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Palladium(0)-Catalysed Synthesis of *cis*- and *trans*-Linalyl Oxides

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Abstract Linalyl oxides are obtained from *(Z)*- or *(E)*-6,7-dihydroxy-3,7-dimethyl-oct-2-enyl carbonate in the presence of $Pd_2(dba)_3$ in association with various ligands.
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INTRODUCTION

Linalyl oxides are found in nature and are mainly used in the perfumery and as aromas. They are usually extracted from flowers or fruit. Only a few syntheses have appeared in the literature. Non stereoselective epoxydation of linalool or geraniol followed by cyclisation gave a mixture of *cis*- and *trans*-linalyl oxides.[1] Iodocyclisation of unsaturated alcohols and ethers gave also a mixture of these oxides but in a 1/20 ratio.[2] If the cyclisation of racemic 6,7-dihydroxy-neryl *N*-phenylcarbamate in the presence of zinc chloride afforded the racemic *trans*-linalyl oxide in good yield and high diastereomeric excess,[3] cyclisation of the *(6S)*- [or *(6R)*-] analogue, obtained by microbiological oxidation of geranyl *N*-phenyl carbamate, in the presence of tin chloride gave a mixture of *(2S,5S)*- and *(2R,5S)*- [or *(2R,5R)*- and *(2S,5R)*-] linalyl oxides in the same ratio.[4] Protection of the secondary hydroxyl function as an acetate allowed the obtention of all four enantiomerically pure tetrahydro-2,2,6-trimethyl-6-vinyl-2*H*-pyran-3-ols.[5] These *cis*- and *trans*-tetrahydropyran linalyl oxides were also obtained in a highly enantioselective way *via* asymmetric Sharpless dihydroxylation of linalool.[6] We have previously shown that alcohols and phenols can be used as nucleophiles under very mild conditions in palladium chemistry.[7] In this paper we describe the use of this methodology for the synthesis of linalyl oxides.

RESULTS AND DISCUSSION

The allylic carbonate **2** was obtained in 82% yield by reaction of geraniol **1** with ethyl chloroformate and pyridine in dichloromethane in the presence of a catalytic amount of dimethylaminopyridine. This carbonate **2** was transformed in a "one pot" reaction into dihydroxycompound **3**, in 68% yield, by reaction

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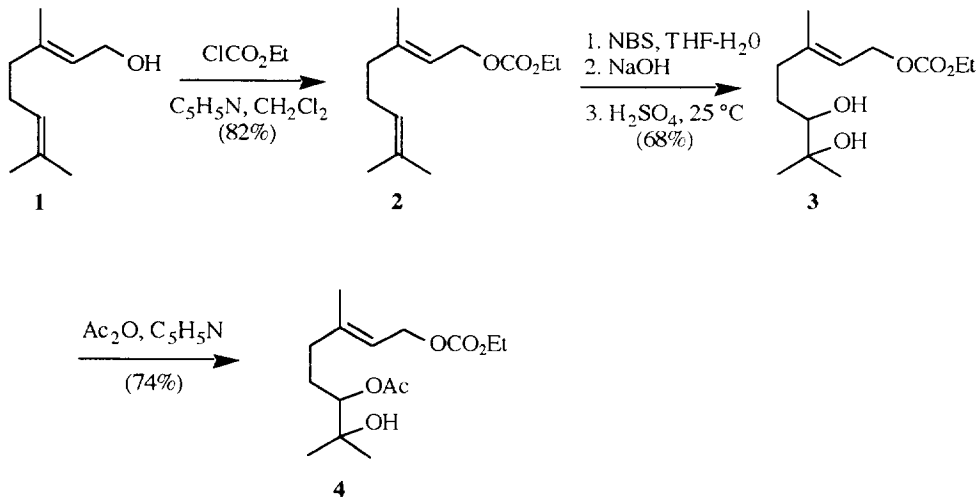
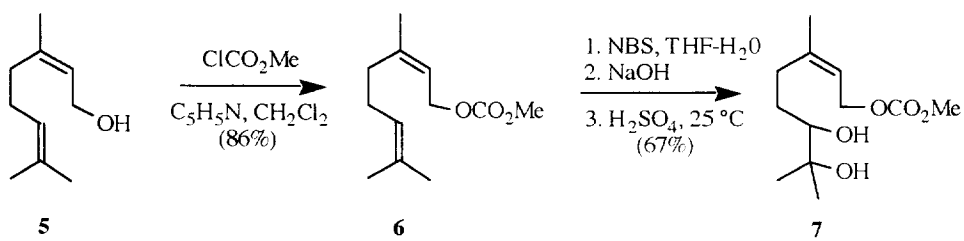
with *N*-bromosuccinimide to give the bromohydrine, cyclisation to an intermediate epoxide and hydrolysis of this epoxide (Scheme 1). Acetylation of this diol under usual conditions afforded the monoacetate **4** in 74% chemical yield. The *(Z)*-stereoisomer **7** was obtained in quite good yield using the same procedure starting from nerol **5** (Scheme 2).



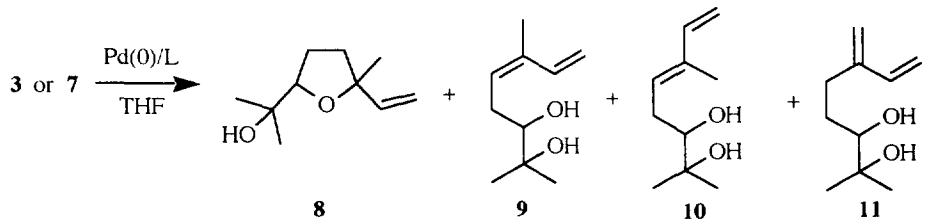
Scheme 1



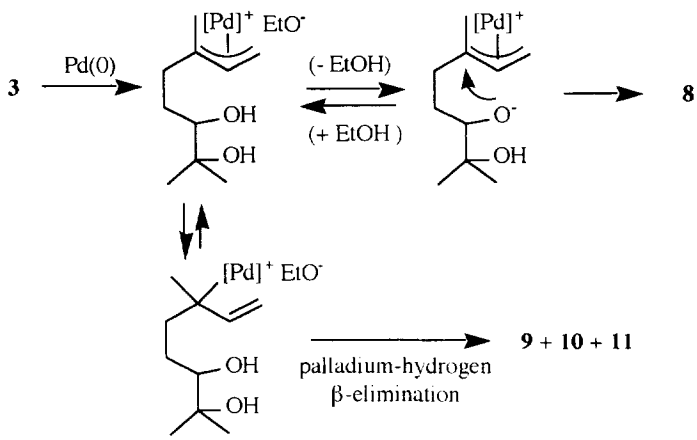
Scheme 2

Cyclisation of compound **3** was attempted in THF at 50 °C in the presence of a catalytic amount of tris(dibenzylidenacetone)dipalladium and 1,4-bis(diphenylphosphino)butane (dppb); the only isolated compound was linalyl oxide **8** in 52 % chemical yield as a mixture of *cis*- and *trans*-isomers (20/80) (Scheme 3). The *cis-trans* ratio was measured on the crude product by GC analysis on an OV1 capillary column and confirmed by ^{1}H and ^{13}C NMR by comparison with the literature data.[4] The cyclisation probably proceeds according to Scheme 4. Oxidative addition of the carbonate **3** to the palladium(0)-complex gives a cationic π-allyl complex. Deprotonation of the hydroxyl group by the methoxide anion could occur at the secondary or the tertiary hydroxyl function; the alkoxide formed by deprotonation of the tertiary hydroxyl function being more sterically hindered for further reaction on the π-allyl system, only the attack by the secondary alkoxide occurs to give the tetrahydrofuran **8**. It is noteworthy that the attack of the alkoxide occurs on the most

substituted position of the π-allyl system, but is in agreement with Baldwin's rules[8] which predict in this case a 5-*exo-trig* cyclisation.



Scheme 3



Scheme 4

We then studied the influence of the phosphine on the stereoselectivity of the cyclisation using THF as the solvent. The results summarized in Table 1 show that the *cis-trans* ratio is independent of the nature of the ligand used: bidentate ligands such as 1,2-bis(diphenylphosphinoethane) (dppe), 1,3-bis (diphenyl phosphinopropane) (dppp), 1,4-bis(diphenylphosphinobutane) (dppb), 1,5-bis(diphenylphosphinopentane) (dpppe) and 1,6-bis(diphenylphosphinohexane) (dpph), monophosphines such as PPh_3, P(2-furyl)$_3$, P(*m*-tolyl)$_3$, or the more basic P(2,6-di-MeO-C_6H_3)$_3$ gave stereoselectivities in the 20/80 range in favour of the *trans*-isomer. Comparison of entries 3 and 4, and 7 and 8 respectively, showed that the reaction temperature of the cyclisation had no effect on the stereoselectivity. Using the catalytic system $Pd(OAc)_2$ + PPh_3 gave almost the same result. The only difference in stereoselectivity was observed when P(*o*-tolyl)$_3$, having a large cone angle, was used as the ligand; the stereoselectivity was 65/35 in favour of the *cis*-isomer. However, the chemical yield was lower, and conversion into the dienes **9**, **10** and **11** in a 62/14/24 ratio was considerable (38% chemical yield). These dienes are formed by a palladium-hydrogen β-elimination reaction of the intermediate σ-allyl complex (Scheme 4). The *E/Z* stereochemistry of dienes **9** and **10** was attributed by ^{13}C NMR on the mixture: the methyl group and the vinylic carbon on the trisubstituted double bond appeared respectively at δ 20.0 and 133.3 ppm for the *Z*-isomer **9** and at δ 12.0 and 141.2 ppm for the *E*-isomer **10**.

Table 1. Palladium(0)-Catalysed Cyclisation of Hydroxycarbonates **3** and **7**. [a]

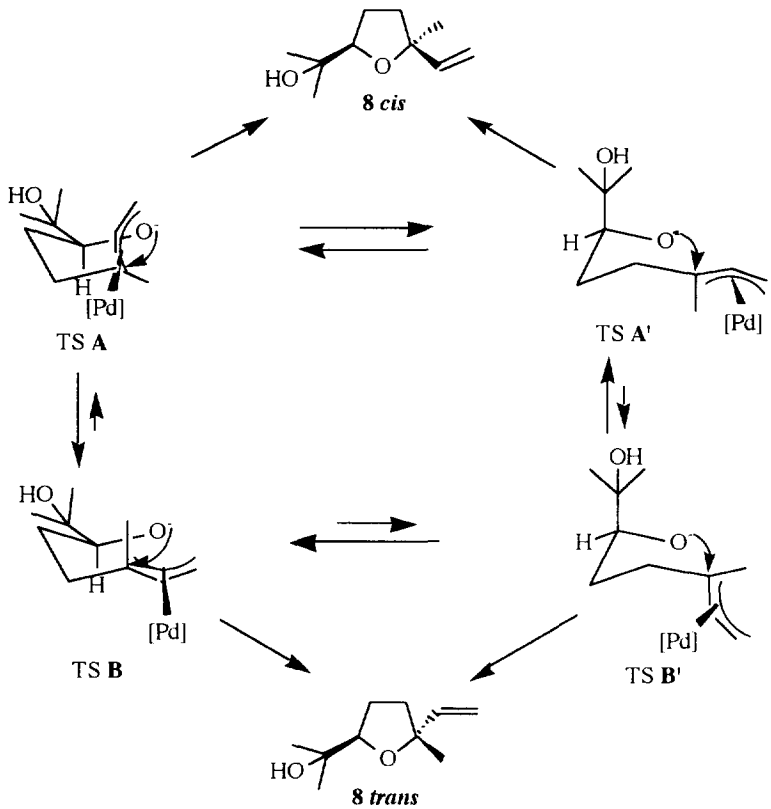
Entry	Compound	Ligand	T °C	Yield in **8** (%) [b]	*trans/cis* (%) [c]
1	**3**	dppe	50	53	84/16
2	**3**	dppp	50	64	80/20
3	**3**	dppb	50	52	80/20
4	**3**	dppb	25	54	80/20
5	**3**	dpppe	50	52	84/16
6	**3**	dpph	50	51	76/21
7	**3**	PPh_3	50	70	81/19
8	**3**	PPh_3	25	65	82/18
9	**3**	PPh_3 [d]	50	65	79/21
10	**3**	P(2-furyl)$_3$	50	65	82/18
11	**3**	P(*o*-tolyl)$_3$	50	35 [e]	35/65
12	**3**	P(*o*-tolyl)$_3$	25	25 [f]	35/65
13	**3**	P(*m*-tolyl)$_3$	50	52	75/25
14	**3**	P(2,6-diMeOC$_6$H$_3$)$_3$	50	50	74/26
15	**7**	dppb	50	59	83/17
16	**7**	PPh_3	50	50	86/14
17	**7**	PPh_3 [d]	50	70	87/13
18	**7**	P(2-furyl)$_3$	50	60	85/15
19	**7**	P(*o*-tolyl)$_3$	50	31	27/73

[a] General conditions: [carbonate]:[Pd]:[P] = 20:1:4, solvent THF, 24 h, 100% conversion. [b] Isolated yields after column chromatography. [c] Determined by GC. [d] $Pd(OAc)_2$ was used. [e] 38% chemical yield in dienes **9**, **10** and **11**. [f] 80% conversion.

In order to examine the role of the double bond geometry on the stereochemical outcome of this cyclisation, the *(Z)*-carbonate **7** was subjected to the palladium(0)-catalysed reaction. The results summarized in Table 1 show that the stereochemistry of the double bond has no influence on the stereoselectivity of the reaction. We observed the formation of the two stereoisomers in a *cis/trans* ratio of approximately 15/85 whatever the ligand used even in the case of P(*o*-tolyl)$_3$; however the formation of dienes **9**, **10** and **11** was also noticed in this latter case. Thus, it is concluded that the diastereoselectivity of the cyclisation is independent of the geometry of the double bond.

The observed stereochemistry could be rationalised according to Scheme 5. The oxidative addition of compound **3** or **7** to the palladium(0) complex gives a π-allyl complex. The *(E)*- or *(Z)*-isomers giving the same stereoselectivity in the cyclisation reaction, it could be assumed that the $\eta^3 \rightleftharpoons \sigma \rightleftharpoons \eta^3$ equilibrium is faster than the attack of the nucleophile on the π-allyl system, the π-allyl complex with the *(E)*-stereochemistry being the most probable. Between the four possible transition states **A**, **A'**, **B** and **B'**, it would be expected that the transition state **B**, with only the methyl group disposing in an axial orientation, is the most favoured. In contrast, the transition states **A**, **A'** and **B'**, with respectively the π-allyl palladium complex, the

$C(CH_3)_2OH$ and methyl groups, and the $C(CH_3)_2OH$ and π-allyl palladium complex in the axial position may suffer from an $A^{1,3}$-strain. So the most advantageous transition state **B** is favoured and gives the *trans*-stereochemistry.

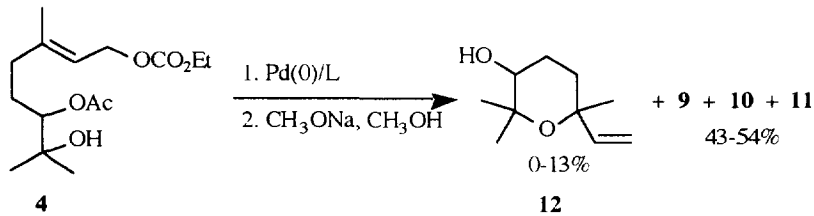


Scheme 5

The reasons for the inversion of diastereoselectivity observed in the cyclisation of **3** using P(*o*-tolyl)$_3$ as the ligand are not clear. However it is noticeable that it is the only case where large amounts of dienes arising from a palladium-hydrogen β-elimination reaction are formed and this secondary reaction could change the *cis-trans* ratio.

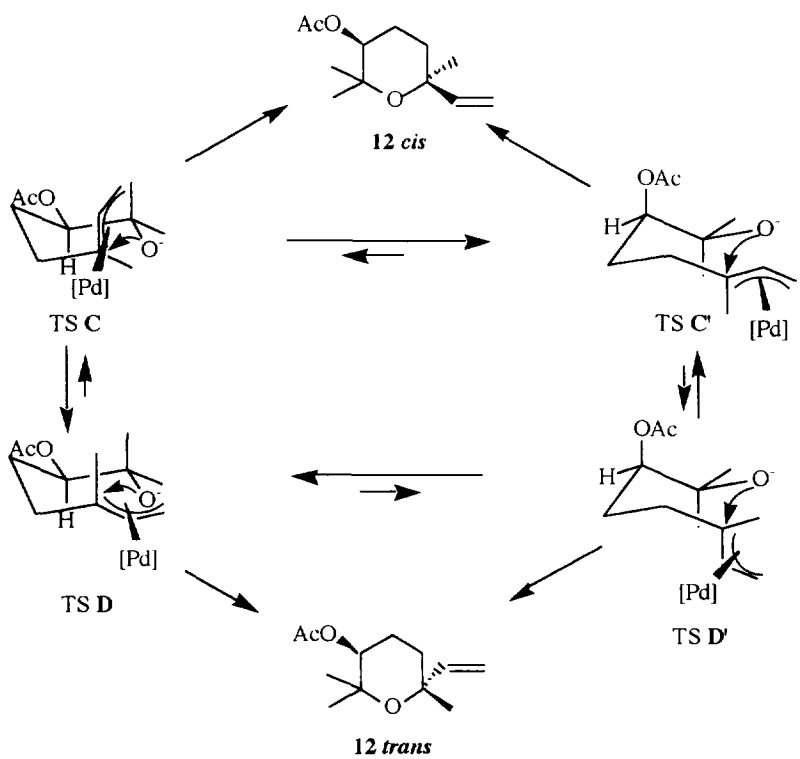
We obviously expected that, by masking the secondary hydroxyl function, the palladium cyclisation would involve the tertiary hydroxyl group, allowing an easy access to tetrahydro-2,2,6-trimethyl-6-vinyl-2*H*-pyran-3-ol. Thus, acetate **4** was treated by a catalytic amount of $Pd_2(dba)_3$ associated with dppb in THF at 50 °C for 24 h and the obtained mixture was directly deacetylated using sodium methoxide in methanol as shown in Scheme 6; unfortunately the only formed products were the dienes **9**, **10** and **11** in 54% yield and in a 30/7/63 ratio as determined by GC analysis. However the use of a catalytic system obtained from $Pd(OAc)_2$ and PPh_3 in a 1/4 ratio allowed the formation of the dienes **9**, **10** and **11** in 43% yield and a 23/13/64 ratio, but also of the desired cyclised product **12** in 13% yield as a mixture of the two *cis*- and *trans*-diastereoisomers in

a 58/42 ratio as shown by GC analysis and comparison of their ^{1}H and ^{13}C NMR spectra with the data of the literature.[5] The very low yield observed in the formation of **12** is probably due to the difficulty for the tertiary alkoxide to approach the π-allyl system.



Scheme 6

The very low stereoselecty observed in the cyclisation of compound **4** in the presence of palladium complex as catalyst could also be rationalised according to Scheme 7. After oxidative addition of the carbonate to the palladium complex, the formation of the tetrahydropyran ring could occur by attack of the alloxide on the π-allyl system according to the four intermediates shown in this Scheme: if chair-like transition states **C** and **C'**



Scheme 7

led to the formation of the *cis*-isomer, **D** and **D'** led to the *trans*-isomer. We believed that the most favoured transition states are **C'** (an acetate group and two methyl groups in an axial orientation) and **D** (only two methyl groups in an axial orientation), where the palladium complex is equatorially disposed; the small energy difference between the two transition states **C'** and **D** could explain the low stereoselectivity of the cyclisation.

CONCLUSION

In conclusion, the palladium(0)-catalysed cyclisation of alkyl *(Z)*- or *(E)*-6,7-dihydroxy-3,7-dimethyl oct-2-enyl carbonate provides a very easy access to linalyl oxides in quite good yields. Owing to the accessibility of the starting diols **3** and **7** in an optically pure form using the methodology of Furstoss and coll.[9] or the asymmetric Sharpless dihydroxylation of geraniol,[10] this cyclisation procedure could be used for the synthesis of the pure enantiomers of **8**. The formation of the tetrahydropyranic analogues is more difficult, and we observed in this case the formation, in large amount, of the products resulting from a β-elimination reaction.

EXPERIMENTAL SECTION

All reactions involving palladium catalysis were carried out under nitrogen using Schlenk techniques. THF was distilled in the presence of sodium-benzophenone and stored under nitrogen. ^{1}H NMR (200 MHz) and ^{13}C NMR (50.4 MHz) spectra were recorded on a BRUKER AM 200 spectrometer using Me_4Si as internal standard. Chromatography was carried out on Merck silica gel, grade 60 (230-400 mesh, 66 Å). GLC analysis were recorded with a GIRDEL DELSI 330 capillary gas chromatography equipped with an OV 101 (25 m x 0.32 mm) capillary column. Geraniol, nerol, PPh_3, P(2-furyl)$_3$, P(*o*-tolyl)$_3$, P(*m*-tolyl)$_3$, P(2,6-di $MeOC_6H_3)_3$, 1,2-bis(diphenylphosphino)ethane (dppe), 1,3-bis(diphenylphosphino)propane (dppp), 1,4-bis (diphenylphosphino)butane (dppb), 1,5-bis(diphenylphosphino)pentane (dpppe), 1,6-bis(diphenylphosphino) hexane (dpph), $Pd_2(dba)_3$, $Pd(OAc)_2$ are from Aldrich. Ethyl geranyl carbonate **2** and methyl neryl carbonate **6** were prepared according to the literature.[11]

Preparation of compounds 3 and 7. To a solution of 12.8 mmol of compound **2** or **6** in a mixture of THF/H_2O (13/5 mL) was slowly added 2.28 g (12.8 mmol) of *N*-bromosuccinimide. When the bromohydrine was completely formed (approximately 30 mn) 19.2 mmol of a 5 N aqueous solution of NaOH (4 mL) was added. After being stirred at 25 °C for 20 h the solution was extracted with diethylether. After evaporation of the solvent, the residue was dissolved in a mixture of THF/H_2O (70/30 mL) and 19.2 mmol of H_2SO_4 20% (6.3 mL) were added. After stirring at 25 °C for 8 h, the solution was washed with a saturated solution of NaCl and extracted with diethylether. After evaporation of the solvent, the residue was purified by column chromatography on silica gel (petroleum ether/ethyl acetate 1:1) to give the dihydroxycarbonate **3** or **7**.

Ethyl *(E)*-6,7-dihydroxy-3,7-dimethyloct-2-enyl carbonate 3. Yield 68%; R_f 0.40; ^{1}H NMR ($CDCl_3$) δ 1.16 (s, 3 H, CH_3), 1.21 (s, 3H, CH_3), 1.30 (t, *J* = 7.1 Hz, 3H, CH_3CH_2), 1.40-2.40 (m, 6H, H-4, H-5, 2 x OH), 1.74 (s, 3H, CH_3), 3.34 (bd, *J* = 10.1, 1H, H-6), 4.19 (q, *J* = 7.1 Hz, 2H, CH_2CH_3), 4.65 (d, *J* = 7.2 Hz, 2H, H-1), 5.43 (t, *J* = 7.2 Hz, 1H, H-2). ^{13}C NMR ($CDCl_3$) δ 14.3 (CH_3CH_2), 16.5 (CH_3), 23.2 (CH_3), 26.5 (CH_3), 29.4 (C-5), 36.6 (C-4), 63.9 (CH_2CH_3), 64.4 (C-1), 73.1 (C-7), 78.0 (C-6), 118.2 (C-2), 142.9 (C-3), 155.3 (C=O). Anal. Calcd. for $C_{13}H_{24}O_5$: C, 59.98; H, 9.29. Found: C, 59.59; H, 9.35.

Methyl *(Z)*-6,7-dihydroxy-3,7-dimethyloct-2-enyl carbonate 7. Yield 67%; R_f 0.38; ^{1}H NMR ($CDCl_3$) δ 1.16 (s, 3H, CH_3), 1.21 (s, 3H, CH_3), 1.40-2.40 (m, 5H, H-4, H-5, OH), 1.77 (s, 3H, CH_3), 2.82 (d, *J* = 4.7, 1H, OH), 3.29 (bdd, *J* = 4.7 and 10.6 Hz, 1H, H-6), 3.78 (s, 3H, CH_3O), 4.66 (dd, *J* = 7.5 and 12.2 Hz, 1H, H-1), 4.72 (dd, *J* = 7.8 and 12.2 Hz, 1H, H-1), 5.42 (dd, *J* = 7.5 and 7.8 Hz, 1H, H-2). ^{13}C NMR ($CDCl_3$) δ 23.2 (CH_3), 23.3 (CH_3), 26.3 (CH_3), 28.7 (C-5), 29.4 (C-4), 54.8 (CH_3O), 64.5 (C-1), 72.9 (C-7), 77.2 (C-6), 119.4 (C-2), 143.1 (C-3), 156.0 (C=O). Anal. Calcd. for $C_{12}H_{22}O_5$: C, 58.52; H, 9.00. Found: C, 58.92; H, 8.94.

Ethyl *(E)*-6-acetoxy-7-hydroxy-3,7-dimethyloct-2-enyl carbonate 4. To a solution of the carbonate **3** (1.10 g, 4.22 mmol) in 4 mL of pyridine were slowly added 4 mL (42.2 mmol) of acetic anhydride. After stirring for 15 h à 25 °C, the mixture was hydrolysed and extracted with diethylether. The organic phase was washed with an aqueous HCl solution (10%), an aqueous $NaHCO_3$ solution (10%) and water. After evaporation of the solvent, the residue was purified by column chromatography on silica gel (petroleum ether/ethyl acetate 2:1) to afford compound **4** in 74% chemical yield. R_f 0.41; ^{1}H NMR ($CDCl_3$) δ 1.19 (s, 3H, CH_3), 1.20 (s, 3H, CH_3), 1.30 (t, *J* = 7.1 Hz, 3H, CH_3CH_2), 1.72 (s, 3H, CH_3), 1.75-2.00 (m, 5H, H-4, H-5, OH), 2.11 (3H, s, CH_3CO), 4.19 (q, *J* = 7.1 Hz, 2H, CH_2CH_3), 4.64 (d, *J* = 7.2 Hz, 2H, H-1), 4.79 (dd, *J* = 3.5 and 9.3 Hz, 1H, H-6), 5.38 (dt, *J* = 1.1 and 7.2 Hz, 1H, H-2). ^{13}C NMR ($CDCl_3$) δ 14.3 (CH_3CH_2), 16.6 (CH_3), 21.1 (CH_3CO), 25.0 (CH_3), 26.5 (CH_3), 27.5 (C-5), 36.0 (C-4), 63.9 (CH_2CH_3), 64.3 (C-1), 72.4 (C-7), 79.5 (C-6), 118.3 (C-2), 142.2 (C-3), 155.3 (CO), 171.3 (CO). Anal. Calcd. for $C_{15}H_{26}O_6$: C, 59.58; H, 8.67. Found: C, 59.20; H, 8.71.

Typical procedure for the palladium(0)-catalysed cyclisation of 3 and 7. To a solution of $Pd_2(dba)_3$ (23 mg, 0.025 mmol) and the diphosphine (0.1 mmol) or the monophosphine (0.2 mmol) in THF (3 mL) was added a solution of hydroxycarbonate **3** or **7** (1 mmol) in THF (3 mL). After stirring at the desired temperature for 24 h, the solvent was removed in vacuo and the residue was chromatographed on silica gel (petroleum ether/ethyl acetate 5:1) to give the cyclised product **8**. The stereoselectivity of the reaction was determined by gas chromatography using an OV 101 (25 m x 0.32 mm) capillary column at 60 °C.

***trans*-2-Methyl-2-vinyl-5-(2-hydroxyprop-2-yl)tetrahydrofuran 8.** R_f 0.40; ^{1}H NMR ($CDCl_3$) δ 1.14 (s, 3H, CH_3), 1.24 (s, 3H, CH_3), 1.32 (s, 3H, CH_3), 1.70-1.95 (m, 4H, H-3, H-4), 2.15 (s, 1H, OH), 3.80 (m, 1H, H-5), 5.00 (dd, *J* = 1.6 and 10.6 Hz, 1H, =CH_2), 5.19 (dd, *J* = 1.6 and 17.3 Hz, 1H, =CH_2), 5.88 (dd, *J* = 10.6 and 17.3 Hz, 1H, =CH-). ^{13}C NMR ($CDCl_3$) δ 24.2 (CH_3), 26.3 (C-4), 26.8 (CH_3), 27.2 (CH_3), 37.5 (C-3), 71.1 (COH), 83.0 (C-2), 85.5 (C-5), 111.3 (=CH_2), 143.7 (=CH-). These data are in agreement with the literature.[4]

***cis*-2-Methyl-2-vinyl-5-(2-hydroxyprop-2-yl)tetrahydrofuran 8.** R_f 0.35; ^{1}H NMR ($CDCl_3$) δ 1.14 (s, 3H, CH_3), 1.24 (s, 3H, CH_3), 1.33 (s, 3H, CH_3), 1.75-1.95 (m, 4H, H-3, H-4), 2.08 (s, 1H, OH), 3.87 (m, 1H, H-

5), 5.02 (dd, J = 1.2 and 10.7 Hz, 1H, =CH_2), 5.20 (dd, J = 1.2 and 17.4 Hz, 1H, =CH_2), 5.98 (dd, J = 10.7 and 17.4 Hz, 1H, =CH-). ^{13}C NMR ($CDCl_3$) δ 24.3 (CH_3), 26.0 (CH_3), 26.5 (C-4), 27.4 (CH_3), 37.9 (C-3), 71.2 (COH), 82.8 (C-2), 85.5 (C-5), 111.6 (=CH_2), 144.3 (=CH-). These data are in agreement with the literature.[4]

When the reaction was performed in the presence of P(*o*-tolyl)$_3$ as the ligand, the dienes **9**, **10** and **11** were eluted with petroleum ether/ethyl acetate 3:2 (R_f 0.41) and the selectivity in the formation of these compounds was determined with an OV 101 (25 m x 0.32 mm) capillary column at 100 °C. The products were not separated and the spectra were determined on the mixture.

***(5Z)*-2,6-Dimethyl-octa-5,7-dien-2,3-diol 9**. ^1H NMR ($CDCl_3$) δ 1.21 (s, 3H, CH_3), 1.25 (s, 3H, CH_3), 1.60-2.00 (m, 4H, H-4, 2 x OH), 1.87 (s, 3H, CH_3), 3.41 (bd, J = 9.6 Hz, 1H, H-3), 5.20 (dd, J = 1.3 and 10.8 Hz, 1H, H-8), 5.28 (dd, J = 1.3 and 17.3 Hz, 1H, H-8), 5.51 (dd, J = 7.3 and 7.5 Hz, 1H, H-5), 6.76 (dd, J = 10.8 and 17.3 Hz, 1H, H-7). ^{13}C NMR ($CDCl_3$) δ 20.0 (CH_3), 23.6 (CH_3), 26.5 (CH_3), 29.9 (C-4), 72.8 (C-2), 78.0 (C-3), 114.6 (C-8), 127.1 (C-5), 133.3 (C-7), 135.2 (C-6).

***(5E)*-2,6-Dimethyl-octa-5,7-dien-2,3-diol 10**. ^1H NMR ($CDCl_3$) δ 1.20 (s, 3H, CH_3), 1.24 (s, 3H, CH_3), 1.50-2.10 (m, 4H, H-4, 2 x OH), 1.77 (s, 3H, CH_3), 3.42 (m, 1H, H-3), 5.19 (dd, J = 1.4 and 10.6 Hz, 1H, H-8), 5.26 (dd, J = 1.4 and 17.5 Hz, 1H, H-8), 5.60 (dd, J = 7.4 and 7.6 Hz, 1H, H-5), 6.39 (dd, J = 10.6 and 17.5 Hz, 1H, H-7). ^{13}C NMR ($CDCl_3$) δ 12.0 (CH_3), 26.5 (CH_3), 30.8 (C-4), 30.9 (CH_3), 73.1 (C-2), 78.2 (C-3), 111.4 (C-8), 129.3 (C-5), 136.4 (C-6), 141.2 (C-7).

2-Methyl-6-methylene-oct-7-en-2,3-diol 11. ^1H NMR ($CDCl_3$) δ 1.16 (s, 3H, CH_3), 1.21 (s, 3H, CH_3), 1.40-2.40 (m, 6H, H-4, H-5, 2 x OH), 3.41 (bd, J = 9.6 Hz, 1H, H-3), 5.05 (bs, 2H, =CH_2), 5.08 (dd, J = 1.4 and 10.5 Hz, 1H, H-8), 5.26 (dd, J = 1.4 and 17.6 Hz, 1H, H-8), 6.38 (dd, J = 10.5 and 17.6 Hz, 1H, H-7). ^{13}C NMR ($CDCl_3$) δ 23.2 (CH_3), 26.5 (CH_3), 28.5 (C-4), 30.2 (C-5), 73.2 (C-2), 78.2 (C-3), 113.5 (C-8), 116.0 (=CH_2), 138.7 (C-7), 146.1 (C-6).

Anal. Calcd for $C_{10}H_{18}O_2$: C, 70.55; H, 10.66. Found: C, 71.00; H, 10.62.

Typical procedure for the palladium(0)-catalysed cyclisation of 4. To a solution of $Pd_2(dba)_3$ (23 mg, 0.025 mmol) and the diphosphine (0.1 mmol) or the monophosphine (0.2 mmol) in THF (3 mL) was added a solution of hydroxycarbonate **4** (302 mg, 1 mmol) in THF (3 mL). After stirring at the desired temperature for 24 h, the solvent was removed in vacuo and the residue was treated by a 0.1 M solution of sodium methylate in methanol (50 mL) at room temperature for 2 h. After evaporation of the solvent, the residue was chromatographed on silica gel (petroleum ether/ethyl acetate 3:1) to give the cyclised product **12** and the dienes **9**, **10** and **11**. The stereoselectivity of the reaction was determined by gas chromatography using an OV 101 (25 x 0.32 mm) capillary column at 60 °C.

***trans*-3-Hydroxy-2,2,6-trimethyl-6-vinyltetrahydropyran 12.** R_f 0.53; ^1H NMR ($CDCl_3$) δ 1.21 (s, 3H, CH_3), 1.22 (s, 3H, CH_3), 1.25 (s, 3H, CH_3), 1.50-2.10 (m, 5H, H-4, H-5, OH), 3.42 (m, 1H, H-3), 4.97 (dd, J = 1.2 and 17.6 Hz, 1 H, =CH_2), 5.00 (dd, J = 1.2 and 11.2 Hz, 1H, =CH_2), 5.94 (dd, J = 11.2 and 17.6 Hz, 1H, =CH-). ^{13}C NMR ($CDCl_3$) δ 24.3 (C-4), 26.5 (CH_3), 27.3 (CH_3), 27.7 (C-5), 31.0 (CH_3), 71.3 (C-3), 73.7 (C-2), 75.4 (C-6), 110.6 (=CH_2), 146.9 (=CH-). These data are in agreement with the literature.[5]

***cis*-3-Hydroxy-2,2,6-trimethyl-6-vinyltetrahydropyran 12**. R_f 0.58; ^1H NMR ($CDCl_3$) δ 1.16 (s, 3H, CH_3), 1.17 (s, 3H, CH_3), 1.22 (s, 3H, CH_3), 1.50-2.10 (m, 5H, H-4, H-5, OH), 3.44 (m, 1H, H-3), 4.97 (dd, J = 1.0

and 17.6 Hz, 1 H, =CH_2), 5.04 (dd, J = 1.0 and 11.4 Hz, 1H, =CH_2), 5.97 (dd, J = 11.4 and 17.6 Hz, 1H, =CH-). ^{13}C NMR ($CDCl_3$) δ 20.9 (CH_3), 25.8 (C-4), 29.6 (CH_3), 31.8 (CH_3), 32.6 (C-5), 73.6 (C-2), 74.9 (C-3), 76.1 (C-6), 110.7 (=CH_2), 146.4 (=CH-). These data are in agreement with the literature.[5]

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