"Gated Migration" for Enantioselective Synthesis of Palladium Allyls Using a "PdHBr" Synthon

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The synthesis of enantiomerically pure palladium cyclic allyl complexes is accomplished by reaction of "PdHBr" with several chiral cyclic terpenes. The strategy used involves a 100% stereoselective Pd-migration from an attached chain to the ring through a chiral carbon ("gated migration"). "PdHBr" species are produced by β-H elimination in the benzylic moiety of $[Pd_2(\mu\text{-Br})_2(\eta^3\text{-PfCH}_2\text{CHPh})_2]$ (**1**, Pf = C_6F_5). The allylic complexes prepared are transformed by carbonylation reactions into chiral unsaturated methyl esters.

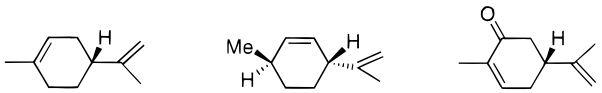
Introduction

Palladium allyls can be synthesized in a variety of ways.[1] Subsequent palladium elimination using selective transformations affords functionalized alkenes, and it is the final step in the Pd-mediated allylic substitution.[2] Optically active organic derivatives can also be obtained from enantiomerically pure Pd-allyls, since the Pd−allyl bond can be cleaved in a stereoselective way.[2−4]

The strategies reported for the few enantioselective syntheses of Pd-allyls are the following: (a) face selection in the coordination of a prochiral alkene, assisted by another stereocenter in the molecule;[5,6] (b) transmetalation of an optically active allylic silane to Pd(II);[7] and (c) oxidative addition of an optically active allylic acetate to Pd(0).[8]

In this paper we describe a new approach that makes use of the stereoselective palladium migration to a ring from an external hydrocarbon chain. We have used some cyclic terpenes with exo- and endocyclic double bonds (Chart 1). Cyclic allyls can be obtained from these dienes by addition of a Pd−R moiety to the exocyclic double bond and Pd-migration to reach the endocyclic double bond. Pd-migration is a stereoselective process and occurs via syn-Pd−H eliminations and readditions.[5,9] Thus, the palladium must necessarily enter the cycle from the same face where the H atom is in the carbon bearing the chain (gated Pd-migration). This imposes 100% face selection in the formation of the palladium allyl.

Chart 1



(*R*)-(+)-limonene (1*R*)-(+)-trans-isolimonene (*R*)-(-)-carvone

Since Pd−R addition to the exocyclic double bond does not discriminate the enantiofaces of the double bond, we used Pd−H instead of Pd−R to avoid the formation of an exocyclic asymmetric carbon and the corresponding diastereomeric mixture. Addition of Pd−H creates a nonchiral isopropyl substituent and, after Pd-migration, an enantiomerically pure allyl complex.

Most of the hydridopalladium complexes available contain phosphines as coligands and lack of easily available coordination sites on the metal that are necessary for reaction with the diene.[10] However, it has been reported that some reactive, "in situ" generated, palladium hydrides react with dienes.[5,11−13] The hydrido moieties in these examples are formed by β-H elimination from palladium alkyls, which in turn require the use of toxic organomercury derivatives in their syntheses.[5,12−14] We have described before a palladium benzylic derivative $[Pd_2(\mu\text{-Br})_2(\eta^3\text{-PfCH}_2\text{CHPh})_2]$ (**1**, Pf = C_6F_5), prepared without the use of toxic organometallic derivatives, which is slightly soluble in chlorinated solvents and decomposes slowly by β-H elimination to give a palladium hydride.[15] In the presence of the dienes collected in Chart 1, the hydride generated from **1** reacts

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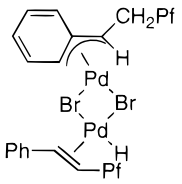
Chart 2

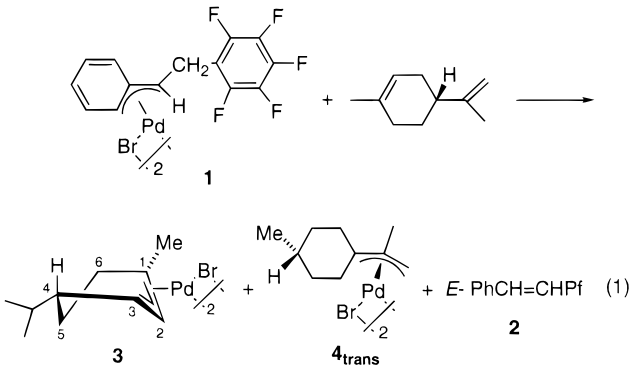


efficiently to give enantiomerically pure Pd-allyls in good yields. These complexes can be stereoselectively functionalized, and one of these transformations along with the syntheses of the allylic complexes is described here.

Results and Discussion

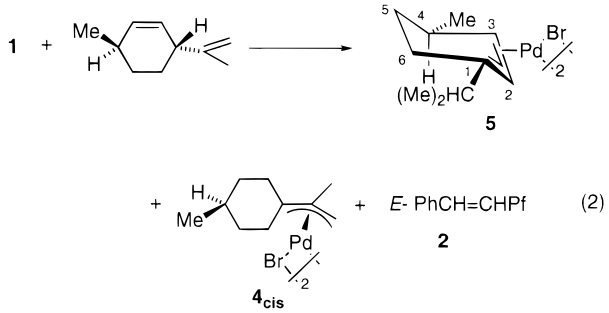
Complex $[Pd_2(\mu\text{-}Br)_2(\eta^3\text{-}PfCH_2CHPh)_2]$ (**1**, Pf = C_6F_5) suspended in chloroform or dichloromethane, where it is sparingly soluble, slowly gets in solution and decomposes at room temperature via Pd−(β-H) elimination to (*E*)-PhCH=CHPf (**2**) and a hydrido-containing palladium species. In the absence of other ligands, this species, which can be represented as the mixed dimer depicted in Chart 2, undergoes an interesting H-transfer that has been described in detail elsewhere.[15]

When a suspension of **1** in $CDCl_3$ decomposed in the presence of (*R*)-(+)-limonene, selective insertion of the exocyclic double bond into the Pd−H bond of the smoothly generated "PdHBr" was observed (eq 1). The



Pd atom migrates along the hydrocarbon chain to reach the second double bond and forms an η^3-allylpalladium complex (**3**). The entrance to the ring via an asymmetric tertiary carbon (C^4) determines a cis arrangement of Pd and H^4 (gated Pd-migration). Thus the migration of palladium creates **3** as a single enantiomer. The crude product of the reaction (after chromatographic separation of **2** and an excess of limonene) was analyzed by ^{1}H NMR and contained **3** (96% of the mixture), $\mathbf{4_{trans}}$ (ca. 2%), and traces of unidentified products. Compound **3** arises from Pd−H addition to the external double bond followed by gated Pd-migration.[16] $\mathbf{4_{trans}}$ is formed by Pd−H addition to the endocyclic double bond followed by gated migration to the exocyclic one, this imposing a trans arrangement of Pd and Me. The allyl **3** could be isolated by crystallization from *n*-hexane (67% isolated yield) and fully identified by ^{1}H NMR, 2D ^{1}H−^{1}H correlation, and elemental analyses.

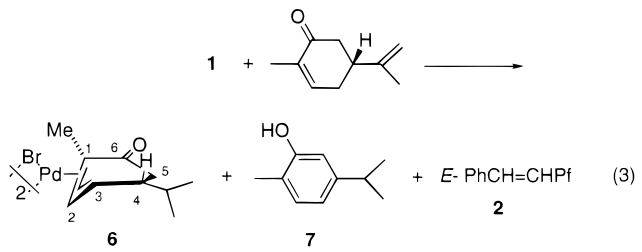
The reaction of **1** with (1*R*)-(+)-*trans*-isolimonene (eq 2) gave **5** as the major product (85% of the mixture after



chromatographic separation of **2** and excess diene, based on integration of ^{1}H NMR signals). A minor product, $\mathbf{4_{cis}}$ (3%), and several other unidentified Pd-allyls (12%) were formed. The latter might be the result of the reaction with dienes formed by isomerization of (1*R*)-(+)-*trans*-isolimonene. $\mathbf{4_{cis}}$ is the result of Pd−H addition to the endocyclic double bond, the cis arrangement being imposed by the stereoselective gated Pd-migration. Although **5** is very soluble, it could be isolated as a pure solid by crystallization in *n*-hexane (28% yield).

The conformations assigned to **3** and **5** are based on the analysis of coupling constants and comparison with previous data reported for η^3-cyclohexenylpalladium derivatives.[17] Compound **3** adopts a pseudo boat conformation, as shown by the ^3J values found: $^3J_{4-5}$ = 5.4 Hz, $^3J_{5-6}$ = 5.8 Hz, and $^3J_{5-6'}$ = 3.2 Hz. However, the observed coupling constants for **5** ($^3J_{5-6'}$ = 11.7 Hz, $^3J_{5'-6'}$ = 5.7 Hz) suggest a pseudo chair conformation. In both cases it seems that the preferred conformation accommodates the isopropyl or methyl group bound to C^4 in the equatorial position (eqs 1 and 2), as it has been observed in the X-ray stuctures of other substituted cyclic Pd-allyls.[18]

The reaction of **1** with (*R*)-(−)-carvone is summarized in eq 3. The insertion of the exocyclic double bond into



the Pd−H bond generated from complex **1**, followed by gated Pd-migration, afforded the allylic derivative **6**. Compound **7** was also formed in a ratio **6**:**7** = 9:1. The products in the reaction mixture could be separated by column chromatography, and **6** could be crystallized as a yellow solid in 50% yield.

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(16) We did not observe any symmetrical Pd-allyl coming from Pd-migration along the longer way in the ring. It seems that Pd−H elimination of one of the H atoms in the allylic position leading to an intermediate conjugated diene is much more favorable. This is consistent with our previous results: Albéniz, A. C.; Espinet, P.; Lin, Y.-S. *Organometallics* **1995**, *14*, 2977−2986.

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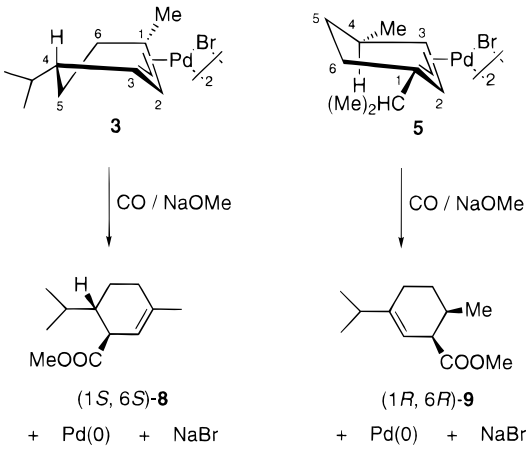
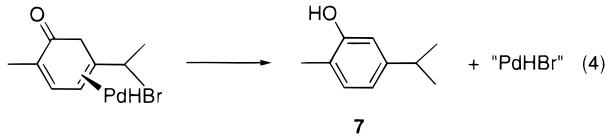
Scheme 1



7 is the tautomeric form of the cyclohexadienone expected to be formed in the palladium migration process (eq 4). Pd-migration is generally very efficient,

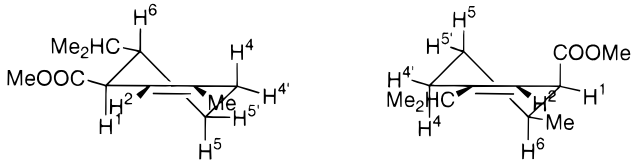


and Pd−H readdition occurs faster than decoordination of the diene. However the stabilization associated with aromatization may be the driving force that promotes the decoordination of the dienone at that point.

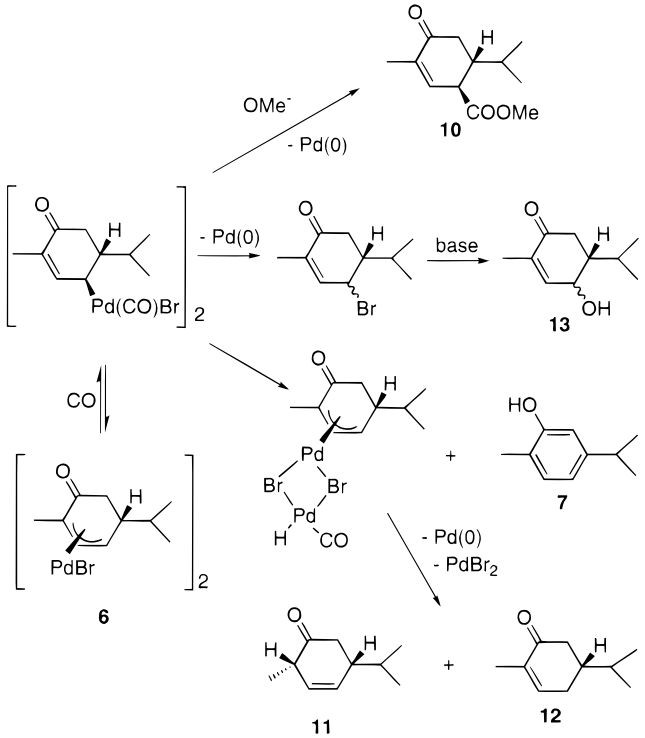
The carbonylation of η^3-allylpalladium complexes to give ester derivatives is highly regio- and stereoselective.[19,20] Thus, **3** or **5** reacted with CO and NaOMe to yield the enantiomerically pure methyl esters (1*S*,6*S*)-**8** (94%) or (1*R*,6*R*)-**9** (90%), respectively, each of them having two chiral centers with fixed configurations (Scheme 1). This means that CO insertion has occurred preferably into the less substituted Pd−C external allylic bond, C^3. Subsequent attack by MeO^- on the intermediate acyl formed gives the final ester with retention of the stereochemistry of the Pd-allyl derivative. Their ^{1}H NMR spectra reveal the presence of a regioisomeric methyl ester (6% in the reaction of **3** and 10% for **5**). These minor regioisomers were not completely identified due to severe overlap of their ^{1}H NMR signals with the major derivatives. However, the presence of AB systems in the olefinic region in either case is consistent with a 1,2-disubstituted cyclic double bond, as expected from carbonylation at the most substituted allylic carbon in each of the starting allylic complexes, C^1.

The conformational assignments of **8** and **9** were made by measurement of $^3J_{H-H}$ coupling constants (Chart 3). These show the axial-trans arrangement of H^1 and H^6 for (1*S*,6*S*)-**8** ($^3J_{1-6}$ = 8.6 Hz; $^3J_{5'-6}$ = 4.5 Hz; $^3J_{5-6}$ = 11 Hz) and an equatorial-axial-cis arrangement of H^1 and H^6 for (1*R*,6*R*)-**9** ($^3J_{1-6}$ = 5 Hz; $^3J_{5'-6}$ = 3.4 Hz; $^3J_{5-6}$ = 13.6 Hz).[21]

Chart 3



Scheme 2



The carbonylation of complex **6** is much less selective. In the presence of CO, **6** decomposes through several competitive pathways. The ester derivative (1*R*,6*R*)-**10** is formed stereoselectively but accounts for only 20% of the final reaction mixture. CO insertion into the less substituted Pd−C bond of a transient palladium σ-allyl seems to be slower in this case, and two other processes compete: β-H elimination and reductive elimination of an allylic bromide (Scheme 2). β-H elimination is favored since it gives the stable phenol derivative **7** (15%). The Pd−H species generated undergo H-transfer between Pd atoms to give cyclic monoolefins **11** (5%) and **12** (10%).[15] An allylic alcohol **13** (16%, mixture of diastereoisomers) is also found. **13** could be formed in the basic reaction medium by nucleophillic substitution of Br in the allylic bromide formed by reductive elimination from the starting allyl complex (Scheme 2). Some unreacted Pd-complex (10%) and other unidentified compounds are also found. Ester **10** can be isolated by careful chromatographic separation of the reaction mixture.

The conversion of the Pd allyls synthesized into enantiomerically pure organic derivatives can be achieved if a selective reaction (i.e., carbonylation) is chosen. This works very well for our derivatives except when linked to a thermodynamically favored process, i.e., enol tautomerization in the synthesis and reactions of **6**; in this

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(21) Trost, B. M.; Schmuff, N. R. *J. Am. Chem. Soc.* **1985**, *107*, 396−405.

case we found β-H elimination and decoordination detrimental for our purposes. Otherwise the desired route is faster than other possibly competing processes.

Conclusions

The results obtained show that the selective Pd-migration produces an efficient face selection provided there is a tertiary carbon in a cycle connecting a reactive center inside and outside the cycle (a "gate"). For the dienes used in this work we observe that, when the Pd atom enters the cycle, an optically active Pd-cyclic allyl is formed (complexes **3**, **5,** and **6**); on the other hand when Pd exits the cycle, the configuration of the tertiary carbon (the "gate") also brings about the steroselective formation of an exocyclic allyl (complexes **4**). The addition of "PdHBr" is produced preferentially in the less substituted double bond, and the allyl is formed in the position of the most substituted olefin; in the examples given this affords, as expected, an endocyclic palladium allyl.

Experimental Section

General Comments. ^{19}F, ^{1}H, and ^{13}C NMR spectra were recorded on Bruker AC-300 and ARX-300 instruments. Chemical shifts are reported in δ units (parts per million, ppm) downfield from Me_4Si for ^{1}H and from $CFCl_3$ for ^{19}F. Carbon and hydrogen analyses were carried out on a Perkin-Elmer 2400 CHN elemental analyzer. Organic products were analyzed using a HP-5890 gas chromatographer connected to a HP-5988 mass spectrometer at an ionizing voltage of 70 eV using a quadrupole analyzer. Relative rotations were determined with a Perkin-Elmer 241 polarimeter in $CHCl_3$ solution.

All solvents were dried and distilled before use by standard methods. (*R*)-(+)-Limonene, (1*R*)-(+)-isolimonene, and (*R*)-(−)-carvone were commercially available (Aldrich and Fluka). $[Pd_2(\mu\text{-Br})_2(\eta^3\text{-PfCH}_2\text{CHPh})_2]$ (**1**) was prepared as previously reported.[15]

Synthesis of the η^3-Allylpalladium Derivatives. Synthesis of 3. To a suspension of **1** (0.300 g, 0.328 mmol) in CH_2Cl_2 (20 mL) was added (*R*)-(+)-limonene (0.213 mL, 1.311 mmol). After 2 days the small amount of metallic palladium formed was eliminated by filtration through activated carbon. The yellow solution was evaporated, and the residue was fractionated by column chromatography (silica, neutral), eluting first with *n*-hexane and then with ether. The latter fraction was evaporated to dryness, *n*-hexane was added to the residue, and the mixture was cooled. A yellow solid **3** crystallized (0.142 g, 67% yield).

3: Anal. Calcd for $C_{20}H_{34}Br_2Pd_2$: C 37.12, H 5.30. Found: C 37.20, H 5.24. ^{1}H NMR (300 MHz, δ, $CDCl_3$), 5.30 (d, J = 6.5 Hz, 1H, H^2), 4.89 (d, J = 6.5 Hz, 1H, H^3), 2.08 (ddd, J = 19.6, 11.2, 5.8 Hz, 1H, H^6), 1.87 (dt, J = 10.0, 5.4 Hz, 1H, H^4), 1.79 (ddd, J = 19.6, 5.0, 3.2 Hz, 1H, $H^{6'}$), 1.64 (m, 2H, H,^{5} (Me)-C*H*Me), 1.60 (s, 3H, Me), 0.92 (d, J = 6.8 Hz, 3H, (*Me*)CHMe), 0.89 (d, J = 6.8 Hz, 3H, (Me)CH*Me*), 0.77 (m, J = 11.2, 10.0, 5.0 Hz, 1H, $H^{5'}$); $[\alpha_D]^{20}$ = +130.3 (c = 10 mg/mL in $CHCl_3$).

4_{trans}: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 3.78 (s, 1H, H^{1}_{syn}), 3.25 (s, 1H, H^{1}_{anti}), 2.02 (s, 3H, Me^2), 1.2−2.4 (m, 9H, H,^{4} H,^{5} H,^{6} H,^{7} H^8)*, 0.80 (d, J = 6.5 Hz, 3H, Me^6). *: overlapped with other signals.

Synthesis of 5. It was prepared as described above for **3** but using (1*R*)-(+)-isolimonene instead of limonene. Crystallization from *n*-hexane gave yellow solid **5** (28% yield).

5: Anal. Calcd for $C_{20}H_{34}Br_2Pd_2$: C, 37.12; H, 5.30. Found: C, 37.22; H, 5.22. ^{1}H NMR (300 MHz, δ, $CDCl_3$), 5.25 (d, J = 7.0 Hz, 1H, H^2), 4.74 (d, J = 7.0 Hz, 1H, H^3), 2.33 (m, J = 12.5, 11.7, 5.9 Hz, 1H, H^5), 2.17 (sep., J = 6.8 Hz, 1H, MeC*H*(Me)−), 2.01 (ddd, J = 15.8, 5.9, 2.3 Hz, 1H, H^6), 1.58 (m, J = 12.5, 5.7, 2.3 Hz, 1H, $H^{5'}$), 1.38 (ddd, J = 15.8, 11.7, 5.7 Hz, 1H, $H^{6'}$), 1.20 (b, 4H, Me, H,^{4} AB_3 system), 1.19 (d, J = 6.8 Hz, 3H, *Me*CH(Me)−), 1.18 (d, J = 6.8 Hz, 3H, MeCH-(*Me*)−). $[\alpha_D]^{20}$ = −45.4 (c = 28 mg/mL in $CHCl_3$).

4_{cis}: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 3.75 (s, 1H, H^{1}_{syn}), 3.21 (s, 1H, H^{1}_{anti}), 2.02 (s, 3H, Me^2), 1.2−2.4 (m, 9H, H,^{4} H,^{5} H,^{6} H,^{7} H^8)*, 0.83 (d, J = 6.3 Hz, 3H, Me^6). *: overlapped with other signals.

Synthesis of 6. To a suspension of **1** (0.640 g, 0.7 mmol) in CH_2Cl_2 (30 mL) was added (*R*)-(−)-carvone (0.44 mL, 2.8 mmol). The mixture was stirred for 26 h, and the solution was filtered through activated carbon and evaporated to dryness. The residue was chromatographed through silica (neutral), eluting with *n*-hexane first (**2**), then *n*-hexane/ethyl acetate = 9:1 (**7** and excess diene), and finally *n*-hexane/ethyl acetate = 1:1 (**6**). The last batch was evaporated to dryness, and the residue was triturated with Et_2O and then cooled. The yellow solid (**6**) obtained was filtered, washed with Et_2O, and air-dried (0.24 g, 50% yield).

6: Anal. Calcd for $C_{20}H_{30}O_2Br_2Pd_2$: C, 35.58; H, 4.47. Found: C, 36.07; H, 4.53. ^{1}H NMR (300 MHz, δ, $CDCl_3$), 5.73 (d, J = 6.7 Hz, 1H, H^2), 5.07 (d, J = 6.7 Hz, 1H, H^3), 2.48 (m, 2H, H,^{4} H^5), 1.75 (m, 1H, H^7), 1.64 (s, 3H, Me^1), 1.56 (m, 1H, $H^{5'}$), 0.89 (d, J = 6.6 Hz, 3H, Me^7), 0.86 (d, J = 6.7 Hz, 3H, $Me^{7'}$). $[\alpha_D]^{20}$= −205.48 (c = 12.2 mg/mL in $CHCl_3$).

7: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 7.03 (d, J = 7.7 Hz, 1H, H^3), 6.72 (dd, J = 7.7, 1.7 Hz, 1H, H^4), 6.66 (d, J = 1.7 Hz, 1H, H^6), 4.63 (s, 1H, OH), 2.82 (sep, J = 6.9 Hz, 1H, H^7), 2.21 (s, 3H, Me^2), 1.22 (d, J = 6.9 Hz, 6H, Me^7); MS(EI) *m*/*z* (relative intensity), 150 (M^+, 42), 135 (100), 115 (12), 107 (56), 91 (39), 77 (23), 67 (8), 53 (12), 51 (9).

Preparation of (1*S*,6*S*)-8. A solution of **3** (0.040 g, 0.062 mmol) in CH_2Cl_2 (6 mL) was mixed with another of NaOMe (0.020 g, 0.372 mmol) in MeOH (4 mL). CO was bubbled through the mixture for 15 min. Metallic palladium precipitated, which was filtered through Celite. The resulting solution was evaporated to dryness using a water pump to avoid losing volatiles. The residue was extracted with ether. Solvent evaporation gave a colorless oil (83% yield), which was a mixture of (1*R*,6*S*)-**8** and an unidentified methyl ester in a ratio of 16:1.

(1*S*,6*S*)-**8**: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 5.25 (m, J = 2.3, 0.8 Hz, 1H, H^2), 3.68 (s, 3H, COOMe), 3.04 (m, J = 8.6, 2.3 Hz, 1H, H^1), 1.90−2.05 (m, 2H, H,^{4} $H^{4'}$), 1.78 (m, J = 11, 8.6, 4.5, 2.5 Hz, 1H, H^6), 1.72 (m, 1H, $H^{5'}$), 1.67 (m, $W_{1/2}$ = 4.5 Hz, 3H, Me), 1.62 (m, J = 6.8, 6.7, 2.5 Hz,1H, (Me)C*H*Me), 1.30 (m, J = 13, 11, 6 Hz, 1H, H^5), 0.92 (d, J = 6.7 Hz, 3H, (*Me*)-CHMe), 0.82 (d, J = 6.8 Hz, 3H, (Me)CH*Me*); MS(EI) *m*/*z* (relative intensity), 196 (M^+, 6), 137 (36), 95 (32), 93 (44), 81 (100), 79 (29), 41 (24). $[\alpha_D]^{20}$ = −106.3 (94% purity, c = 5.1 mg/mL in $CHCl_3$).

Preparation of (1*R*,6*R*)-9. It was prepared as described for **6**, using allylpalladium complex **5** as starting material. Crude yield: 66%, a mixture of **9** and an unidentified methyl ester in a 9:1 ratio.

(1*R*,6*R*)-**9**: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 5.41 (m, J = 3.6 Hz, 1H, H^2), 3.67 (s, 3H, COOMe), 3.14 (m, J = 5.0, 3.6 Hz, 1H, H^1), 2.20 (sep., J = 6.9 Hz, 1H, MeC*H*(Me)−), 2.05−2.15 (m, J = 13.6, 5.0, 3.4 Hz, 1H, H^6), 1.90−2.05 (m, J = 18.4, 13.0, 6.2, 6.0, 2.0 Hz, 2H, H,^{4} $H^{4'}$), 1.76 (m, J = 16.0, 13.6, 6.2, 2.0 Hz, 1H, H^5), 1.36 (m, J = 16.0, 13.0, 6.0, 3.4 Hz, 1H, $H^{5'}$), 1.01 (d, J = 6.9 Hz, 6H, Me_2CH−), 0.88 (d, J = 7.0 Hz, 3H, Me); MS(EI) *m*/*z* (relative intensity), 196 (M^+, 4), 95(43), 93 (49), 81 (100), 79 (38), 43 (40), 41 (78). $[\alpha_D]^{20}$ = +56.4 (90% purity, c = 6.1 mg/mL in $CHCl_3$).

Carbonylation of 6. CO was bubbled through a mixture of complex **6** (0.04 g, 0.06 mmol) and NaOMe (0.019 g, 0.35 mmol) in CH_2Cl_2 (6 mL)/MeOH (4 mL). After 30 min, the black suspension obtained was filtered through Celite and the solvent was evaporated to dryness. The residue was extracted

with diethyl ether, and the resulting suspension was filtered. The filtrate was evaporated to dryness, and the residue was chromatographed using preparative TLC (silica sheets 0.25 mm thick) and a mixture of *n*-hexane/ethyl acetate, 7:1. The following products were separated (percentages based on integration of ^{1}H signals in the residue before separation): **10** (20%, R_f = 0.21), **7** (15%, R_f = 0.29), **11** (5%, R_f = 0.29) **12** (10%, R_f = 0.39), **13** (mixture of diastereoisomers **13$_1$** and **13$_2$**, 16%, R_f = 0.04), unreacted **6** (10%, R_f = 0.04).

(1*R*,6*R*)-**10**: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 6.53 (dc, J = 3.0, 1.5 Hz, 1H, H^3), 3.75 (s, 3H, OMe), 3.35 (ddc, J = 9, 3.0, 2.1 Hz, 1H H^4), 2.53 (dd, J = 15.6, 3.7 Hz, 1H H^6), 2.37 (m, J = 11.9, 9, 4.2, 3.7, Hz, 1H, H^5), 2.2 (dd, J = 15.6, 11.9 Hz, 1H, H$^{6'}$), 1.8 (m, J = 2.1, 1.5 Hz, 3H, Me^2), 1.73 (m, J = 6.9, 4.2 Hz, 1H, H^7), 0.93 (d, J = 6.9 Hz, 3H, Me^7), 0.88 (d, J = 6.9 Hz, 3H, Me$^{7'}$); MS(EI) *m*/*z* (relative intensity), 210 (M$^+$, 55), 178 (11), 167 (61), 140 (57), 112 (100), 97 (37), 79 (53), 59 (33), 43 (25), 41 (23).

11: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 5.82, 5.67 (2H, AB system, J = 10.5 Hz, H^3, H^4), 2.45 (m, 1H, H^5), 2.0 (m, 1H, H^2), 1.72 (m, 1H, H^7), 0.98 (d, J = 6.7 Hz, 3H, Me^2), 0.91 (d, J = 6.8 Hz, 3H, Me^7), 0.75 (d, J = 6.6 Hz, 3H, Me$^{7'}$); MS(EI) *m*/*z* (relative intensity), 152 (M$^+$, 25), 135 (4), 109 (100), 95 (10), 79 (9), 67 (2), 43 (8).

12: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 6.75 (m, J = 1.6 Hz, 1H, H^3), 2.53 (ddd, J = 3.6, 2.5, 1.6, 1H, H^6), 2.37 (m, 1H, H^4), 2.15−2 (m, 2H, H$^{4'}$, H$^{6'}$), 1.85 (m, 1H, H^5), 1.76 (m, 3H, Me^2), 0.9 (d, J = 6.7 Hz, 6H, Me^7); MS(EI) *m*/*z* (relative intensity), 152 (M$^+$, 37), 109 (100), 91 (6), 70 (4), 56 (7).

13$_1$: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 6.65 (q, J = 1.6 Hz, 1H, H^3), 4.34 (m, J = 9.3 Hz, 1H, H^4), 2.45 (dd, J = 16, 3.4 Hz, 1H H^6), 2.17 (m, 1H, H^7), 2.08 (d, J = 16 Hz, 1H, H$^{6'}$), 1.97 (dt, J = 9.3, 3.4 Hz, 1H, H^5), 1.77 (m, 3H, Me^2), 0.95 (d, J = 7 Hz, 3H, Me^7), 0.89 (d, J = 7 Hz, 3H, Me$^{7'}$); MS(EI) *m*/*z* (relative intensity), 168 (M$^+$, 48), 126 (48), 111 (44), 98 (100), 77 (10), 70 (46), 41 (30).

13$_2$: ^{1}H NMR (300 MHz, δ, $CDCl_3$), 6.77 (dc, J = 6, 1.4 Hz, 1H, H^3), 4.41 (m, 1H, H^4), 2.4−2.6 (m, 1H, H^6), 2.17 (m, 1H, H^7), 2.1 (m, 1H, H$^{6'}$), 1.92 (dt, J = 8, 2.9 Hz, 1H, H^5), 1.79 (m, 3H, Me^2), 1.02 (d, J = 7 Hz, 6H, Me,^{7} Me$^{7'}$); MS(EI) *m*/*z* (relative intensity), 168 (M$^+$, 48), 126 (48), 111 (44), 98 (100), 77 (10), 70 (46), 41 (30).

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