Chiral Bis(oxazoline)copper(II) Complexes as Lewis Acid Catalysts for the Enantioselective Diels-Alder Reaction

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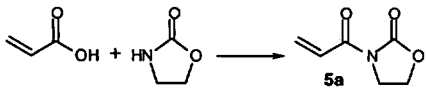
Supporting Information

General. All reactions were carried out under an atmosphere of nitrogen in oven- or flame-dried glassware with magnetic stirring. Solvents were distilled prior to use. Tetrahydrofuran (THF) was distilled from sodium metal/benzophenone ketyl. Dichloromethane (CH_2Cl_2), triethylamine (Et_3N), 1,2-dichloroethane, acetonitrile (CH_3CN), nitromethane (CH_3NO_2) and benzene were distilled from calcium hydride. Cyclopentadiene was distilled by cracking dicyclopentadiene (J. T. Baker) over calcium hydride or anhydrous Na_2SO_4, and was stored over molecular sieves or anhydrous Na_2SO_4 at -10°C for periods of up to one week. Other dienes were distilled immediately prior to use. $Cu(OTf)_2$ was purchased from Aldrich Chemical Co.; $CuCl_2$, $AgBF_4$, $AgPF_6$ and $AgSbF_6$ were purchased from Cerac Inc., Milwaukee. These salts were used without further purification, and stored and handled in an inert atmosphere dry box. Purification of reaction products was carried out by flash chromatography using EM Reagents silica gel 60 (230-400 mesh). Analytical thin layer chromatography was performed on EM Reagent 0.25 mm silica gel 60-F plates. Visualization was accomplished with UV light and aqueous ceric ammonium molybdate or *p*-anisaldehyde solution followed by heating.

Melting points were measured with a Büchi SMP-20 melting point apparatus equipped with an Omega Model 450 AET thermocouple and are uncorrected. Infrared spectra were recorded on a Perkin Elmer 1600 series FT-IR spectrometer. ^1H NMR spectra were recorded on a Bruker AM-300 (300 MHz), AM-400 (400 MHz) or AM-500 (500 MHz) spectrometer and are reported in ppm from internal tetramethylsilane. Data are reported as (br=broad, s=singlet, d=doublet, t=triplet, q=quartet, m=multiplet; integration; coupling constant(s) in Hz; proton assignments). Ambiguous assignments were resolved on the basis of standard one dimensional proton decoupling experiments. ^{13}C NMR spectra were recorded on a Bruker AM-400 (100 MHz) or AM-500 (125 MHz) spectrometer and are reported in ppm from internal tetramethylsilane with solvent resonance employed as the internal standard ($CDCl_3$ at 77.0 ppm). All ^{13}C NMR spectra were obtained with complete proton decoupling. Combustion analyses were performed by Spang Microanalytical Laboratory (Eagle Harbor, MI) and Galbraith Microanalytical Laboratory (Knoxville, TN). High resolution mass spectra were obtained on Jeol AX-505 or SX-102 spectrometers in the Harvard University Mass Spectrometry Laboratory.

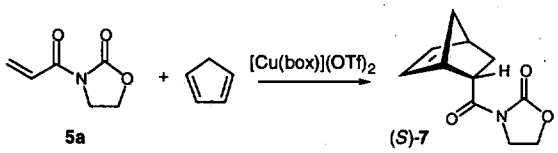
Gas chromatography was performed on a Hewlett Packard 5880A Level 3 gas chromatograph equipped with a split-mode capillary injection system and flame ionization detector using columns specified in the individual experimental. Analytical high performance liquid chromatography (HPLC) was performed on a Hewlett Packard 1090 chromatograph equipped with a diode array UV detector, using the column specified in the individual experimental. Product enantiomer ratios were assayed in two different ways: by HPLC with a Daicel Chiralcel OD or OD-H column, or through GLC analysis with an Astec chiraldex G-TA (γ-cyclodextrin) column as described in the individual experimentals. Bis(oxazoline) ligands **6a-d** were prepared according to published methods.[1] Acrylate imides **5b** and **5c** were prepared according to the method of Evans[2] and have been reported previously.[3]



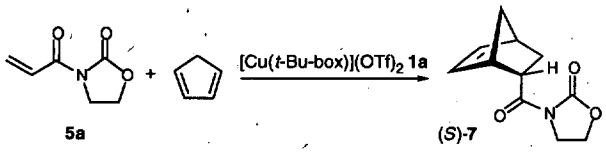
3-(2-Propenoyl)-2-oxazolidinone (5a). A modification of the method of Ho and Mathre was employed.[4] To a solution of freshly distilled acrylic acid (17.2 mL, 250 mmol, 1.25 equiv) in 1.25 L EtOAc at 0 °C was added first triethylamine (35 mL, 250 mmol, 1.25 equiv), followed by acrolyl chloride (20.2 mL, 250 mmol, 1.25 equiv) via syringe over a period of about 2 min. An immediate white precipitate formed. The reaction was stirred at 0 °C for 40 min, then at room temperature for 30 min. The reaction was then filtered through paper, and the filter cake was washed with EtOAc. The resultant cloudy solution was concentrated *in vacuo*. The residue was taken up in 500 mL hexanes and swirled, then filtered and concentrated *in vacuo* again. The anhydride was dissolved in 50 mL THF and immediately used in the following step.

To a suspension of 2-oxazolidinone (17.4 g, 200 mmol, 1.0 equiv) and LiCl (10.6 g, 250 mmol, 1.25 equiv) in 180 mL THF was added triethylamine (35 mL, 250 mmol, 1.25 equiv)*via* syringe, followed by the anhydride

solution *via* cannula, followed by a 20 mL wash. The resulting slurry was stirred at room temperature for 4h. The solvent was removed in vacuo. 500 mL 1N HCl solution was added and extracted 3X with CH_2Cl_2. The combined CH_2Cl_2 layers were washed with 1:1 sat. aq. $NaHCO_3/H_2O$ then brine, then dried over $MgSO_4$, filtered and concentrated *in vacuo*. The resulting oil was loaded onto 100 mL SiO_2, then placed atop a column of 1L SiO_2, and chromatographed with 30% EtOAc/hexanes then 50% EtOAc/hexanes to yield 23.4 g (83%) of the desired product as a white crystalline solid which was pure by NMR analysis, and which exhibited physical characteristics (^1H NMR, ^{13}C NMR, IR) identical to those reported in the literature.[3]



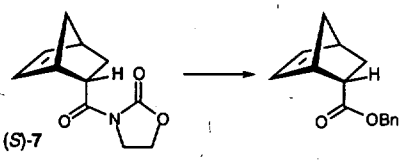
General Procedure for the catalyzed Diels-Alder reaction of 3-(2-propenoyl)-2-oxazolidinone (5a) with cyclopentadiene using catalysts [Cu(box)](OTf)$_2$. Copper(II) triflate (36.1 mg, 0.10 mmol) and ligand **6** (0.11-0.12 mmol) were combined in an inert atmosphere dry box. The sealed flask was then removed from the box and connected to a nitrogen line. Anhydrous CH_2Cl_2 (1.5 to 3 mL) was added, whereupon a green solution was formed within 5 min. The solution was stirred for 2-3 h at ambient temperature. At the end of this time period the solution was checked visually for the presence of colorless, undissolved copper(II) triflate. If present, stirring was continued until all the triflate salt had dissolved, forming a homogeneous but slightly cloudy green solution of the ligand complex, which was then cooled to -78 °C. Longer catalyst aging times (up to 24 h) were not deleterious to the efficacy of the catalyst. 3-(2-Propenoyl)-2-oxazolidinone (**5a**, 141 mg, 1.00 mmol) was then added as a solution in 1 mL of CH_2Cl_2 *via* cannula. Immediately thereafter, cyclopentadiene (250 μL, 3.03 mmol) was added *via* syringe. The resulting solution was stirred at the indicated temperature for the specified amount of time. The reaction mixture was then diluted with 10 mL of 1:1 ethyl acetate/hexane and applied directly to a short column of silica gel (1.5 cm x 1.5 cm) and then eluted with approximately 100 mL of 1:1 ethyl acetate/hexane to remove the copper salts. Concentration afforded the unpurified product which was then analyzed. Purification of (*S*)-**7** was accomplished by chromatography (1.5 cm x 12 cm silica gel, 1:2 ethyl acetate hexane) to afford the known cycloadduct (176-197 mg; 85-95%).[3]



3-[(1*S*, 2*S*, 4*S*)-Bicyclo[2.2.1]hept-5-en-2-ylcarbonyl]-2-oxazolidinone [(*S*)-7]. Imide **5a** (141 mg, 1 mmol) was converted to the cycloadduct (*S*)-**7** (166 mg, 80%, *endo*/*exo* = 98:2, *endo* ee > 98%) according to the General Procedure using catalyst [Cu((*S*,*S*)-*tert*-Bu-box)](OTf)$_2$ (**1a**). The reaction mixture was stirred for 18 h at -78 °C. The product was recrystallized from ether/hexane to afford the pure *endo* adduct: mp 70-71 °C; $[\alpha]_{589}$ -160° (*c* 0.83, $CHCl_3$); IR ($CDCl_3$) 3000, 1780, 1698, 1386, 1230 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 6.22 (dd, 1H, J = 3.1, 5.6 Hz), 5.82 dd, 1H, J=2.8, 5.6 Hz), 4.42-4.35 (m, 2H), 3.99-3.89 (m, 3H) 3.29 (br s, 1H), 2.93 (br s, 1H), 1.96-1.38 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 174.76, 153.4, 138.0, 131.6, 61.9, 50.1, 46.4, 43.2, 42.9, 42.9, 29.6; exact mass calcd for $C_{11}H_{13}N_1O_3$ + Na requires *m/z* 230.0793. found *m/z* 230.0786 (FAB, *m*-nitrobenzyl alcohol, NaI added).

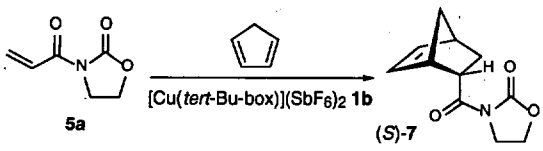
Assay for acrylate-derived cycloadducts (*S*)-7. The unpurified reaction mixture was analyzed as follows: The *endo*/*exo* ratio was determined by ^1H NMR analysis. The *endo* enantiomeric excess (ee) was determined through chiral HPLC analysis using a Daicel OD-H column (flow rate = 1.00 mL/min; 95% hexane, 2% isopropyl alcohol, 3% ethyl acetate), which resolves the four diastereomers of an authentic racemic mixture obtained from a thermally conducted reaction (*exo*$_1$ t_r=35.5 min, *exo*$_2$ t_r=37.0 min, *endo*$_1$ t_r=38.5 min, *endo*$_2$ t_r=44.9 min). In addition, chiral GLC analysis could be employed (chiraldex G-TA column; temperature program: 110 °C 10 min, then 0.4 °C/min to 143 °C; flow rate = 8 psi; *exo*$_1$ t_r = 115.39 min, *exo*$_2$ t_r = 118.70 min, *endo*$_1$ t_r = 122.42 min, endo$_2$ t_r = 123.32 min). The optimized reaction affords the product in >98% ee. The assignment of the absolute configuration of the major product was made by analogy, and confirmed as described below.

Absolute configuration: - General procedure for converting imide cycloadducts to the corresponding benzyl esters: The previously described General Procedure for the conversion of the cycloadduct imides to their corresponding benzyl esters was followed.[2]

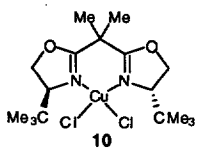


Benzyl (1*S*, 2*S*, 4*S*)-Bicyclo[2.2.1]hept-5-ene-2-carboxylate. To a cooled (-78 °C) solution of benzyl alcohol (120 μL, 1.16 mmol) in 3 mL of THF was added *n*-BuLi (424 μL, 2.0 M in hexane, 0.870 mmol). The resulting solution was stirred for 5 min and a solution of imide (*S*)-**7** (120 mg, 0.58 mmol, 95% ee)) in THF (1.25 mL) was added *via* cannula. The solution was warmed to 0 °C and stirred for 3.5 h, over which time it became cloudy. The reaction mixture was then poured into 50 mL of saturated NH_4Cl solution, and extracted with two 50-mL portions of CH_2Cl_2. The combined organic layers were washed with 100 mL of brine, dried over Na_2SO_4 and concentrated. Purification by chromatography (1.5 cm x 10 cm silica, 20% ethyl acetate/hexane) afforded 95 mg (72%) of the desired benzyl ester, which possessed the same absolute configuration as an authentic sample: $[\alpha]_{589}$ -109° (*c* 1.00, $CHCl_3$); (lit. $[\alpha]_{589}$ -129° (*c* 1.37, $CHCl_3$).[3]

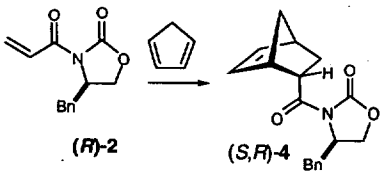
General procedure for the screening of 6d-M(OTf)$_n$ complexes in the catalytic Diels-Alder reaction (Table 2). The metal salt (0.1 mmol), bis(oxazoline) ligand **6d** (0.12 mmol), and CH_2Cl_2 (2 mL) were stirred at room temperature for 3 h to generate the active catalyst. In all instances except $Mn(OTf)_2$ and $Co(OTf)_2$ the catalyst mixtures were heterogeneous. $Co(OTf)_2$, $Lu(OTf)_3$, $Mn(OTf)_2$ were made by treatment of the corresponding oxides with triflic acid. In the case of $Zn(OTf)_2$, complexation was conducted additionally in acetonitrile for 3 h. The solvent was then removed by high vacuum, and CH_2Cl_2 was added. Acrylate **5a** (1 mmol) was then added as a solution in CH_2Cl_2 (1 mL) at -78°C, followed by cyclopentadiene (0.66 mL, 8 mmol). The reactions were allowed to warm up to room temperature, and after 24 h the standard workup procedure and the above analysis and characterization procedures were performed.



General Procedure for the catalyzed Diels-Alder reaction of 3-(2-propenoyl)-2-oxazolidinone (5a) with cyclopentadiene using catalyst [Cu((*S*,*S*)-*tert*-Bu-box)](SbF$_6$)$_2$ (1b). Copper(II) chloride (13.4 mg, 0.10 mmol), ligand **6d** (32.4 mg, 0.11 mmol) and $AgSbF_6$ (68.7 mg, 0.2 mmol) were combined in an inert atmosphere dry box. The sealed flask was removed from the box and connected to a nitrogen line. Anhydrous CH_2Cl_2 (1 mL) was added, and the flask was wrapped in alumina foil to protect the reaction mixture from light. The heterogeneous mixture was vigorously stirred for 6-8 h at ambient temperature. At the end of this time period the mixture was filtered through a short column of Celite (rinsed with 0.2 mL of CH_2Cl_2) to give a clear, dark blue solution of [Cu((*S*,*S*)-*tert*-Bu-box)](SbF$_6$)$_2$ (**1b**), which was cooled to -78 °C. 3-(2-Propenoyl)-2-oxazolidinone (**5a**, 141 mg, 1.00 mmol) was added as a solution in 1 mL of CH_2Cl_2 *via* cannula. Immediately thereafter, cyclopentadiene (0.83 mL, 10 mmol) was added *via* syringe. The resulting solution was stirred at the indicated temperature for the specified amount of time. Work-up and purification were analogous to the procedure using catalyst **1a** (X = OTf).

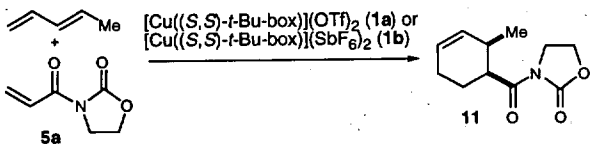


[Cu((*S*,*S*)-*tert*-Bu-box)]Cl$_2$ (10). The complex was synthesized by heating a mixture of $CuCl_2$ and a two-fold excess of ligand **6d** in a sealed tube in a drybox for 6 h. The resulting mixture was then cooled, and the undissolved metal salt was allowed to settle out. The supernatant (2 mL) was drawn off and placed into a test tube, and a layer of hexane (2 mL) was placed carefully on top of the ligand solution. After 2 days, green crystals were deposited, and one was selected for X-ray analysis.

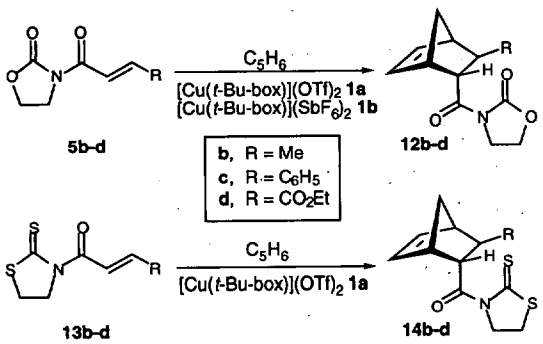


Double Stereodifferentiating reactions employing the chiral imides (*R*)- and (*S*)-2 and 6-Cu(OTf)$_2$ complexes. (4*R*)-Phenylmethyl-3-[(1*S*, 2*S*, 4*S*)-bicyclo[2.2.1]hept-5-en-2-ylcarbonyl]-2-oxazolidinone ((*S*,*R*)-4). To a -78 °C solution of catalyst **1a** (X = OTf) (0.10 mmol based on $Cu(OTf)_2$; prepared as described in the General Procedure above) was added acrylate imide (*R*)-**2** (231 mg, 1.00 mmol) as a solution in CH_2Cl_2 (1 mL) *via* cannula, followed by cyclopentadiene (220 μL, 2.67 mmol). The reaction mixture was stirred at -78 °C for 11 h, after which time TLC analysis indicated that the reaction was complete. The reaction mixture was diluted with 10 mL of 40% ethyl acetate/hexane, applied directly to a short silica gel column (1.5 cm x 1.5 cm) and eluted with 100 mL of 40% ethyl acetate/hexane. Concentration

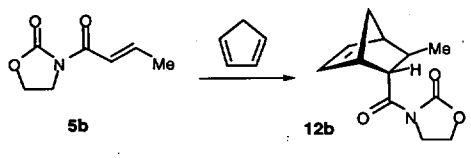
afforded the unpurified product, which was analyzed by GLC according to a modification of the published procedure[7] (30 m DB-5, oven temp = 185 °C; *endo*1 t_r= 14.48 min, *exo*1 t_r=14.76, *exo*2 t_r=14.96, *endo*2 t_r=15.53) showed >95% conversion, and *endo*2 as the major product in a 99:1 ratio with the minor product as one of the *exo* products; *endo*1 was not detected. The reaction mixture was purified by flash chromatography to afford 249 mg (84%) of the title compound as a white crystalline solid: mp 117-118 °C; $[\alpha]_D$ -174° (*c* 2.49, $CHCl_3$); (lit. for the enantiomer $[\alpha]_{589}$ +175° (*c* 1.57, $CHCl_3$)[7]; IR (CH_2Cl_2) 3000, 1778, 1697, 1383, 1236, 1199 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.30 (m, 5H), 6.32 (dd, 1H, J=3.0, 6.2 Hz), 5.94 (dd, 1H, J=3.0, 6.2 Hz), 4.64 (m, 1H), 4.21-4.01 (m, 3H), 3.43 br s, 1H), 3.27 (dd, 1H, J=3.2, 13.3 Hz), 2.99 (br s, 1H), 2.70 (dd, 1H, J= 9.9, 13.2 Hz), 2.00-1.40 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.5, 153.3, 138.3, 135.4, 131.4, 129.4, 128.9, 127.3, 66.1, 55.4, 50.2, 46.6, 43.5, 43.0, 38.1, 29.5; exact mass calcd for $C_{18}H_{19}N_1O_3$ + Na requires *m/z* 320.1263. found *m/z* 320.1277 (FAB, *m*-nitrobenzyl alcohol, NaI added). The procedure described above was conducted for imide (*S*)-**2**. GLC analysis showed the reaction to have proceeded to <20% conversion. The *endo* cycloadducts were formed in a 68:32 ratio, with *endo*1 ((*R*,*S*)-**4**) appearing as the major product.



Comparison of [Cu(*tert*-Bu-box)(H_2O)n]X_2 complexes in the Diels-Alder of imide 5a with piperylene. 3-[(1*S*,2*R*)-2-Methylcyclohex-3-en-1-ylcarbonyl]-2-oxazolidinone (11).[5] In the cases of complexes **1a** (X = OTf) and **1b** (X = SbF6), the catalyst solution (0.05 M, 1.0 mL, 0.05 mmol, 0.1 equiv) was added to a solution of the imide **2** (71 mg, 0.5 mmol) in 0.5 mL of CH_2Cl_2. The piperylene (0.5 mL, 5 mmol, 10 equiv) was then added. The reaction was stirred at room temperature for the indicated time (15 h for complex **1a**, and 50 min for complex **1b**). Product isolation was accomplished by addition of 5 mL of EtOAc, and the resulting solution was loaded onto a silica gel column, and eluted with EtOAc. After concentration, the residue was analyzed for conversion by NMR spectroscopy, and for selectivity by GLC analysis [Chiraldex G-TA column; oven temp = 145 °C, flow rate = 10 psi; $endo_{major}$ t_r = 43.91 min, $endo_{minor}$ t_r = 43.11 min; retention times for the other three sets of racemic diastereomers: 30.64, 33.60; 37.13, 37.57; 40.23, 42.47]. In the case of the bis(aquo) complexes **10a** and **10b**, imide **2** and the catalyst (0.05 mmol) were mixed together, and 1.5 mL of CH_2Cl_2 was added, followed by the piperylene. When 3Å molecular sieves were employed, the catalyst and molecular sieves (0.1–0.2 g) were stirred together for 150 min in 1.5 mL of CH_2Cl_2, followed by addition first of the imide then of the piperylene.



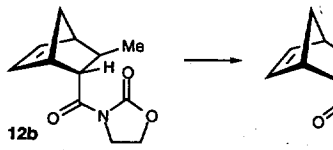
General Procedure for the Catalyzed Diels-Alder Reaction of Substrates 5b-c, 13b-c. Catalyst solutions were prepared according to the General Procedures described above for reactions of imide **5a**. The solution of the copper(II) complex was cooled to -78 °C, and the dienophile (1 mmol) was added as a solution in 1 mL of CH_2Cl_2, followed immediately by cyclopentadiene (0.83 mL, 10 mmol). After the addition of cyclopentadiene at -78 °C, the reaction mixture was maintained at the indicated temperature for the specified time (see individual substrates). The reaction mixture was diluted with 1:1 ether/ethyl acetate (3 mL) and filtered through a small column of silica gel (1 cm X 2 cm) to remove copper salts. The silica gel was washed repeatedly with ether (3 X 20 mL) to ensure complete elution of the product. Analysis of the unpurified reaction mixtures was performed as described for the individual substrates below. Silica gel chromatography afforded the pure Diels-Alder adducts.



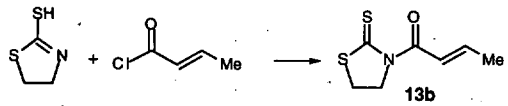
3-[[(1*S*,2*S*,3*R*,4*R*)-3-Methylbicyclo[2.2.1]hept-5-en-2-yl]carbonyl]-2-oxazolidinone (12b). Imide **5b** (23.59 g, 152 mmol) was converted to the cycloadduct **12b** (33.52 g, 99%, *endo*/*exo* = 85:15, *endo* ee = 99%) according to the General Procedure using catalyst **1b** (X = SbF_6), prepared by stirring $CuCl_2$ (1.73 g, 12.9 mmol), ligand **6d** (4.18 g, 14.2 mmol) and $AgSbF_6$ (8.89 g, 25.8 mmol) in 130 ml of CH_2Cl_2 for 8 h at ambient temperature. Data for the *endo* isomer: $[\alpha]_{589}$ -209° (*c* 0.5, $CHCl_3$); IR ($CHCl_3$) 1775, 1695 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 6.43 (dd, 1H, J = 3.4, 5.4 Hz), 5.78 (m, 1H), 4.45-4.35 (m, 2H), 4.05-3.85 (m, 2H) 3.55 (m, 1H), 3.28 (s, 1H), 2.52 (s, 1H), 2.10

(m, 1H), 1.70 (d, 1H, J = 8.5 Hz) 1.48 (d, 1H, J = 8.5 Hz) 1.13 (d, 3H, J = 7.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.4, 142.5, 128.6, 120.0, 50.9, 40.4, 38.6, 36.5, 36.1, 32.0, 25.5, 9.4; exact mass calcd for $C_{12}H_{15}N_1O_3$ requires *m/z* 221.2560. found *m/z* 221.2554 (EI).

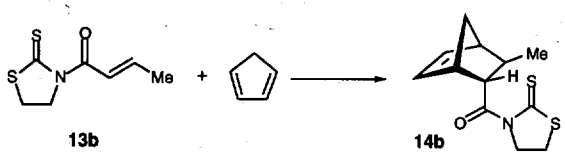
Assay for crotonate-derived cycloadducts 12b. The *endo* ee was determined by HPLC Analysis using a Daicel OD-H column (flow rate = 1.15 mL/min; 94.2% hexane, 2.9% isopropyl alcohol, 2.9% ethyl acetate), which resolves the four diastereomers of an authentic racemic mixture obtained from a thermally conducted reaction (*exo* products t_r=18.8 min, *endo*1 t_r=20.5 min, *endo*2 t_r=23.0 min). The optimized reaction yields a 99.5:0.5 enantioselectivity (99% ee). The assignment of the absolute configuration of the major product was made by correlation to the derived benzyl ester (see below).



Assignment of the absolute configuration of adduct 12b: Benzyl (1*S*,2*S*,3*R*,4*R*)-3-methylbicyclo[2.2.1]hept-5-en-2-carboxylate. Imide **12b** (13.3 mg, 0.06 mmol) was converted to the corresponding benzyl ester as described in the General Procedure to afford 13.7 mg of the pure *endo* benzyl ester (90%) which posessed the same absolute configuration as an authentic sample: $[\alpha]_{589}$ -129° (*c* 1.2, $CHCl_3$); (lit $[\alpha]_{589}$ = -130° (*c* 2.14, $CHCl_3$)).[2]

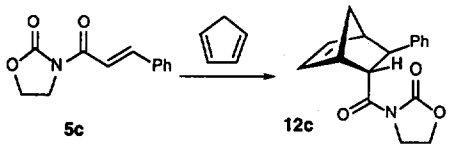


3-((*E*)-2-Butenoyl)-2-thiazolidinethione (13b). Triethylamine (10.0 mL, 71.7 mmol) was added dropwise to a cooled (-78 °C), rapidly stirred solution of 1,3-thiazolidine-2-thione (7.8 g, 65 mmol) and crotonoyl chloride (6.23 mL, 65 mmol) in CH_2Cl_2 (100 mL). The reaction mixture instantly became bright yellow, then turned orange, and a precipitate formed. Stirring was continued for 30 min at -78 °C and 30 min at 0 °C. The mixture was diluted with ether (200 mL) and washed with saturated $NaHCO_3$ (1 X 100 mL) and water (1 X 100 mL). Drying (Na_2SO_4), filtration and concentration afforded a brown oil which was purified by column chromatography on silica gel (30% ethyl acetate/hexane) to yield 8.26 g of **13b** as a bright yellow liquid (44.1 mmol, 68%). Slight decomposition of the product was noted upon chromatography, and the material was used immediately or else stored at -15 °C: IR ($CHCl_3$) 1729, 1684, 1636 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.22 (d, 1H, J = 17.5 Hz), 7.00 (m, 1H), 4.50 (t, 2H, J = 3 Hz), 3.28 (t, 2H, J = 4.9 Hz), 1.90 (d, 3H, J= 6.9 Hz). ^{13}C NMR (125 MHz, $CDCl_3$) δ 201.6, 167.0, 145.0, 124.7, 56.0, 29.0, 18.4; exact mass calcd for $C_7H_9N_1O_1S_2$ requires *m/z* 187.0126. found *m/z* 187.0128 (EI).



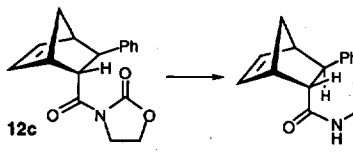
3-[[(1*S*,2*S*,3*R*,4*R*)-3-Methylbicyclo[2.2.1]hept-5-en-2-yl]carbonyl]-2-thiazolidinethione (14b). Imide **13b** (187 mg, 1 mmol) was converted to the cycloadduct **14b** (207 mg, 82%, *endo*/*exo* = 96:4, *endo* ee = 94%) according to the General Procedure using catalyst **1a** (X = OTf). The reaction mixture was stirred for 36 h at -45 °C. Recrystallization of the crude product afforded the pure *endo* adduct (>99% *endo*) as light yellow needles. mp 107-108 °C; $[\alpha]_{589}$ -284.6° (*c* 0.85, $CHCl_3$); IR ($CHCl_3$) 1699 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.45-6.35 (m, 1H), 5.80 (m, 1H,), 4.6-4.4 (m, 2H) 4.38 (m, 1H), 3.38 (s, 1H), 3.35-3.15 (m, 2H), 2.53 (s, 1H), 1.63 (d, 1H, J= 8.7 Hz), 1.44 (d, 1H, J= 6.2 Hz), 1.13 (d, 3H, J = 7 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 201.4, 176.4, 139.9, 131.0, 56.9, 52.9 49.6, 47.5, 46.8, 38.0, 28.2, 20.4; exact mass calcd for $C_{12}H_{15}N_1O_1S_2$ requires *m/z* 253.0595. found *m/z* 253.0605 (EI).

Assay for crotonate-derived cycloadduct 14b. Adduct **14b** was converted to the oxo-analog **12b** as follows: *n*-BuLi (67 μL, 0.14 mmol, 2.09 M in hexane) was added to a solution of 2-oxazolidinone (12 mg, 0.14 mmol) in THF (1 mL) at -78 °C. The mixture was warmed to 0 °C and stirred for 15 min. Unpurified cycloadduct **14b** (20 mg, 0.07 mmol) was added as a solution in 1 mL of THF, and the bright yellow color of **14b** gradually faded over the course of 15 min. The mixture was stirred for an additional 5 h at room temperature, diluted with ethyl acetate (5 mL), washed with saturated aqueous $NaHCO_3$ (1 X 20 mL), dried ($MgSO_4$), filtered, and concentrated. Purification as described for the imide **12b** above yielded 14.7 mg of product (95%). This material was then assayed as specified for **12b** above and found to be of 97:3 optical purity (94% ee).

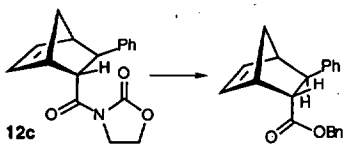


3-[[(1*S*,2*R*,3*R*,4*R*)-3-Phenylbicyclo[2.2.1]hept-5-en-2-yl]carbonyl]-2-oxazolidinone (12c). Imide **5c**[3] (217 mg, 1 mmol) was converted to the cycloadduct **12c** (272 mg, 96%, *endo*/*exo* = 81:19, *endo* ee = 96%) according to the General Procedure using catalyst **1b** (X = SbF_6). Data obtained for the *endo* isomer obtained from the *endo*/*exo*-mixture: IR ($CHCl_3$) 1770, 1696 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.30-7.15 (m, 5H), 6.51 (dd, 1H), 5.91 (dd, 1H), 4.40-4.30 (m, 2H), 4.18 (m, 1H), 4.00-3.93 (m, 2H), 3.46 (s, 1H), 3.34 (m, 1H), 2.99 (s, 1H), 1.94 (d, 1H), 1.57 (d, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 173.9, 153.4, 143.8, 140.2, 132.19, 128.5, 127.6, 126.1, 61.9, 50.3, 49.8, 48.1, 47.5, 47.0, 43.0; exact mass calcd for $C_{17}H_{17}N_1O_3$ requires *m/z* 283.1208. found *m/z* 283.1167 (EI).

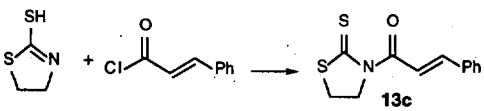
Assay for cinnamate-derived cycloadducts 12c and 14c. The enantiomeric excess of the cycloadducts **12c** and **14c** was determined by conversion to the diastereomeric amides, followed by HPLC analysis. Execution of the transamination procedures described below on racemic samples showed in each case two sets of racemic diastereomers, indicating that kinetic resolution was not occurring in the transamination reaction. Chiralcel OD column, eluent hexane/i-PrOH/ethyl acetate 95:2:3, flow rate = 1.1 mL/min *exo* products elute at t_r = 16-19 min *endo*1 t_r = 20.2 min *endo*2 t_r = 26.6 min.



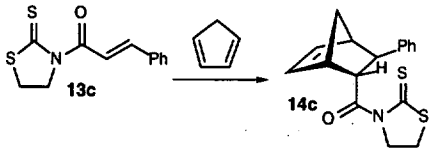
Procedure for the conversion of cycloadduct 12c to the corresponding diastereomeric amides. An adaptation of Weinreb's procedure[6] was employed. Trimethylaluminum (0.5 mL, 1.0 mmol, 2.0 M in hexane) was added dropwise to a solution of (R)-(+)-α-methylbenzylamine (129 μL, 1.0 mmol) in 1,2-dichloroethane (2 mL) at 0 °C. The resulting solution was warmed to room temperature and stirred for 15 min. Diels-Alder adduct **12c** (28.3 mg, 0.1 mmol) was added as a solution in 1,2-dichloroethane (2 mL). The reaction mixture was heated at reflux for 12 h. TLC showed clean formation of product. The reaction mixture was cooled and diluted with ethyl acetate (20 mL), washed with ice-cold 4 N HCl (2 X 50 mL), saturated aqueous $NaHCO_3$ (1 X 50 mL), dried (Na_2SO_4), filtered, and concentrated to afford a fluffy white solid (22 mg, 0.08 mmol). Nonrecrystallized material was assayed for optical purity by HPLC. Recrystallized amide was then assayed at >99% de under the same conditions. Physical data for the major amide diastereomer: **(1*S*,2*R*,3*R*,4*R*)-*N*-[(α*R*)-α-Methylbenzyl]-3-phenylbicyclo[2.2.1]hept-5-en-2-carboxamide.** mp 170-171 °C; $[\alpha]_{589}$ -66.9° (*c* 1.0, $CHCl_3$); IR 1670 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.40-7.15 (m, 11H), 6.45 (m, 1H), 6.18 (m, 1H), 5.61 (d, 1H), 5.13 (m, 1H), 3.18 (s, 1H), 3.04 (m, 2H, J = 3.4 Hz), 2.80 (m, 1H), 1.82 (d, 1H, J = 8.5 Hz), 1.63 (d, 1H, J = 8.5 Hz), 1.48 (d, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.5, 144.5, 143.4, 138.8, 134.3, 128.7, 128.6, 127.4, 127.3, 126.2, 126.1, 54.1, 48.8, 48.6, 47.8, 46.7, 21.8; exact mass calcd for $C_{22}H_{23}N_1O_1$ requires *m/z* 317.1779. found *m/z* 317.1763 (EI).



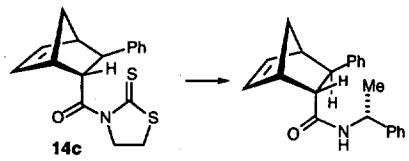
Assignment of the absolute configuration of cycloadduct 12c. Benzyl (1*S*,2*S*,3*R*,4*R*)-3-phenylbicyclo[2.2.1]hept-5-en-2-carboxylate. The *endo* imide Diels-Alder adduct **12c** was converted to the corresponding benzyl ester as described in the General Procedure to afford the pure *endo* product of known absolute configuration: $[\alpha]_{589}$ -116° (*c* 1.0, $CHCl_3$); (lit $[\alpha]_{589}$ = +121° (*c* 1.33, $CHCl_3$) for the opposite enantiomer).[2]



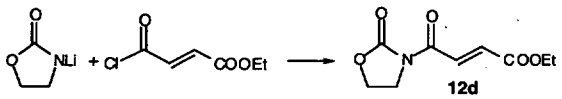
3-((*E*)-3-Phenyl-2-propenoyl)-2-thiazolidinethione (13c). Triethylamine (7.7 mL, 55 mmol) was added dropwise to a cooled (-78°C), rapidly stirred solution of 1,3-thiazolidine-2-thione (6.0 g, 50 mmol) and cinnamoyl chloride (4.8 g, 50 mmol) in CH_2Cl_2 (100 mL). The reaction mixture became bright yellow, then orange, and a precipitate formed. Stirring was continued for 30 min at -78 °C and 30 min at 0 °C. The mixture was diluted with ether (100 mL) and washed with saturated $NaHCO_3$ (1 X 200 mL) and water (1 X 200 mL). Drying (Na_2SO_4), filtration, and concentration afforded an orange solid which was purified by column chromatography on silica gel (25% ethyl acetate/hexane) to yield 7.5 g (60%) of **13c** as a bright yellow solid which was stored at -15 °C: mp 80-83 °C; IR ($CHCl_3$) 1678, 1616, 1577 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.88 (d, 1H, J = 16 Hz), 7.70 (d, 1H, J = 16 Hz), 7.60-7.50 (m, 2H), 7.41-7.33 (m, 3H), 4.62-4.53 (t, 2H, J = 7 Hz), 3.40-3.30 (t, 2H, J = 7 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 201.8, 167.7, 144.1, 134.8, 130.5, 128.91, 128.5, 120.0, 56.0, 29.1; exact mass calcd for $C_{12}H_{11}N_1O_1S_2$ requires *m/z* 249.0282. found *m/z* 249.0277 (EI).



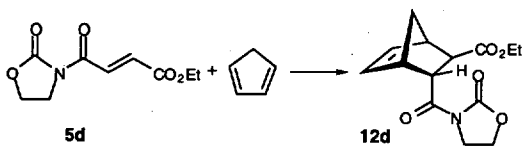
3-[[(1*S*,2*R*,3*R*,4*R*)-Phenylbicyclo[2.2.1]hept-5-en-2-yl]carbonyl]-2-thiazoli-dinethione (14c). Imide **13c** (249 mg, 1 mmol) was converted to the cycloadduct **14c** (271 mg, 86%, *endo*/*exo* = 92:8, *endo* ee = 97%) according to the General Procedure using catalyst **1a** (X = OTf). The reaction mixture was stirred for 72 h at -35 °C. Recrystallization afforded the pure *endo* adduct (>98% *endo*) as light yellow needles: mp 120-121°C; $[\alpha]_{589}$ -191.6° (*c* 1.0, $CHCl_3$); IR ($CHCl_3$) 1696 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.53-7.15 (m, 5H), 6.57-6.53 (m, 1H), 5.98-5.93 (m, 1H), 5.18 (dd, 1H, J = 4, 5 Hz) 4.56-4.48 (m, 2H) 3.6 (s, 1H), 3.32 (m, 1H), 3.3-3.1 (m, 2H), 2.98 (s, 1H), 1.87-1.80 (d, 1H, J = 8.7 Hz), 1.55-1.49 (d, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 201.8, 175.7, 143.7, 140.3, 132.2, 128.5, 127.7, 126.1, 56.8, 51.1, 50.3, 48.6, 47.6, 47.5, 28.1; exact mass calcd for $C_{17}H_{17}N_1O_1S_2$ requires *m/z* 315.0752. found *m/z* 315.0745 (EI).



Procedure for the conversion of cycloadducts 14c to the corresponding diastereomeric amides. A mixture of Diels-Alder adduct **14c** (31.7 mg, 0.1 mmol), (*R*)-(+)-α-methylbenzylamine (>98% ee, 129 μL, 1 mmol), CH_2Cl_2 (2 mL), and 4-(dimethylamino)pyridine (5 mg, 0.04 mmol) was heated at reflux for 12 h. The resulting solution was cooled, diluted with ethyl acetate (2 mL), and washed with ice-cold 4 N HCl (2 X 4 mL), and saturated aqueous $NaHCO_3$ (1 X 4 mL), dried (Na_2SO_4) and concentrated. Filtering through silica gel yielded a fluffy white solid, which could be purified by recrystallization from hexane/ethyl acetate to afford the desired amide (25 mg, 0.08 mmol, 80%). Nonrecrystallized material was assayed for optical purity by HPLC with the Chiralcel OD column as described above and was found to possess 97% de.



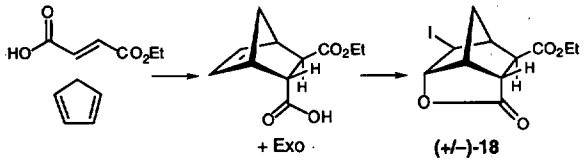
3-[(*E*)-3-(Ethoxycarbonyl)propenyl]-2-oxazolidinone (12d). To a cooled (-78 °C) suspension of 2-oxazolidinone (6.09g, 69.4 mmol) in 250 ml of THF was added *n*-BuLi (36.0 mL, 69.4 mmol, 1.93 M in hexane). The suspension was stirred at -78 °C for 30 min and at 0 °C for 20 min. The suspension was recooled to -78 °C and fumaryl chloride monoethyl ester (11.28 g, 69.4 mmol, freshly prepared from fumaric acid monoethyl ester) was added. The solution was warmed to room temperature, stirred for 4 h, and then quenched by addition of 200 mL of saturated NH_4Cl solution. The layers were separated and the aqueous layer was extracted with two 200 mL portions of ethyl acetate. The combined organic layers were washed with 200 mL of brine, dried over $MgSO_4$, filtered, and concentrated. Purification by flash chromatography (6 cm x 28 cm silica gel, 50% ethyl acetate/hexane) afforded 11.69 g (79%) of the product **12d** as a white solid, which was recrystallized from ethyl acetate/hexane: mp = 62 °C; IR (CH_2Cl_2) 3000, 1785, 1688, 1387, 1360, 1302, 1270, 1200 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) 8.12 (d, 1H, J=15.5 Hz), 6.93 (d, 1H, J=15.5 Hz), 4.47 (t, 2H, J=8.1Hz), 4.25 (q, 2H, J=7.1 Hz), 4.09 (t, 2H, J=7.9 Hz), 1.31 (t, 3H, J=7.1Hz); ^{13}C NMR (100 MHz, $CDCl_3$) 164.8, 163.8, 153.0, 134.4, 131.7, 62.3, 61.4, 42.6, 14.1; exact mass calcd for $C_9H_{11}O_5N_1$ + Na *m/z* 236.0535. found *m/z* 236.0540 (FAB, *m*-nitrobenzyl alcohol, NaI added).



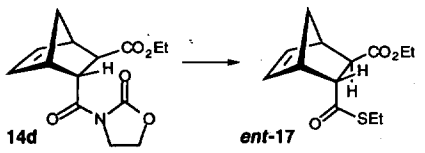
Ethyl (1*R*,2*R*,3*R*,4*S*)-3-[(2-oxo-3-oxazolidinyl)carbonyl] bicyclo[2.2.1]hept-5-ene-2-carboxylate (12d). The catalyst solutions was prepared according to the General Procedure described above. Only 5 mol% catalyst **1a** (X = OTf) was employed for fumarate-derived substrates. Imide **12d** (213 mg, 1.00 mmol) was then added as a solution in 1 mL of CH_2Cl_2 *via* cannula at -55 °C. Immediately thereafter, cyclopentadiene (400 μL, 4.85 mmol) was added *via* syringe. The resulting solution was stirred at -55 °C for 20 h. The reaction mixture was then diluted with 10 mL of 1:1 ethyl acetate/hexane, applied directly to a short column of silica gel (1.5 cm x 1.5 cm), eluted with approximately 100 mL of 1:1 ethyl acetate/hexane, and concentrated to afford the unpurified product. The *endo*/*exo* ratio was shown by ^1H NMR to be 94:6. The *endo* and *exo* isomers were not readily separable by flash chromatography. Chromatography (1.5 cm x 12 cm silica gel, 40% ethyl acetate/hexane) provided 256 mg (92%) of the mixture of *endo* and *exo* cyloadducts. Data for the *endo* isomer obtained from the mixture: ^1H NMR (400 MHz, $CDCl_3$) δ 6.35 (dd, 1H, J=3.1, 5.0 Hz), 5.90 (dd, 1H, J=2.8, 5.6 Hz), 4.42 (t, 1H, J=8.2 Hz),

4.34 (dd, 1H, J=3.5, 4.7 Hz), 4.17-3.90 (m, 4H), 3.43 (br s, 1H), 3.19 (br s, 1H), 2.88 (dd, 1H, J=1.7, 4.8 Hz), 1.74 (br d, 1H, J=8.8 Hz), 1.49 (m, 1H), 1.25 (t, 3H, J=7.1 Hz); exact mass calcd for $C_{14}H_{17}O_5N_1$ + Na requires *m/z* 302.1004. found *m/z* 302.0992 (FAB, *m*-nitrobenzyl alcohol, NaI added).

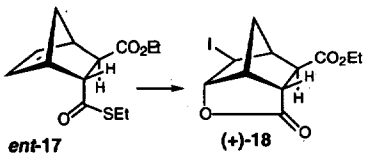
Assay for cycloadduct 12d. The ee of the cycloadducts derived from the catalytic reactions of fumarate **5d** was determined by conversion to iodolactone **18**. The enantiomers of a racemic mixture were resolved by chiral GLC analysis using the chiraldex G-TA column (oven temp = 150 °C, flow rate = 15 psi; t_r for the (–)-**18** = 78.20 min, t_r for the (+)-**18** = 88.93 min; *vide infra* for assignments).



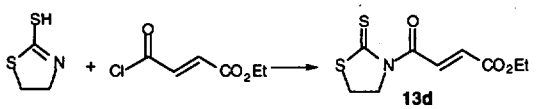
Synthesis of racemic iodolactone standards. Ethyl hexahydro-6-iodo-2-oxo-3,5-methano-2*H*-cyclopenta[*b*]furan-7-carboxylate (+/–)-18. Fumaric acid monoethyl ester (1.0 g, 6.94 mmol) and cyclopentadiene (2.00 mL, 24.2 mmol) were dissolved in CH_2Cl_2 (20 mL), and stirred at room temperature for 20 h. The reaction mixture was extracted with three portions of saturated $NaHCO_3$ solution. The organic layer was discarded and the combined aqueous layers were poured into a seperatory funnel containing 10 g of ice, and subsequently acidified to pH = 1 using concentrated HCl. The aqueous layer was then extracted with 4 80 mL portions of ethyl acetate, with NaCl added to the aqueous layer between each extraction. The combined organic layers were washed with 100 mL of brine, dried over Na_2SO_4, filtered, and concentrated to afford 1.48 g (quantitative yield) of the desired cycloadducts as a 1:1 mixture of *exo* and *endo* acids (^{1}H NMR). Without further purification, 1.25 g (approx. 5.95 mmol) of the mixture was dissolved in 15 mL of CH_3CN, cooled to 0 °C and I_2 (4.53 g, 19.9 mmol) was added. The resulting deep purple mixture was stirred for 24 h at 0 °C in the dark. The mixture was diluted with 50 mL of Et_2O, and treated with 50 mL of saturated $NaHCO_3$. The organic layer was separated and washed with 100 mL of 1N $Na_2S_2O_3$ which produced clear aqueous and organic layers. The organic layer was washed with 100 mL of H_2O, 100 mL of brine, dried over Na_2SO_4, filtered and concentated. Purification of the residue by flash chromatography (1.5 cm x 12 cm silica gel, 15% ethyl acetate/hexane) afforded 700 mg (35% based on *endo* and *exo* isomers; approx. 70 % based on *endo*) of racemic **18** as an amorphous white solid which was pure by ^{1}H NMR: TLC: R_f 0.35 (20% ethyl acetate/hexane); IR ($CHCl_3$) 3000, 1781, 1731, 1464, 1347, 1300, 1243, 1213cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.13 (d, 1H, J=5.0 Hz), 4.21-4.16 (m, 2H), 3.89 (d, 1H, J=2.5 Hz), 3.21 (m, 1H), 3.10 (m, 1H), 3.02 (br s, 1H), 2.83 (br s, 1H), 2.32 (br d, 1H, J=13.8 Hz), 1.96 (br d, 1H, J=16.2 Hz), 1.29 (t, 3H, J= 7.2 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 177.2, 170.1, 88.4, 61.9, 50.6, 50.4, 46.1, 40.9, 35.0, 28.0, 14.1; exact mass calcd for $C_{11}H_{13}O_4I_1$ + Na *m/z* 358.9758. found *m/z* 358.9771 (FAB, *m*-nitrobenzyl alcohol, NaI added). The enantiomers of the racemic mixture were resolved by chiral GLC analysis using the chiraldex G-TA column (oven temp = 150 °C, flow rate = 15 psi; t_r for the (–)-**18** = 78.20 min, t_r for the (+)-**18** = 88.93 min; *vide infra* for assignments).



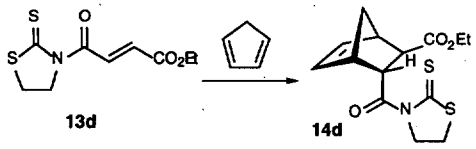
***O,S*-Diethyl (1*S*,2*R*,3*R*,4*R*)-2-thiobicyclo[2.2.1]hept-5-ene-2,3-dicarboxylate (*ent*-17).** To a cooled (-78 °C) solution of ethanethiol (230 μL, 3.09 mmol) in THF (15 mL) was added *n*-BuLi (1.10 mL, 2.28 mmol, 2.05 M solution in hexane). The resulting solution was stirred for 5 min at -78 °C and was then warmed to 0 °C, and stirred for 10 min at this temperature as a white precipitate formed. The imide **17c** (254 mg, 0.91 mmol) was added as a solution in THF (15 mL) *via* cannula. The resulting pale orange solution was stirred for 10 min at 0 °C, and then 1 h at room temperature after which time TLC analysis showed the reaction to be complete. The reaction mixture was partitioned between 50 mL of 1N NaOH solution and 100 mL of ethyl acetate. The aqueous layer was extracted with 100 mL of ethyl actetate, and the combined organic layers were washed with 100 mL of brine, dried over Na_2SO_4, filtered, and concentrated. The oxazolidinone byproduct was removed by flash chromatography (1.5 cm X 12 cm silica gel, 20% ethyl acetate/hexane) to afford 234 mg (100%) of a mixture of *endo* and *exo* thioesters (*ent*-**25**). Data for the *endo* thioester obtained from the mixture: ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.27 (dd, 1H, J=3.2, 5.5 Hz), 6.06 (dd, 1H, J=2.8, 5.6 Hz), 4.18-4.06 (m, 2H), 3.58 (t, 1H, J=4.2Hz), 3.30 (br s, 1H), 3.11 (br s, 1H), 2.88-2.69 (m, 3H), 1.63 (br d, 1H, J=8.5 Hz), 1.45 (dd, 1H, J=1.6, 8.8 Hz), 1.27 (t, 3H, J=7.1 Hz), 1.22 (t, 3H, J=7.4 Hz); exact mass calcd for $C_{13}H_{18}O_3S_1$ + Na requires *m/z* 277.0874. found *m/z* 277.0884 (FAB, *m*-nitrobenzyl alcohol, NaI added).



Ethyl (3*R*,3a*R*,5*S*,6*S*,6a*S*,7*R*)-hexahydro-6-iodo-2-oxo-3,5-methano-2H-cyclopenta[b]-furan-7-carboxylate [(+)-18]. To a solution of the thioester *ent*-**17** in 2:1 THF/H_2O (~0.1 M) was added 2.10 equiv of solid $Hg(O_2CCF_3)_2$, and the resulting mixture is stirred for 3 h, when TLC analysis indicated the reaction had gone to completion. At this stage, iodine (4.0 equiv) was added in two equal portions at 2 minute intervals to produce a deep purple solution. This mixture was stirred in the dark for 3 h, at which time the reaction has proceeded to produce the iodolactone. The reaction was quenched by addition of 1N $Na_2S_2O_3$ solution until the purple color had been completely dissipated. The reaction mixture was extracted with two portions of ethyl acetate and the combined organic layers were washed with brine and dried over Na_2SO_4. Purification by flash chromatography (20% ethyl acetate/hexane) afforded the iodolactone [(+)-**18**] (50-70% yield), which matched the authentic sample prepared above in all ways reported above, except for optical rotation. The sample obtained from the catalytic reaction of **12d** showed $[\alpha]_D$ +38.9 (*c* 1.78, $CHCl_3$).



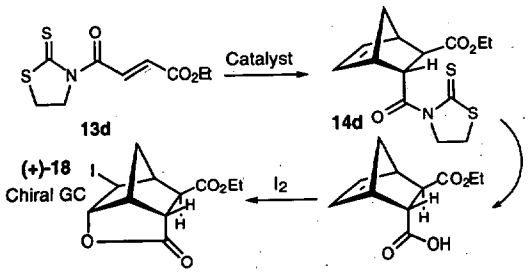
3-[(*E*)-3-(Ethoxycarbonyl)propenyl]-2-thiazolidinethione (13d). To a cooled (-78 C) solution of fumaryl chloride monoethyl ester (4.1 g, 25 mmol) in CH_2Cl_2 (100 mL) was added thiazoline-2-thione (2.9 g, 25 mmol), followed by Et_3N (3.7 mL, 27.0 mmol). The resulting mixture was stirred at this temperature for 1 h, and then 1 h at 0 °C. The reaction was quenched by addition of 50 mL of $NaHCO_3$ solution, and extracted with two 50 mL portions of CH_2Cl_2. The combined organic layers were dried over Na_2SO_4, filtered and concentrated. Purification by flash chromatography (30% ethyl acetate/hexane) afforded 4.9 g (80%) of **13d**: IR (CH_2Cl_2) 3000, 1720, 1686, 1370, 1300 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) 8.02 (d, 1H, J=15.3 Hz), 6.67 (d, 1H, J=15.3 Hz), 4.53 (t, 2H, J=7.4 Hz), 4.24 (q, 2H, J=7.2 Hz), 3.42 (t, 2H, J=7.4 Hz), 1.30 (t, 3H, J=7.1Hz); ^{13}C NMR (100 MHz, $CDCl_3$) 201.6, 165.9, 165.0, 134.9, 130.5, 61.2, 55.1, 29.5, 14.1; exact mass calcd for $C_9H_{11}O_5N_1$ + Na *m/z* 268.0078. found *m/z* 268.0063 (FAB, *m*-nitrobenzyl alcohol, NaI added).



Ethyl (1*R*,2*R*,3*R*,4*S*)-3-[(2-thio-3-thiazolidinyl)carbonyl]bicyclo-[2.2.1]hept-5-ene-2-carboxylate (14d). The catalyst solution was prepared according to the General Procedure described above for reactions of imide **5a** using catalyst **1a** (X = OTf), employing 5 mol% catalyst. Fumarate **13d** (245 mg, 1.00 mmol) was added as a solution in CH_2Cl_2 (1 mL) *via* cannula. Immediately thereafter, cyclopentadiene (400 µL, 4.85 mmol) was added *via* syringe. The resulting solution was stirred at -55 °C for 20 h. The reaction mixture was then diluted with 10 mL of 1:1 ethyl acetate/hexane, applied directly to a short column of silica gel (1.5 cm x 1.5 cm), eluted with approximately 100 mL of 1:1 ethyl acetate/hexane, and concentrated to afford the product. The *endo*/*exo* ratio was shown by ^1H NMR to be 84:16. The *endo* and *exo* isomers were not readily separabe by flash chromatography. Chromatography (1.5 cm x 12 cm silica gel, 30% ethyl acetate/hexane) provided 274 mg (88%) of the cycloadducts as a mixture. Data for the *endo* isomer obtained from the mixture: ^1H NMR (500 MHz, $CDCl_3$) δ 6.36 (dd, 1H, J=3.3, 5.1 Hz), 5.88 (dd, 1H, J=2.7, 5.7 Hz), 5.25 (t, 1H, J=4.3 Hz), 4.49 (m, 2H), 4.12 (q, 2H, J=7.1 Hz), 3.50 (br s, 1H), 3.32-3.18 (m, 3H), 2.85 (d, 1H, J=4.4 Hz), 1.66 (br d, 1H, J=8.6 Hz), 1.44 (br d, 1H, J=8.7 Hz), 1.24 (t, 3H, J=7.2 Hz); exact mass calcd for $C_{14}H_{17}O_3S_2N_1$ + Na requires *m/z* 334.0548. found *m/z* 334.0566 (FAB, *m*-nitrobenzyl alcohol, NaI added).

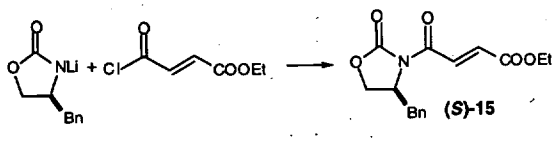
Assay for adduct 14d. The ee of the cycloadducts derived from the catalytic reactions of the fumarate **13d** was determined by conversion to the corresponding iodolactone **18**.

Conversion of cycloadduct 14d to iodolactone (+)-18. To a cooled (0 °C) solution cycloadduct **14d** (274 mg, 0.88 mmol) in 6 mL of 3:1 THF/H_2O was added solid LiOH (25.4 mg, 0.66 mmol). The solution was warmed to room temperature and stirred for 40 min, after which time the solution became clear and TLC analysis indicated the starting material had been consumed. The reaction mixture was poured in 5 mL of saturated $NaHCO_3$ solution, and extracted with CH_2Cl_2 (2 X 20 mL). Ice (~10 g) and CH_2Cl_2 (5 mL) were added to the aqueous layer, which was acidified to pH = 1 with concentrated HCl. The layers were separated, and the aqueous layer was extracted with three 40 mL portions of CH_2Cl_2, with solid NaCl added to the aqueous layer between extractions. The combined organic layers were dried over Na_2SO_4, filtered and concentrated to afford

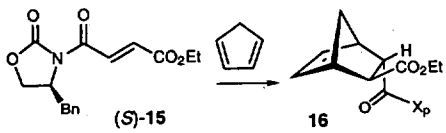


154 mg (73%) of the intermediate *endo* and *exo* carboxylic acids. Without further purification, the mixture of acids was dissolved in 4 mL of anhydrous CH_3CN. The solution was cooled to 0 °C and 558 mg (2.20 mmol) of solid I_2 was added to give a purple solution. After 20 h at 0 °C, the reaction was quenched by addition of 10 mL of 1N $Na_2S_2O_3$ solution, which dissipated the purple color to produce a colorless mixture. The mixture was extracted with two 20 mL portions of ethyl acetate. The combined organic layers were washed with 50 mL of brine, dried over Na_2SO_4, filtered and concentrated. Purification of the residue by flash chromatography (1.5 cm x 12 cm silica gel, 20% ethyl acetate/hexane) afforded 178 mg (83% based on *endo* starting material) of the desired lactone **18** as a clear glass which matched the above samples in all ways, except for optical rotation. The sample ultimately obtained from the catalytic reaction of **13d** using complex **1a** (X = OTf) showed $[\alpha]_D$ +40.0 (*c* 1.78, $CHCl_3$); GLC analysis showed the sample to be 96% ee.

Assignment of absolute stereochemistry of fumarate derivatives. The absolute stereochemical assignment of the fumarate products was assigned by correlation to the product of the Et_2AlCl-mediated reaction of the chiral fumarate derivative as described below. The stereoregularity of this process has been documented previously.[7] In addition, iodolactone (-)-**26** was converted to the known (5*S*,6*S*)-bis(hydroxymethyl)bicyclo[2.2.1]hept-2-ene, followed by comparison of optical rotation (*vide infra*).



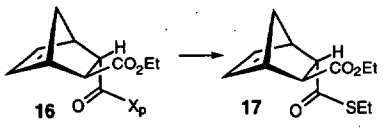
(4*S*)-3-((*E*)-3-(Ethoxycarbonyl)propenyl)-4-benzyl-2-oxazolidinone [(*S*-)-15]. To a cooled (-78 °C) suspension of (*S*)-4-(phenylmethyl)-1,3-oxazolidin-2-one (2.15 g, 12.1 mmol) in 100 mL of THF was added *n*-BuLi (7.60 mL, 12.1 mmol, 1.6M in hexane). The solution was stirred at this temperature for 15 min, and fumaryl chloride monoethyl ester (1.98 g, 12.1 mmol) was addedas a solution in THF (20 mL). The solution was stirred at -78 °C for 30 min, and was then quenched by addition of 100 mL of saturated NH_4Cl solution. The layers were separated and the aqueous layer was extracted with two 100 mL portions of EtOAc. The combined organic layers were washed with 100 mL of brine, dried over Na_2SO_4, filtered and concentrated. Purification by flash chromatography (5 cm x 18 cm silica gel, solvent gradient: 25% ethyl acetate/hexane to 30% ethyl acetate/hexane) afforded 3.09 g (84%) of the pure product (*S*)-**15** as a clear oil: $[\alpha]_D$ +63.2° (*c* 0.75, $CHCl_3$); IR (thin film) 3000, 1782, 1723, 1685, 1475, 1360, 1300 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.17 (d, 1H, J=15.5 Hz), 7.30 (m, 5H), 7.02 (d, 1H, J=15.5 Hz), 4.77 (m, 1H), 4.34-4.23 (m, 4H), 3.36 (dd, 1H, J=3.3, 13.4 Hz), 2.85 (dd, 1H, J=9.5, 13.4 Hz), 1.36 (t, 3H, J=7.1 Hz); ^{13}C NMR (100MHz, $CDCl_3$) δ 164.8, 163.8, 153.0, 134.9, 134.5, 132.2, 129.4, 129.1, 127.5, 66.5, 61.4, 55.3, 37.6, 14.1; exact mass calcd for $C_{16}H_{17}O_5N_1$ + Na *m/z* 326.1004. found *m/z* 326.0980 (FAB, *m*-nitrobenzyl alcohol, NaI added).



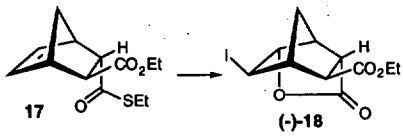
Ethyl (1*S*,2*S*,3*S*,4*R*)-3-[[(4*S*)-4-benzyl-2-oxo-3-oxazolidinyl]carbonyl]-bi-cyclo[2.2.1]hept-5-ene-2-carboxylate (16). To a cooled (-78 °C) solution of the imide (*S*)-**15** (342 mg, 1.13 mmol) in CH_2Cl_2 (20 mL) was added Et_2AlCl (877 μL, 1.58 mmol) to produce a yellow solution. Cyclopentadiene (1.50 mL, 18.2 mmol) was then added at -78 °C, and the resulting clear solution was stirred for 30 min at -78 °C. The reaction was then poured into 100 mL of 1N HCl solution, and the resulting mixture was extracted with three 80 mL portions of CH_2Cl_2. The combined organic layers were washed with 100 mL of brine, dried over Na_2SO_4, filtered and concentrated to afford the unpurified product. HPLC analysis using a chiral Baker DNBDG column (flow rate = 1.0 mL/min; hexane/*i*-PrOH 96:4) showed the reaction to have produced a mixture of four diastereomers in the ratio of 7:8:76:8 (t_r for the major isomer = 14.6 min). The four isomers were not readily separable by flash chromatography. Flash chromatography (1.5 cm x 12 cm silica gel, 25% ethyl acetate/hexane) was performed to obtain a mixture of isomers. Data for the major product **16** obtained from the mixture: ^1H NMR (400 MHz, $CDCl_3$) δ 7.40 (m, 5H), 6.35 (dd, 1H, J=3.4, 5.2 Hz), 5.89 (dd, 1H, J=2.9), 4.63-4.57 (m, 1H), 4.28 (t, 1H, J=4.5 Hz), 4.16-4.06 (m, 4H), 3.45 (br s, 1H), 3.18-3.15 (m, 2H), 2.87 (d, J=4.7 Hz), 2.62 (dd, 1H, J=9.9, 13.1 Hz), 1.71 (br d, 1H, J=8.7 Hz), 1.47 (br d, 1H, J=8 Hz), 1.20 (t,

3H, J=7.2 Hz); exact mass calcd for $C_{21}H_{23}O_5N_1$ + Na requires *m/z* 392.1474. found *m/z* 392.1493 (FAB, *m*-nitrobenzyl alcohol, NaI added).

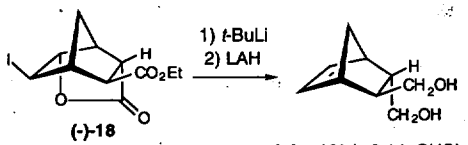
Standards for this reaction were prepared in the following way: To a solution of imide (*S*)-**15** (60 mg, 0.20 mmol) in CH_2Cl_2 (20 mL) was added cyclopentadiene (150 µL, 1.82 mmol). The reaction mixture was stirred at room temperature for 3 h, after which time TLC analysis showed the starting imide to have been consumed. The reaction mixture was concentrated, and directly analyzed by HPLC (conditions described in the preceding paragraph) which showed the four diastereomers in a 1:2:2:1 ratio (t_{r1} = 12.60 min, t_{r2} = 13.17 min, t_{r3} = 14.61 min, t_{r4} = 16.12).



***O,S*-Diethyl (1*R*,2*S*,3*S*,4*S*)-2-thiobicyclo[2.2.1]hept-5-ene-2,3-dicarboxylate (17).** To a cooled (-78 °C) solution of ethanethiol (285 µL, 3.84 mmol) in THF (15 mL) was added n-BuLi (1.37 mL, 2.83 mmol, 2.05 M solution in hexane). The resulting solution was stirred for 5 min at this temperature, warmed to 0 °C, and stirred for 10 min at this temperature whereupon a white precipitate formed. Cycloadduct **16** (380 mg, 1.03 mmol) was added as a solution in 15 mL of THF *via* cannula. The resulting pale orange solution was stirred for 10 min at 0 °C, and then for 1 h at room temperature at which time TLC analysis showed the reaction to be complete. The reaction mixture was partitioned between 50 mL of 1 N NaOH solution and 50 mL of ethyl acetate. The aqueous layer was extracted with 50 mL of ethyl actetate, and the combined organic layers were washed with 50 mL of brine, dried over Na_2SO_4, filtered, and concentrated. The byproduct oxazolidinone was removed by flash chromatography (1.5 cm x 12 cm silica gel, 20% ethyl acetate/hexane) to afford 167 mg (64%) of a mixture of *endo* and *exo* thioesters. The data collected for this sample matched with that obtained for the thioester *ent*-**17** described above.

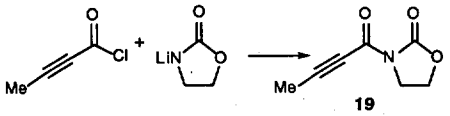


Ethyl (3*S*,3a*S*,5*R*,6*R*,6a*R*,7*S*)-hexahydro-6-iodo--2-oxo-3,5-methano-2H-cyclopenta[b]-furan-7-carboxylate [(-)-18]. Following the above procedure for forming the iodolactone from the thioester **17**, the thioester ultimately derived from the Al-mediated reaction of the chiral imide (*S*)-**15** was converted to iodolactone (-)-**18**, which matched the authentic sample in all respects reported above, except for optical rotation. The sample derived from the Et_2AlCl-mediated Diels-Alder reaction showed $[\alpha]_D$ -39.7 (*c* 1.05, $CHCl_3$); GLC analysis as described above for the standards showed the sample to be 90% ee.

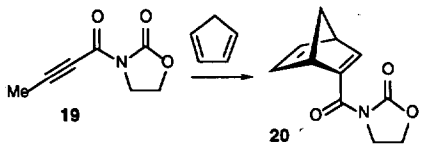


(5*S*,6*S*)-bis(hydroxymethyl)bicyclo[2.2.1]hept-2-ene. To a -78 °C solution of iodolactone (–)-**18** (50 mg, 0.15 mmol) in THF (30 mL) was added *tert*-butyl lithium (0.4 mmol). The solution was stirred at -78 °C for 30 min, quenched with 20 mL of saturated NH_4Cl solution, and the resulting biphasic mixture was extracted with CH_2Cl_2 (3 X 30 mL). The combined organic layers were dried over Na_2SO_4, filtered and concentrated. At this point ^1H NMR spectroscopic analysis indicated the reaction had proceeded to 20% conversion. The unpurified reaction mixture was then resubmitted to the above procedure, after which time ^1H NMR spectroscopic analysis indicated the reaction had proceeded to 50% conversion. The unpurified product was then dissolved in 20 mL of anhydrous THF and treated with solid $LiAlH_4$ (40 mg, 1.00 mmol). After the vigorous bubbling ceased, the reaction mixture was heated at reflux for 12 h. The reaction mixture was cooled to 0 °C and treated with 10 mL of H_2O, followed by 10 mL of 2*N* NaOH solution. The resulting slurry was stirred for 30 min, filtered through Celite with ethyl acetate and concentrated. Purification of the diol by chromatography (1 cm X 12 cm silica gel, 75% ethyl acetate/benzene) afforded 5.6 mg (24%) of the pure diol as a clear glass, which was identical to the known sample by ^1H and ^{13}C NMR analysis. Comparison of optical rotation confirmed the assignment of absolute stereochemistry: 90% ee: $[\alpha]_D$ = -18° (*c* 0.14, $CHCl_3$); (lit. $[\alpha]_D$ -23° (*c* 0.80, $CHCl_3$).[7]

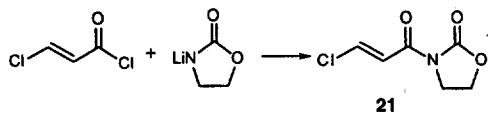
Synthesis and Diels-Alder reaction of acetylene and equivalent dienophiles.



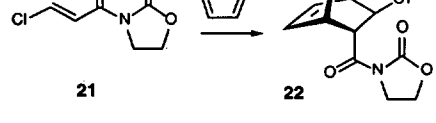
3-(2-Butynoyl)-2-oxazolidinone (19). To a cooled (-78 °C) suspension of 2-oxazolidinone (3.50 g, 40.0 mmol) in THF (200 mL) was added *n*-BuLi (19.5 mL, 40.0 mmol, 2.05 *M* in hexane). The suspension was allowed to stir at this temperature for 20 min, and was then warmed to 0 °C over 20 min. The suspension was recooled to -78 °C and freshly prepared propiolyl chloride (59.5 mmol) was added as a solution in THF (20 mL). The solution was warmed to room temperature and stirred for 30 min at which time it was quenched by addition of 100 mL of saturated NH_4Cl solution. The layers were separated and the aqueous layer was extracted with two 100 mL portions of Et_2O. The combined organic layers were washed with 100 mL of brine, dried over Na_2SO_4, filtered and concentrated. Purification by recrystallization (50 ml 1:1 ethyl acetate/hexane) afforded 3.80 g (63%) of the product **19** as pale yellow crystals: mp 85-86 °C; IR (CH_2Cl_2) 2230, 1795, 1660, 1477, 1383 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 4.41 (t, 2H, J=7.7 Hz), 4.03 (t, 2H, J=7.8 Hz), 2.10 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.0, 150.7, 94.8, 72.4, 61.8, 42.2, 4.4; exact mass calcd for $C_7H_7N_1O_3 + NH_4$ requires *m/z* 171.0770. found *m/z* 171.0768 (CI, NH_3).



3-[(3-Methylbicyclo[2.2.1]hepta-2,5-dien-2-yl)carbonyl]-2-oxazolidinone (20). The solution of catalyst **1a** (X = OTf) was prepared according to the General Procedure described above for reactions of imide **5a**. Imide **19** (153 mg, 1.00 mmol) was then added as a solution in 1 mL of CH_2Cl_2 *via* cannula. Immediately thereafter, cyclopentadiene (1.0 mL, 12 mmol) was added *via* syringe. The resulting solution was stirred at room temperature for 18 h. The reaction mixture was diluted with 10 mL of 1:1 ethyl acetate/hexane, applied directly to a short column of silica gel (1.5 cm x 1.5 cm) and then eluted with approximately 100 mL of 1:1 ethyl acetate/hexane. Concentration afforded the product which was then analyzed. The reaction mixture was then purified by chromatography (1.5 cm x 12 cm silica gel, 40% ethyl acetate/hexane) to afford 130 mg (59%) of the desired cycloadduct **20**. Chiral HPLC analysis: Daicel OD column, flow rate = 1.00 ml/min, hexane/*i*PrOH 96:4; tr_{major} = 51.8 min, tr_{minor} = 45.8 min. $[\alpha]_D$ -20.5 °(*c* 2.56, CH_2Cl_2); IR (CH_2Cl_2) 2984, 1786, 1660, 1384 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 6.95 (m, 1H), 6.70 (m, 1H), 4.43 (m, 2H), 4.03 (m, 2H), 3.75 (br s, 1H), 3.42 (br s, 1H), 2.25 (dd, 1H, J= 6.4, 1.3 Hz), 2.08 (s, 3H), 1.99 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.9, 166.4, 153.1, 144.5, 140.2, 139.5, 70.8, 62.4, 57.5, 53.2, 43.3, 17.4; exact mass calcd for $C_{12}H_{13}N_1O_3$ requires *m/z* 219.0895. found *m/z* 219.0885 (EI).



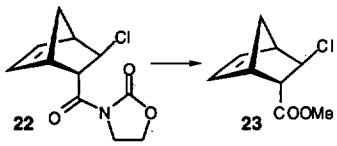
3-[(3*E*)-3-Chloro-2-propenoyl]-2-oxazolidinone (21). To a cooled (-78 °C) suspension of 2-oxazolidinone (653 mg g, 7.5 mmol) in THF (40 mL) was added *n*-BuLi (3.6 mL, 7.5 mmol, 2.05 *M* in hexane). The suspension was allowed to stir at this temperature for 20 min, and was then warmed to 0 °C over 20 min. The suspension was recooled to -78 °C and freshly prepared β-chloroacroloyl chloride (8.9 mmol) was added. The solution was stirred at -78 °C for 90 min, then it was quenched by addition of 100 mL of saturated NH_4Cl solution. The layers were separated and the aqueous layer was extracted with two 100 mL portions of Et_2O. The combined organic layers were washed with 100 mL of brine, dried over Na_2SO_4, filtered and concentrated. Purification by flash chromatography (3 cm x 12 cm silica gel, 30% ethyl acetate/hexane) afforded 560 mg (43%) of the product **21** as pale yellow solid: IR (CH_2Cl_2) 3100, 1780, 1685, 1601, 1480, 1387 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.68 (d, 1H, J=13.2 Hz), 7.51 (d, 1H, J=13.2 Hz), 4.44 (t, 2H, J=7.9 Hz), 4.06 (t, 2H, J=7.9 Hz); 13C NMR (100 MHz, $CDCl_3$) δ 162.7, 151.0, 139.5, 123.3, 62.1, 42.5; exact mass calcd for $C_6H_6N_1O_3Cl_1 + NH_4$ requires *m/z* 193.0380. found *m/z* 193.0385 (CI, NH_3).



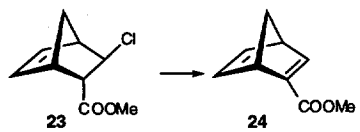
3-[[(1*S*,2*R*,3*R*,4*R*)-3-Chlorobicyclo[2.2.1]hept-5-en-2-yl]carbonyl]-2-oxazolidinone (22). A solution of catalyst **1b** (X = SbF_6) was prepared according to the General Procedure described above for reactions of imide **5a** by mixing $CuCl_2$ (766 mg, 5.7 mmol), ligand **6d** (1.89 g, 6.3 mmol) and $AgSbF_6$ (3.92 g, 11.4 mmol) in CH_2Cl_2 (57 ml), stirring for 8 h at ambient temperature and filtering through Celite. Imide **21** (10.96g, 62.4 mmol) was then added as a solution in CH_2Cl_2 (60 mL) *via* cannula (5 ml rinse of CH_2Cl_2). Immediately thereafter, cyclopentadiene (62 mL, 744 mmol) was

added *via* syringe. The resulting solution was stirred at room temperature for 24 h. The reaction mixture was directly applied to a short column of silica gel (6 cm x 6 cm) and eluted with approximately 1 L of 1:1 ethyl acetate/hexane. Concentration afforded the unpurified product which was analyzed. ^{1}H NMR analysis indicated that the reaction had proceeded to >98% conversion. The unpurified reaction mixture was analyzed directly by chiral GLC, which showed the *endo*/*exo* ratio to be 87:13 (*endo* isomer 96% ee, chiraldex G-TA column; oven temp = 150 °C, flow rate = 20 psi; $endo_{major}$ t_r = 47.40 min, $endo_{minor}$ t_r = 57.62 min, exo_1 t_r = 50.27, exo_2 t_r = 51.85). The product mixture was then purified by chromatography (8 cm x 32 cm silica gel, 30% ethyl acetate/hexane) to afford 14.45 g (59.8 mmol, 96%) of **22** as a white solid. Recrystallization from ethyl acetate/hexane yielded enantiomerically pure **22** (9.80 g, 68% yield): $[\alpha]_D$ -113 °(*c* 1.10, CH_2Cl_2); IR (CH_2Cl_2) 3000, 1781, 1699, 1480, 1387 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.23 (dd, 1H, J=5.6, 3.3 Hz), 5.90 (dd, 1H, J=5.6, 2.7 Hz), 4.41 (t, 2H, J=7.8 Hz), 4.24 (m, 1H), 4.13 (m, 1H), 4.05-3.87 (m, 2H), 3.39 (br d, 1H, J=1.4 Hz), 3.06 (br s, 1H), 2.10 (br d, 1H, J=9.1 Hz), 1.72 (dd, 1H, J=9.0, 1.7 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.0, 153.2, 136.2, 134.4, 62.1, 58.8, 54.8, 52.4, 48.1, 46.9, 42.8; exact mass calcd for $C_{11}H_{12}N_1O_3Cl_1$ requires *m/z* 241.0506. found *m/z* 241.0494 (EI).

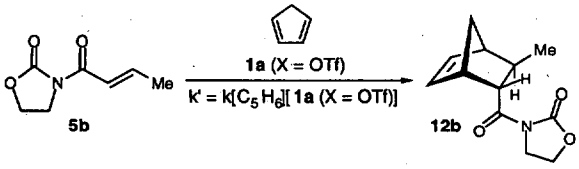
Absolute configuration of cycloadduct 22: The absolute configuration was assigned by analogy to the other cycloadducts in this study.



Methyl (1*S*,2*S*,3*R*,4*R*)-3-chlorobicyclo[2.2.1]hept-5-en-2-carboxylate (23). The transesterification was accomplished using the procedure of Evans and Weber.[8] To a solution of imide **22** (2.44 g, 10.1 mmol) in a mixture of MeOH (50 ml) and THF (25 ml) at 0 °C was added *via* canula a suspension formed by the addition of methylmagnesium bromide (3.7 mL, 3.2 M in diethyl ether, 11.8 mmol) to anhydrous methanol (50 mL). After the reaction mixture was stirred for 1 h at 0 °C, it was quenched by the addition of saturated NH_4Cl solution (50 mL). Volatiles were removed *in vacuo*. The residue was dissolved in 1 N aqueous hydrochloric acid (100 mL) and extracted with three 100 mL-portions of CH_2Cl_2. The combined organic layers were dried over $MgSO_4$, filtered, and concentrated. Purification by flash chromatography (2 cm x 20 cm silica gel, 20% ethyl acetate/hexane) afforded 1.79 g (95%) of the title compound as a clear, colorless oil: $[\alpha]_D$ -165 (*c* 1.16, CH_2Cl_2); IR (CH_2Cl_2) 2953, 1734, 1437, 1331 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.14 (m, 2H), 4.06 (br t, 1 H, J=2.3 Hz), 3.67 (s, 3H), 3.22 (br s, 1H), 3.09 (m, 1H), 3.04 (br s, 1H), 1.98 (br d, 1H, J=9.0 Hz), 1.72 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.5, 136.8, 135.0, 59.5, 55.7, 52.0, 51.9, 46.9, 45.5; exact mass calcd for $C_9H_{11}ClO_2$ requires *m/z* 186.0448, found *m/z* 186.0454 (EI).



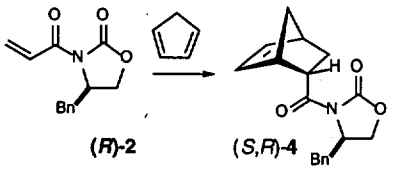
Methyl (1*S*,4*R*)-bicyclo[2.2.1]hepta-2,5-dien-2-carboxylate (24). To a solution of ester **23** (1.07 g, 5.7 mmol) in acetonitrile (10 mL) at 25 °C was added 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU, 1.7 mL, 11.5 mmol). After stirring for 3 h at 25 °C, the colorless reaction mixture was directly applied to a silica gel column (4 cm x 26 cm, 20% ethyl acetate/hexane) to yield 636 mg (74%) of the desired elimination product **24** as a clear, colorless oil: $[\alpha]_D$ +40.8° (*c* 1.01, CH_2Cl_2); IR (CH_2Cl_2) 2947, 1711, 1594, 1556, 1437, 1362 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64 (m, 1H), 6.90 (dd, 1H, J=3.1 and 4.8 Hz), 6.72 (dd, 1H, J=3.1 and 4.5 Hz), 3.89 (br s, 1H) 3.72 (br s, 4H), 2.12 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 155.5, 149.2, 143.4, 141.5, 74.1, 51.3, 51.0, 49.8; exact mass calcd for $C_9H_{10}O_2$ requires *m/z* 150.0681, found *m/z* 150.0676 (EI).



Reaction kinetics of imide 5b with cyclopentdiene catalyzed by 1a (X = OTf) employing standard conditions. The catalyst was made as described above in the General Procedure. The standard concentration of imide **5b** was set at 0.49 M, and the concentration of cyclopentadiene (10 M) was present in large excess over the concentration of dienophile (0.49 M), which was in turn large relative to the concentration of catalyst (10 mol% metal, 0.049 M, 11 mol% ligand). These reaction conditions were defined as the standard procedure for all subsequent kinetics experiments. Additional runs were performed at substrate concentrations of 0.25 M, maintaining 0.049 M catalyst, and were run at 0 °C in an ice bath. Imide **5b** was added to the stirred solution of catalyst at 0°C, with the resultant solution allowed to equilibrate for 30 min. Cyclopentadiene was then added in a cold (ca. 0 °C) syringe. Cyclopentadiene dimerization at

the specified concentration was determined to be ca 4% over a 24 h period (NMR analysis), so was assumed to not be a factor in the reaction kinetics. Additionally, the background reaction (off rate) is also found to be negligible at the reaction temperature. Aliquots (100 μL) of the runs were taken at specified time intervals and quickly quenched in a mixture of ice-cold ethyl acetate and saturated $NaHCO_3$ solution (1 mL each). The mixture was then extracted with 1:1 ethyl acetate/ether (1 mL), the organic layer was separated off and washed with 1 mL water, and dried with Na_2SO_4. The residual cyclopentadiene was removed under vacuum at 0 °C. The reaction products were quantified by GLC analysis with 4,4'-di-*tert*-butyldiphenyl (0.10 M) as a reliable internal standard, employing a DB-1701 column, 180 °C, flow rate 10 mL/min (retention time imide **5b**, 3.85 min, retention time 4,4'-di-*tert*-butyldiphenyl, 15.10 min). Rates were measured as the consumption of dienophile **5b** with respect to time, which also correlated well with the production of adduct **12b** with respect to time. Concentrations of cyclopentadiene were varied (8 M, 10 M, and 20 M) and were found to have minimal effect on the kinetics of the reaction. Nevertheless 10 M cyclopentadiene was chosen as the standard concentration. Under the specified conditions, the reaction was found to follow psuedo-first order kinetics for low substrate conversions as indicated by a linear plot of $\ln\{[\mathbf{5b}_{init}]/[\mathbf{5b}_{init}] - [\mathbf{5b}]\}$ versus time.

Reaction kinetics of imide 5a with cyclopentadiene catalyzed by 1a (X = OTf) in the presence of competitive inhibitors. Kinetics runs was performed on substrate **5b** using the standard conditions specified above in the presence of 0.98 M adduct **12b** at t = 0, indicating an 18% reduction in rate and k'. Reactions were always run in tandem with the standard undoped reaction described above, with the same catalyst batch, to insure uniformity in results. Substrates and inhibitors were introduced to the reaction mixture as standardized solutions, and were allowed to equilibrate to the reaction temperature over the course of 30 min. The reactions uniformily followed psuedo first-order kinetics at low conversions of substrate. Similarly, kinetics employing the standard conditions specified above were run in the presence of competitive inhibitors **26**, **27**, and **30-32** present at a standard concentration of 0.98 M, resulting in reductions in reaction rate of 16%, 7%, 16%, 24% and 6%, respectively. The reactions followed well-behaved psuedo first-order kinetics for low conversions of substrate (<30%).



Double Stereodifferentiating reactions employing the chiral imides (*R*)- and (*S*)-2 and complexes B, C and 8a. These reactions were run in the same manner as the copper-based reactions described above.

References and Notes

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