60.73, 59.03, 50.84, 48.13, 45.40, 45.00, 39.21, 21.68, 17.31; LR MS (EI, *m/z*) 439 (M^+), 394, 348, 284; Anal. Calcd for $C_{26}H_{33}NO_3S$: C, 71.04; H, 7.57; N, 3.19. Found C, 70.98; H, 7.45; N, 3.32.

Conversion of Compound XVI to XVII. A solution of **XVI** (60.0 mg, 0.14 mmol) in Et_2O (4 mL) was cooled to -78 °C and treated with a stream of O_3 at -78 °C for 15 min. Then, the mixture was treated with a stream of dry O_2 at –78 °C for 10 min to purge an excess amount of O_3. To the reaction mixture was added $LiAlH_4$ (51.8 mg, 1.4 mmol) at -78 °C and the resulting mixture was slowly wormed to room temperature and stirred at for additional 30 min at the same temperature. To this was added Na_2SO_4•$10H_2O$ at 0 °C and the mixture was stirred at room temperature until excess $LiAlH_4$ was decomposed. The solids were removed by filtration, and then the filtrate was concentrated in vacuo. The residue was purified by silica gel column chromatography ($CHCl_3$/MeOH=20/1) to afford compound **XVII** (20.9 mg, 46%) as colorless viscous oil.

Compound XVII. $[\alpha]_D^{22.0}$ = -16.0 ° (*c* 1.88, $CHCl_3$); IR (neat) 3438, 2926, 2872, 1654, 1597 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.72 (d, *J* = 8.2 Hz, 2 H), 7.32 (d, *J* = 8.2 Hz, 2 H), 3.86 (br.d, *J* = 10.6 Hz, 1 H), 3.74 (br.d, *J* = 10.6 Hz, 1 H),

3.61 (br, 1 H), 3.55 (dd, *J* = 9.1, 9.1 Hz, 1 H), 3.45-3.52 (m, 2 H), 3.39 (d, *J* = 9.4 Hz, 1 H), 3.32-3.41 (m, 2 H), 3.32 (s, 3 H), 3.13 (dd, *J* = 11.1, 9.4 Hz, 1 H), 3.03 (d, *J* = 9.4 hz, 1 H), 2.97 (br, 1 H), 2.47-2.60 (m, 1 H), 2.43 (s, 3 H), 1.53-1.60 (m, 1 H), 0.69 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.09, 133.82, 129.44, 127.18, 76.48, 66.00, 65.01, 59.49, 57.92, 51.08, 45.41, 39.73, 35.73, 21.78, 16.65; LR MS (EI, *m/z*) 355 (M^+-2H), 324 (M^+-H_2O-Me), 306, 202 (M^+-Ts); Anal. Calcd for $C_{17}H_{27}NO_5S$: C, 57.12; H, 7.61; N, 3.92. Found C, 57.14; H, 7.73; N, 3.81.

Preparation of Compound XVI'. To a cooled solution (0 °C) of **2e** (96% ee, 52 mg, 0.13 mmL) in Et_2O (2.5 mL) was added $LiAlH_4$ (12.6 mg, 0.33 mmol). After the mixture was stirred at 0 °C for 30 min, finely powdered Na_2SO_4•$10H_2O$ was slowly added to this. The resulting mixture was stirred at ambient temperature until excess $LiAlH_4$ was decomposed, and then solids were removed by filtration. The filtrate was concentrated in vacuo to afford a crude alcohol.

To a solution of the crude alcohol in THF/DMF (3/1, 2 mL) was added NaH (60% dispersion in oil, 27 mg, 0.67 mmol) and MeI (0.082 mL, 1.33 mmol) at 0 °C. After the resulting mixture was stirred at room temperature for 2 hr, saturated aqueous solution of NH_4Cl was added at 0 °C. The aqueous layer was extracted with Et_2O. The combined organic layers were washed with brine, dried over Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/EtOAc=5/1) to afford compound **XVI'** (49 mg, 98% from **2e**) as a colorless oil.

Compound XVI'. $[\alpha]_D^{21.2}$ = +35.84 ° (*c* 1.42, $CHCl_3$); IR (neat) 3070, 2963, 2929, 2875, 1639, 1597 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71 (d, *J* = 8.2 Hz, 2 H), 7.32 (d, *J* = 8.2 Hz, 2 H), 5.55 (ddd, *J* = 17.3, 10.3, 9.4 Hz, 1 H), 5.30 (dt, *J* = 15.5, 6.2 Hz, 1 H), 5.17 (d, *J* = 15.5 Hz, 1 H), 4.94 (d, *J* = 17.3 Hz, 1 H), 4.92 (d, *J* = 10.3 Hz, 1 H), 3.56 (dd, *J* = 10.0, 8.5 Hz, 1 H), 3.26 (s, 3 H), 3.21 (d, *J* = 5.0 Hz, 2 H), 3.00-3.13 (m, 3 H), 2.44 (s, 3 H), 2.14-2.24 (m, 1 H), 1.90-2.03 (m, 3 H), 0.90 (t, *J* = 7.3 Hz, 3 H), 0.86 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.96, 138.93, 138.89, 133.97, 131.26, 129.35, 127.13, 115.42, 76.19, 60.83, 59.04, 50.87, 48.03, 45.26, 45.00, 25.89, 21.71, 17.40, 13.72; LR MS (EI, *m/z*) 377 (M^+), 362, 332, 304, 222; Anal. Calcd for $C_{21}H_{31}NO_3S$: C, 66.81; H, 8.28; N, 3.71. Found C, 66.85; H, 8.25; N, 3.77.

Conversion of Compound XVI' to XVII. A solution of **XVI'** (48.0 mg, 0.13 mmol) in Et_2O (4 mL) was cooled to -78 °C and treated with a stream of O_3 at -78 °C for 10 min. Then, the mixture was treated with a stream of dry O_2 at –78 °C for 10 min to purge an excess amount of O_3. To the reaction mixture was added $LiAlH_4$ (48.0 mg, 1.3 mmol) at -78 °C and the resulting mixture was slowly wormed to room temperature and stirred at for additional 30 min at the same temperature. To this was added Na_2SO_4•$10H_2O$ at 0 °C and the mixture was stirred at room temperature until excess $LiAlH_4$ was decomposed. The solids were removed by filtration, and then the filtrate was concentrated in vacuo. The residue was purified by silica gel column chromatography ($CHCl_3$/MeOH=20/1) to afford compound **XVII** (20.9 mg, 46%) as colorless viscous oil. The specific optical rotation of this material was as follows: $[\alpha]_D^{21.0}$ = -15.4 ° (*c* 2.20, $CHCl_3$).

References

(1) (a) Takacs, J. M.; Lawson, E. *Organometallics* **1994**, *13*, 4787. (b) Takacs, J. M.; Clement, F.; Zhu, J.; Chandramouli, S. V.; Gong, X. *J. Am. Chem. Soc.* **1997**, *119*, 5804. (c) Takimoto, M.; Mori, M. *J. Am. Chem. Soc.* **2002**, *124*, 10008.

(2) (a) Uozumi, Y.; Kawatsura, M.; Hayashi, T. *Org. Synth.* **2002**, *78*, 1. (b) Uozumi, Y.; Tanahashi, A.; Lee, S.-Y.; Hayashi, T. *J. Org. Chem.* **1993**. *58*, 1945.

(3) Lei, A.; Lu, X. *Org. Lett.* **2000**, *2*, 2357.

(4) Takeuchi, Y.; Itoh, N.; Satoh, T.; Koizumi, T.; Yamaguchi, K. *J. Org. Chem.* **1993**, *58*, 1812.

(5) Nagai, Y.; Kusumi, T. *Tetrahedron Lett.* **1995**, *36*, 1853.