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Amplification of chirality by transition metal coordination: synthesis of chiral allenes and allene manganese complexes of high enantiomeric purity. Synthesis of methyl (*R*,*E*)-(−)-(2,4,5-tetradecatrienoate (pheromone of *Acanthoscelides obtectus* (say))

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Abstract

The enhancement of the asymmetry of chiral allenes by coordination with a transition metal can be turned to account for (easy) resolution of the complexes and therefore the allenes themselves. This is illustrated here on allene aldehyde complexes of (η-methylcyclopentadienyl) dicarbonylmanganese, possibly bearing a second electron withdrawing substituent, and by the synthesis of an optically active alkenylallenic insect pheromone of high enantiomeric purity.

1. Introduction

Electrophilic allenes have been obtained from the corresponding conjugated alkynes by easy isomerization of their (η-methylcyclopentadienyl) dicarbonylmanganese complexes.[1] The synthesis of optically active allenes[2] can take account of the availability of such allene complexes, since their resolution would lead to allene enantiomers after decomplexation. In this instance, the most interesting functional group for further synthetic use is probably the formyl group, particularly because the poorly stable allene aldehydes are greatly stabilized by complexation. The resolution of chiral allene aldehyde complexes was therefore our main objective.

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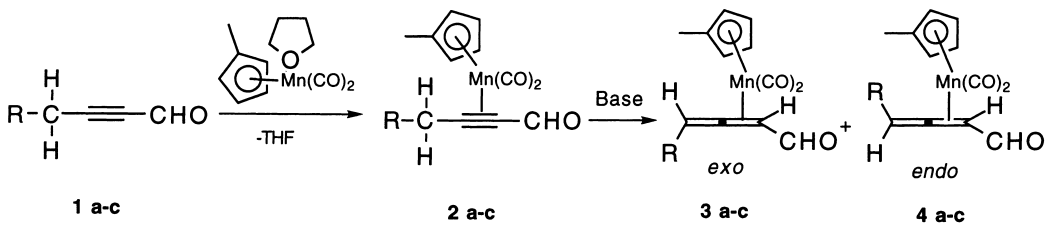
2. Results and discussion

Metal–carbonyl complexes of organic ligands bearing an aldehyde function have been resolved to enantiomers of high enantiomeric purity by use of several chiral auxiliaries. Among them, (*S*)-(−)-5-(α-phenylethyl) semioxamazides[3] have been successfully applied to the resolution of tricarbonylchromium complexes of arenes,[4] and tricarbonyliron complexes of dienes[5] or trimethylenemethanic ligands.[6]

The isomerization of manganese complexes of substituted acetylenic aldehydes (R≠H), performed as previously described with basic aluminium oxide led to mixtures of *endo* and *exo* allene complexes which were in general, separable by chromatography.[1] We observed, however, that only the minor *exo* allene aldehyde complexes could be resolved using the semioxamazide reagent, the mixture of *syn* and *anti* diastereomeric semioxamazones not being well separated by chromatography in the *endo* series. By reinvestigation of the base catalysed isomerisation of alkyne to allene complexes, we found that homogeneous basic systems [KOH–MeOH, MeONa–MeOH, or better 1.8-diazabicyclo(5.4.0)undec-7-ene (DBU) in THF at −40°C] drove the reaction almost exclusively toward *exo* complexes [**2b**,**c**→**3b**,**c** (Scheme 1)].



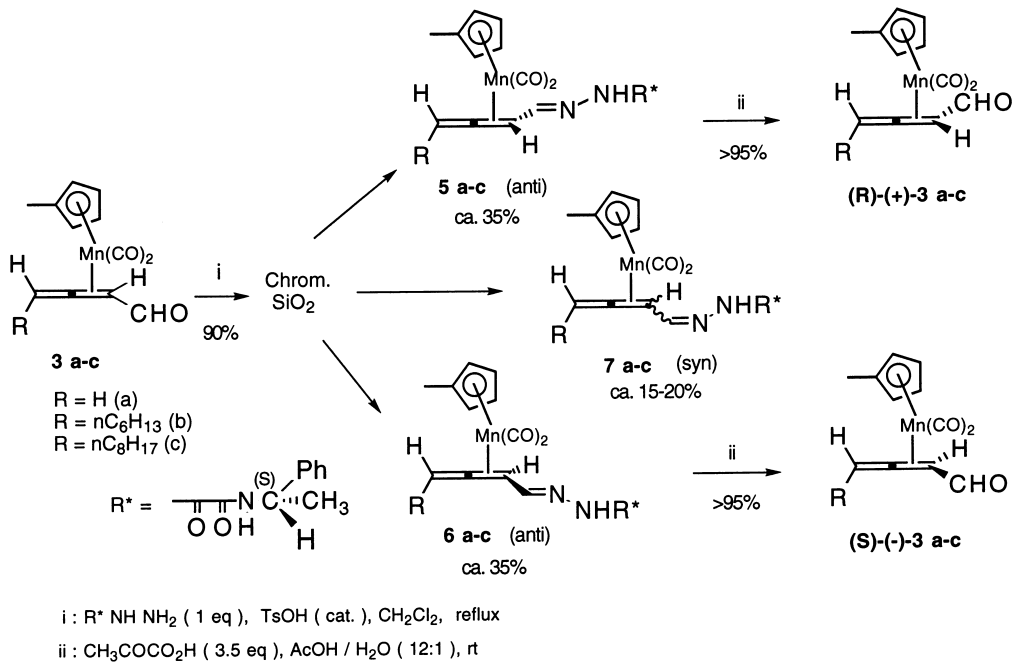
	R	Base	exo (%)	endo (%)	total yield
2a	H	Al_2O_3	**3a**	**3a**	72 %
2b	nC_6H_{13}	Al_2O_3	**3b** (44)	**4b** (56)	60 %
2b	nC_6H_{13}	DBU	**3b** (97)	**4b** (3)	50 %
2c	nC_8H_{17}	DBU	**3c** (98)	**4c** (2)	51 %

Scheme 1.

In this series, the semioxamazones were formed as mixtures of ca 80% separable *anti* diastereomers **5** and **6** (less polar group) and ca 20% unseparable *syn* diastereomers **7** (more polar group). After separation of the *anti* diastereomers by simple SiO_2 column chromatography, followed by cleavage with pyruvic acid,[5,6] the enantiomeric allene aldehyde complexes (+)-**3b**,**c** and (−)-**3b**,**c** were obtained with greater than 95% ee, the method working as well in the simple case of **3a** (Scheme 2).

The enantiomeric excess could be determined directly by ^{1}H-NMR measurements using the chiral shift reagent Eu(hfc)$_3$ (for **3a**) or Eu(dcm)$_3$,[7] which performed best here (estimated precision better than 5% for **3b**,**c**).

Highly electrophilic 1-2-η^3-functionalized 1-formyl allene complexes are also available by isomerization of manganese complexes.[8] However their analogous resolution is handicapped by haptotropic shifts at the stage of the chiral semioxamazones, apparently catalyzed by silica gel.[9] Semioxamazones of 1-2-η^3-formylallene complexes, bearing another electrophilic group at position 1, are thus partially interconverted to 1-2-η^3-functionalized (E=CO_2Me, CHO) allene complexes, bearing now the semioxamazone group at position 1.[10] On the contrary, if the formyl group is in position 1, with the other functional group in 3, the semioxamazones are stable, and can be separated by SiO_2 chromatography. This permitted us to achieve the resolution of the 3-methoxycarbonyl 1-formyl allene complex **9** which gave, with *S*-(−)-5-(α-phenylethyl) semioxamazide, two easily separated diastereomeric semioxamazones **11** ([α]$_D$ +51,



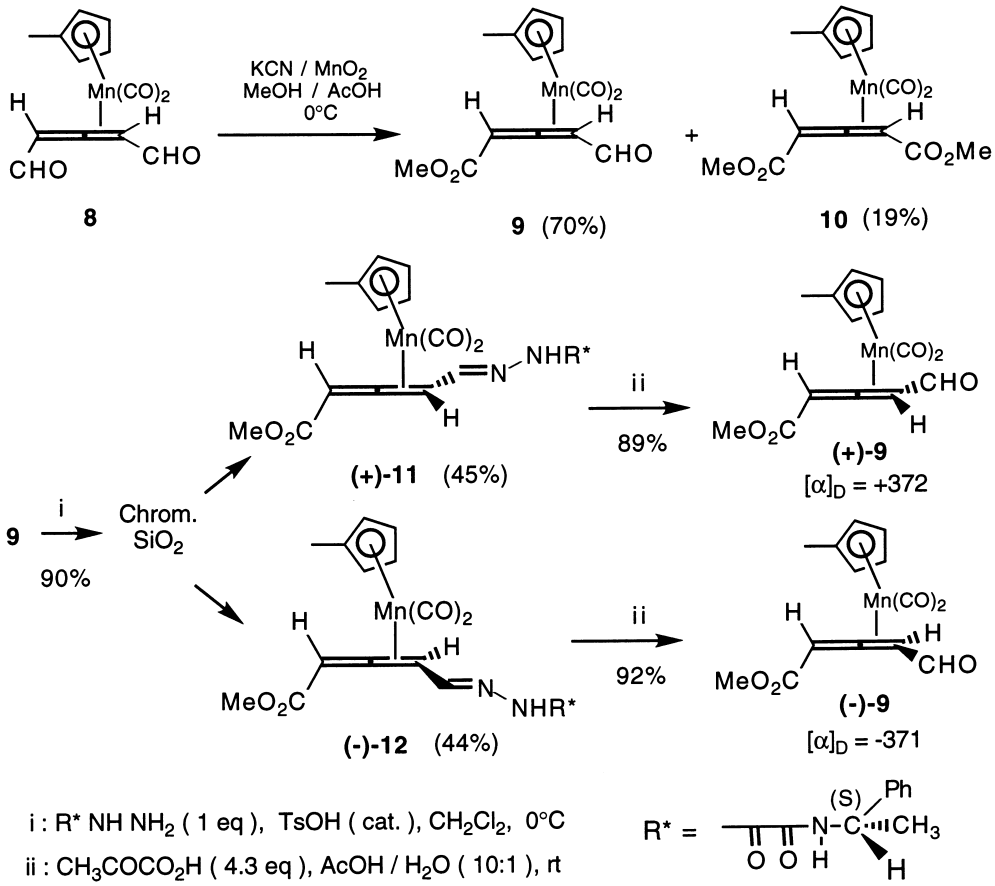
Scheme 2.

45%) and **12** ([α]$_D$ −213, 44%). After regeneration of the aldehyde function the enantiomeric complexes (+)-**9** and (−)-**9** were obtained in good overall yields (89% and 92%) with at least 95% ee (NMR in the presence of Eu(hfc)$_3$; [α]$_D$ +372 and −371). The racemic complex **9** was obtained as a major product by regioselective oxidation of the diformyl allene complex **8**,[8] using Corey's procedure for the conversion of aldehydes into esters (Scheme 3).[11]

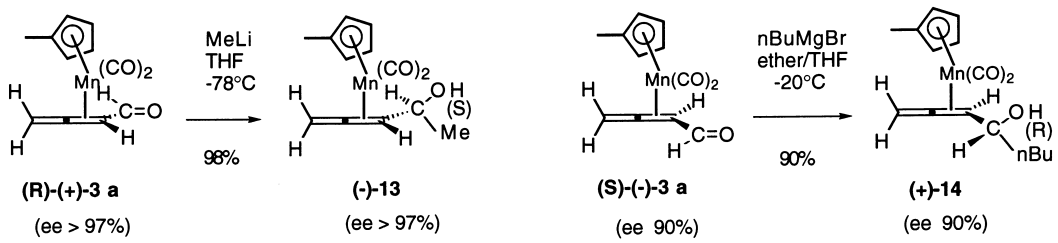
Being stabilized forms of allene aldehydes, the optically active complexes can obviously be used for the synthesis of other chiral allenes. Two reactions are particularly worth mentioning: the highly diastereoselective reaction with Grignard or organolithium reagents to give secondary alcohols and the Horner–Emmons reaction.

The allene aldehyde complexes **3a** and **3c** reacted for instance nearly quantitatively with methyl- or butyllithium in THF at −78°C and with methylmagnesium iodide or n-butylmagnesium bromide in ether at −20°C to give secondary alcohols as single diastereomers (^{1}H-NMR: de >97%). The nucleophilic attack is therefore most probably an *exo* process (i.e. at the face opposite the metal) with a highly preferred *s-trans* conformation for the 'unsaturated' aldehyde. In the solid state, this was the observed conformation for both acrolein subunits of the 1,3-diformylallene manganese complex **8**.[8] As a consequence, the formation of *unlike* diastereomers would be highly favoured ((*S*)-allene complex→(*R*)-alcohol, (*R*)-allene complex→(*S*)-alcohol). In the optically active series, no racemization was observed and secondary allenol complexes of high ee were obtained ((+)-**3a**→(−)-**13**, quant.; (−)-**3a**→(+)-**14**, 90%). The enantiomeric excess could easily be determined by use of the shift reagent Eu(hfc)$_3$ which gave particularly well-split signals with the racemic allenol complexes (ee >97% for (−)-**13** and ≥90% (+)-**14**; Scheme 4).

The Horner–Emmons reaction allowed a rapid synthesis of the relatively labile sex pheromone of the male dried bean beetle (*Acanthoscelides obtectus* (Say))[12] obtained as the natural enantiomer with a high enantiomeric excess (Scheme 5). The formylallene complex (−)-**3c** was converted by Horner–Emmons



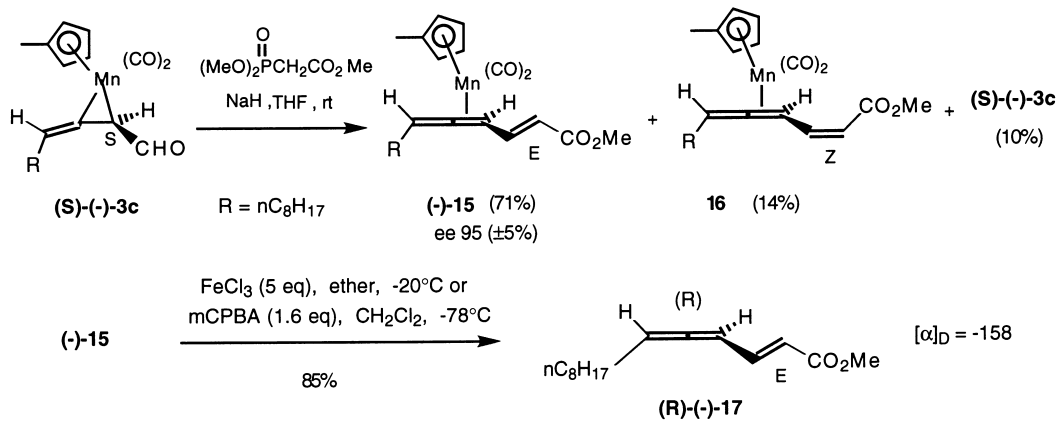
Scheme 3.



Scheme 4.

reaction into the vinylogous *E*-ester (−)-**15** [79%, $[\alpha]_D$=−329, ee 95±5% (^{1}H-NMR in the presence of Eu(dcm)$_3$)] obtained along with 15% separable *Z*-ester **16**. Decomplexation with anhydrous $FeCl_3$ or meta-chloroperbenzoic acid (mCPBA) led to the free allenic pheromone (−)-**17** (85%, $[\alpha]_D$=−158; Scheme 5). Similarly the non-natural enantiomer (+)-**17** of the pheromone ($[\alpha]_D$=+158) was obtained from the formylallene complex (+)-**3c**.

The absolute configuration of (−)-**17** must be *R*,[13,14] so that the configuration of the formyl bearing carbon of the complex (−)-**3c** and, most probably, (−)-**3b** and (−)-**3a** must be *S*. The enantiomeric excess ($[\alpha]_D$=−158) is very high in comparison with the natural pheromone ($[\alpha]_D$=−128), probably 90% based on the value given by Mori et al.[13] for their synthetic pheromone (ee 92%, $[\alpha]_D$=−162).



Scheme 5.

Our synthesis compares favourably with other more tedious syntheses of this optically active allenic pheromone (estimated ee values ranging from 45 to 55%).[14,15] In particular, it is noteworthy that the analogous synthesis of Oehlschalger et al., also using a Horner–Emmons reaction as the last step but with the poorly stable free aldehyde (41% yield), led to a partially racemized product ($[\alpha]_D=-79.5$), although the precursors of the aldehyde were of high enantiomeric purity.[15]

The advantage of using such manganese complexes for the synthesis of allenes is therefore obvious. Not only are reactive allenes highly stabilized by coordination with the metal, but in addition, their efficient resolution is made much easier. Another advantage with chiral allenes is that their enantiomeric excess can, in general, be easily determined at the stage of their metal complexes by simple NMR methods based on optically active shift reagents.[16]

3. Experimental section

Elemental analyses were performed by the Service de Microanalyse du Centre de Recherche Chimie de l'ULP de Strasbourg. IR spectra were recorded on a Perkin–Elmer IR-177 instrument (ν in cm^{-1}). Optical rotations were determined at 22°C on a Perkin–Elmer 241 MC polarimeter at the sodium D line, concentrations are given in g/100 ml. ^1H NMR (200 MHz) spectra were recorded on a Bruker WP-200 SY spectrometer [δ in ppm referenced to $CHCl_3$ (7.27 ppm) as an internal standard with chemical shifts referenced to TMS. Coupling constants J are given in hertz; multiplicities are designated as singlet (s), doublet (d), triplet (t), quartet (q) and multiplet (m)]. The solutions were filtered on Millipore membranes (GS 0.22 μm) and degassed with argon before measurement. Melting points were determined on a Reichert melting point apparatus and are uncorrected. Analytical thin layer chromatography was performed on Merck Kieselgel 60 F_{254} glass plates (0.25 mm), compounds were detected by UV light (254 nm) and by aspersion with an ethanol–vanilline–H_2SO_4 solution followed by heating. Column chromatography was carried out on Merck Kieselgel 60 (70–230 mesh ASTM). Photolyses were carried out with a Philips HPK-125 medium pressure Hg lamp in a Pyrex glass reactor.

All reactions were performed under an argon atmosphere in dried glassware. Solvents were distilled before use: ether and THF over sodium–benzophenone, benzene over sodium and CH_2Cl_2 over P_2O_5. Methyllithium was purchased from Aldrich and titrated with diphenylacetic acid before use.

3.1. Preparation of the racemic allene aldehyde complexes **3a–c** and **4b,c**

The intermediate manganese complexes **2a–c** of the acetylenic aldehydes can be isolated, but this was not necessary for the synthesis of the isomeric allene aldehyde complexes.

3.2. Preparation of racemic (2-3-η-buta-2,3-dien-1-al) (η-methylcyclopentadienyl) dicarbonylmanganese **3a** (isomerization with Al_2O_3)

Methylcyclopentadienyl tricarbonylmanganese (2.00 g, 9.17 mmol) was irradiated in anhydrous THF (200 ml) at −30°C until one equivalent CO was evolved (ca 40 min). Argon was then bubbled through the red solution while warming up to 20°C. Tetrolaldehyde (1.00 g, 15 mmol) was added, the UV source cut off and the mixture was stirred for 4 h. The solution was concentrated to 50 ml in vacuo (15 torr, 25°C), added to a suspension of basic Al_2O_3 (100 g, aluminium oxide 90 active basic Merck no 1076) in hexane (100 ml) and stirred for 2 h at 20°C. The mixture was filtered and the Al_2O_3 was washed with CH_2Cl_2:MeOH (4:1, 3×150 ml). The combined filtrates were evaporated and the crude complex purified by chromatography on a SiO_2 column (150 g, hexane with 20% CH_2Cl_2 and 10% ether): 1.70 g complex **3a** (72%) was obtained.

3a: yellow oil. IR (CCl_4): ν=1995, 1935 (C≡O), 1665 (C=O). ^{1}H-NMR ($CDCl_3$): δ=1.90 (s, 3H), 2.90 (dt, 1H, J=7.5 and 3.0), 4.58 (m, 2H), 4.73 (m, 2H), 5.98 (t, 1H *endo*, J=3.0), 6.55 (t, 1H *exo*, J=3.0), 7.97 (d, 1H, J=7.5). Anal. Calcd for $C_{12}H_{11}MnO_3$ (258.16): C, 55.83; H, 4.29. Found: C, 56.09; H, 4.40.

3.3. Preparation of racemic (2-3-η-deca-2,3-dien-1-al) (η-methylcyclopentadienyl) dicarbonylmanganese **3b** (exo) and **4b** (endo) (isomerization with Al_2O_3)

The same procedure starting from 1.40 g (6.4 mmol) methylcyclopentadienyl tricarbonylmanganese and 1.14 g (7.5 mmol) 2-n-decynal yielded, after stirring for 12 h at 20°C followed by chromatography on SiO_2 (150 g, hexane with 15% ether), yielded the *exo* complex **3b** (less polar, 0.58 g, 26.5%) and the *endo* complex **4b** (more polar, 0.73 g, 33.5%).

3b: yellow oil. IR (CCl_4): ν=1995, 1940 (C≡O), 1670 (C=O). ^{1}H-NMR (C_6D_6): δ=0.91 (t, 3H, J=6.5), 1.00–1.49 (mm, 8H), 1.38 (s, 3H), 2.31 (m, 2H), 2.84 (m, 1H), 3.70 (m, 2H), 3.87 (m, 2H), 6.03 (td, 1H *endo*, J=7.0 and 2.5), 8.26 (d, 1H, J=7.0). Anal. Calcd for $C_{18}H_{23}MnO_3$ (342.32): C, 63.16; H, 6.77. Found: C, 63.33; H, 7.01.

4b: yellow oil. Same IR and nearly the same ^{1}H-NMR with the exception of the signal of the *exo* H: δ=6.76 (td, J=7.0 and 2.5).

3.4. Isomerization with DBU

The crude THF solution resulting from the irradiation of methylcyclopentadienyl tricarbonylmanganese (1.40 g, 6.4 mmol) and 2-n-decynal (1.14 g, 7.5 mmol) was cooled to −40°C. DBU (1.98 g, 13 mmol) was added and stirring was continued for 4 h at −40°C. The mixture was poured into aqueous HCl (100 ml, 1.5 N) and extracted with ether. The organic extracts were washed with saturated brine and dried with $MgSO_4$. After evaporation of the solvents, the complexes were isolated by chromatography on SiO_2 (150 g, hexane with 25% ether). A 1.10 g mixture of the *exo* and *endo* complexes **3b** and **4b** (97:3) was obtained (50% overall yield based on methylcyclopentadienyl tricarbonylmanganese). By a second careful chromatography on SiO_2 (150 g, hexane with 15% ether), the less polar *exo* complex **3b** was completely freed from the more polar *endo* complex **4b**.

The same isomerization gave a ratio of 95:5 *exo*:*endo* complex when performed at +20°C.

3.5. Preparation of racemic exo-(2-3-η-dodeca-2,3-dien-1-al) (η-methylcyclopentadienyl) dicarbonylmanganese **3c** (isomerization with DBU)

The same procedure from methylcyclopentadienyl tricarbonylmanganese (1.40 g, 6.4 mmol) and 2-n-dodecynal (1.35 g, 7.5 mmol) yielded the *exo* complex **3c** (1.16 g, 49%) and the *endo* complex **4c** (0.04 g, 1.7%) slightly contaminated by **3c**.

3c: yellow oil. IR (CCl_4): ν=1995, 1940 (C≡O), 1670 (C=O). ^{1}H-NMR (C_6D_6): δ=0.89 (t, 3H, J=6.5), 1.24–1.43 (m, 12H), 1.38 (s, 3H), 2.31 (m, 2H), 2.83 (m, 1H), 3.70 (m, 2H), 3.87 (m, 2H), 6.04 (td, 1H, J=7.0 and 2.5), 8.25 (d, 1H, J=7.0). Anal. Calcd for $C_{20}H_{27}MnO_3$ (370.37): C, 64.86; H, 7.35. Found: C, 65.10; H, 7.49.

3.6. Preparation of the chiral anti-semioxamazones (+)-**5a**, (−)-**5b**, (−)-**5c**, (−)-**6a**, (+)-**6b** and (+)-**6c**

The allene aldehyde complex **3a** (1.03 g, 4 mmol), **3b** (1.37 g, 4 mmol) or **3c** (1.48 g, 4 mmol) and (*S*)-(−)-(α-phenylethyl)-5-semioxamazide[3] (0.83 g, 4 mmol) were dissolved with pTsOH (0.02 g, cat.) in CH_2Cl_2 (80 ml). After ~1 h reflux, the starting complex had disappeared (TLC). The solution was washed with H_2O and dried with $MgSO_4$. Evaporation of the solvent afforded nearly quantitatively the crude semioxamazone mixtures (+)-**5a**, (−)-**6a** and **7a** (1.79 g); (−)-**5b**, (+)-**6b** and **7b** (2.12 g); (−)-**5c**, (+)-**6c** and **7c** (2.23 g) respectively. By column chromatography on SiO_2 (150 g, hexane with 35% CH_2Cl_2 and 5% ether) the crystalline *anti* semioxamazones were obtained as pure diastereomers, along with unseparable mixtures of the pairs of distinctly more polar *syn* semioxamazones (total yield ca 90%):

(+)-**5a** (less polar, 0.687 g, 38%), (−)-**6a** (more polar, 0.626 g, 35%), **7a** (unseparated mixture, 0.253 g, 14%); (−)-**5b** (less polar, 0.797 g, 37%), (+)-**6b** (more polar, 0.679 g, 32%), **7b** (unseparated mixture, 0.420 g, 20%); (−)-**5c** (less polar, 0.836 g, 37%), (+)-**6c** (more polar, 0.699 g, 31%), **7c** (unseparated mixture, 0.489 g, 22%).

Semioxamazone (+)-**5a**: yellow crystals, dec. >94°C. $[\alpha]_D$=+63 (c=0.4, $CHCl_3$). IR ($CHCl_3$): ν=3380, 3300 (NH), 1980, 1925 (C≡O), 1670 (C=O, C=N). ^{1}H-NMR ($CDCl_3$): δ=1.56 (d, 3H, J=7.0), 1.84 (s, 3H), 3.48 (m, 1H), 4.52 (m, 2H), 4.68 (m, 2H), 5.06 (m, 1H), 5.85 (m, 1H), 6.43 (m, 1H), 6.53 (d, 1H, J=9.0), 7.26–7.32 (m, 5H), 7.76 (broad d, 1H, J=8.0), 9.70 (s, 1H). Anal. Calcd for $C_{22}H_{22}MnN_3O_4$ (447.38): C, 59.07; H, 4.96. Found: C, 59.28; H, 5.23.

Semioxamazone (−)-**6a**: yellow crystals, dec. >90°C. $[\alpha]_D$=−260 (c=0.4, $CHCl_3$). IR and ^{1}H-NMR very similar to (+)-**5a**. Anal. for $C_{22}H_{22}MnN_3O_4$. Found: C, 58.84; H, 4.75.

Semioxamazone (−)-**5b**: yellow crystals, dec. >64°C. $[\alpha]_D$=−339 (c=0.6, $CHCl_3$). IR ($CHCl_3$): ν=3380, 3300 (NH), 1985, 1930 (C≡O), 1675 (C=O, C=N). ^{1}H-NMR (C_6D_6): δ=0.91 (t, 3H, J=6.5), 1.08 (d, 3H, J=7.0), 1.10–1.60 (m, 8H), 1.30 (s, 3H), 2.36 (m, 2H), 3.34 (m, 1H), 3.76 (m, 1H), 3.83 (m, 1H), 3.96 (m, 1H), 4.03 (m, 1H), 5.03 (m, 1H), 6.00 (td, 1H, J=7.0 and 2.5), 6.12 (d, 1H, J=9.0), 7.03–7.11 (m, 5H), 7.88 (broad d, 1H, J=8.0), 10.20 (broad s, 1H). Anal. Calcd for $C_{28}H_{34}MnN_3O_4$ (489.52): C, 68.70; H, 7.00. Found: C, 68.93; H, 7.21.

Semioxamazone (+)-**6b**: yellow crystals, dec. >58°C. $[\alpha]_D$=+140 (c=0.45, $CHCl_3$). IR and ^{1}H-NMR very similar to (−)-**5b**. Anal. for $C_{28}H_{34}MnN_3O_4$. Found: C, 68.75; H, 7.09.

Semioxamazone (−)-**5c**: yellow crystals, dec. >60°C. $[\alpha]_D$=−316 (c=0.7, $CHCl_3$). IR ($CHCl_3$): ν=3380, 3300 (NH), 1980, 1930 (C≡O), 1675 (C=O, C=N). ^{1}H-NMR (C_6D_6): δ=0.92 (t, 3H, J=6.5), 1.05 (d, 3H, J=7.0), 1.20–1.55 (m, 15H), 2.35 (m, 2H), 3.32 (m, 1H), 3.73 (m, 1H), 3.80 (m, 1H), 3.93 (m, 1H), 3.97 (m, 1H), 5.02 (m, 1H), 5.97–6.05 (m, 2H), 7.02–7.12 (m, 5H), 7.78 (d, 1H, J=9.0),

10.07 (s, 1H). Anal. Calcd for $C_{30}H_{38}MnN_3O_4$ (559.59): C, 64.39; H, 6.84. Found: C, 64.11; H, 6.92. Semioxamazone (+)-**6c**: yellow crystals, dec. >58°C. $[\alpha]_D$=+113 (c=0.25, $CHCl_3$). IR and ^{1}H-NMR very similar to (−)-**5c**. Anal. for $C_{28}H_{34}MnN_3O_4$. Found: C, 64.77; H, 6.78.

*3.7. Regeneration of the formyl group: optically active allene aldehyde complexes (+)-**3a**, (−)-**3a**, (−)-**3b**, (+)-**3b**, (−)-**3c** and (+)-**3c***

Pyruvic acid (0.25 g, 2.8 mmol) and H_2O (2 ml) were successively added to a solution of the semioxamazone (0.8 mmol) in acetic acid (25 ml). After stirring for 12 h at rt, H_2O (80 ml) was added and the mixture was extracted with pentane (3×20 ml). The organic phase was washed with H_2O, neutralized with a saturated $NaHCO_3$ solution and dried with $MgSO_4$. After evaporation of the solvent, the crude complex was filtered on SiO_2 (30 g, hexane with 10% ether).

3.8. (+)-exo-*(2,3-η-Buta-2,3-dien-1-al) (η-methylcyclopentadienyl) dicarbonylmanganese (+)-**3a** and its enantiomer (−)-**3a***

From the semioxamazones (+)-**5a** (less polar diastereomer, 0.358 g) and (−)-**6a** (more polar diastereomer, 0.358 g), the aldehydes (+)-**3a** [0.201 g, 97%, $[\alpha]_D$=+560 (c=0.4, $CHCl_3$)], and (−)-**3a** [0.197 g, 95% $[\alpha]_D$=−503 (c=0.35, $CHCl_3$)] respectively, were obtained. In this case the extraction was carried out with ether instead of pentane, and the eluent for the final chromatography was hexane with 20% CH_2Cl_2 and 10% ether. The enantiomeric excess was determined by ^{1}H-NMR in the presence of Eu(hfc)$_3$ with a molar ratio of shift reagent:complex=6:10. The aldehyde complex (+)-**3a** showed an ee >97%, while the ee of (−)-**3a** was only 90%, the more polar semioxamazone (−)-**6a** being slightly contaminated by the other diastereomer.

*3.9. (2*S*)-(−)*-exo-*(2,3-η-Deca-2,3-dien-1-al) (η-methylcyclopentadienyl) dicarbonylmanganese (−)-**3b** and its enantiomer (2*R*)-(+)-**3b***

From the semioxamazone (−)-**5b** (less polar diastereomer, 0.425 g) and (+)-**6b** (more polar diastereomer, 0.425 g), the aldehydes (−)-**3b** [0.268, 98%, $[\alpha]_D$=−602 (c=0.45, $CHCl_3$)] and (+)-**3b** [0.266 g, 97%, $[\alpha]_D$=+595 (c=0.45, $CHCl_3$)] respectively, were obtained. The enantiomeric excess (^{1}H-NMR in the presence of 0.2 molar equivalents of Eu(dcm)$_3$ was >95%, no trace of the other enantiomer being observed.

*3.10. (2*S*)-(−)*-exo-*(2,3-η-Dodeca-2,3-dien-1-al) (η-methylcyclopentadienyl) dicarbonylmanganese (−)-**3c** and its enantiomer (2*R*)-(+)-**3c***

From the semioxamazones (−)-**5c** (less polar diastereomer, 0.445 g) and (+)-**6c** (more polar diastereomer, 0.445 g), the aldehydes (−)-**3** (0.290 g, 98%, $[\alpha]_D$=−549 (c=0.4, $CHCl_3$)] and (+)-**3c** [0.292 g, 99% $[\alpha]_D$=+526 (c=0.4, $CHCl_3$)] respectively, were obtained. The enantiomeric excess was determined as for **3b** and was also >95%.

3.11. Racemic exo-(2,3-η-4-methoxycarbonyl-buta-2,3-dien-1-al) (η-methylcyclopentadienyl) dicarbonylmanganese **9** and diester **10**

The 1,3-diformylallene complex **8** (0.48 g, 1.7 mmol)[8] in MeOH (30 ml) was added at 0°C to a suspension of MnO_2 (3.45 g, 40 mmol, manganese(IV) oxide precipitated active Merck no. 805958) in a solution of KCN (0.65 g, 10 mmol) in acetic acid (0.18 g) and MeOH (35 ml). After stirring 2 h at 0°C and filtration, water (60 ml) was added and the mixture was extracted with CH_2Cl_2 (2×50 ml). The organic phase was dried with $MgSO_4$. Evaporation of the solvent and chromatography on SiO_2 (60 g, hexane with 35% CH_2Cl_2 and 5% ether) afforded the aldehyde–ester complex **9** (more polar, 0.380 g, 70%) and the diester complex **10** (less polar, 0.114 g, 19%).

9: yellow oil. IR (CCl_4): ν=2005, 1960 (C≡O), 1700, 1680 (C=O). ^{1}H-NMR ($CDCl_3$): δ=1.92 (s, 3H), 3.26 (dd, 1H, J=7.0 and 2.5), 3.72 (s, 3H), 4.65 (m, 2H), 4.78 (m, 2H), 6.58 (d, 1H, J=2.5), 8.10 (d, 1H, J=7.0). Anal. Calcd for $C_{14}H_{13}MnO_5$ (316.19): C, 53.18; H, 4.14. Found: C, 53.40; H, 4.32.

3.12. Semioxamazones (+)-**11** and (−)-**12**

To a solution of the complex **9** (0.245 g, 0.78 mmol) in CH_2Cl_2 (10 ml) were added at 0°C (*S*)-(−)-(α-phenylethyl)-5-semioxamazide (0.165 g, 0.8 mmol) and p-TsOH (0.01 g, cat). After stirring for 10 min at 0°C, water (10 ml) was added and the mixture was extracted with CH_2Cl_2 (20 ml). The organic phase was dried with $MgSO_4$ and the solvent was evaporated. The crude mixture (0.395 g) was chromatographed on SiO_2 (100 g, CH_2Cl_2 with 25% hexane and 10% ether). This afforded the diastereomeric semioxamazones (+)-**11** (less polar, 0.175 g, 45%) and (−)-**12** (more polar, 0.172 g, 44%).

Semioxamazone (+)-**11**: yellow crystals, mp 168–170°C. $[\alpha]_D$=+51 (c=0.25, $CHCl_3$). IR ($CHCl_3$): ν=3380, 3300 (NH), 2000, 1940 (C≡O), 1700 (C=O, ester), 1675 (C=O, C=N). ^{1}H-NMR ($CDCl_3$): δ=1.57 (d, 3H, J=7.O), 1.88 (s, 3H), 3.71 (s, 3H), 3.92 (dd, 1H, J=9.0 and 2.0), 4.56 (m, 1H), 4.63 (m, 1H), 4.75 (m, 2H), 5.09 (m, 1H), 6.52 (d, 1H, J=2.0), 6.58 (d, 1H, J=9.0), 7.20–7.45 (m, 5H), 7.75 (broad d, 1H, J=7.5), 10.02 (s, 1H). Anal. Calcd for $C_{24}H_{24}MnO_6$ (463.39): C, 62.21; H, 5.22. Found: C, 62.34; H, 5.36.

Semioxamazone (−)-**12**: yellow crystals, mp 169–170°C. $[\alpha]_D$=−213 (c=0.25, $CHCl_3$). IR and ^{1}H-NMR very similar to (−)-**12**. Anal. for $C_{24}H_{24}MnO_6$. Found: C, 62.50; H, 5.43.

3.13. Regeneration of the formyl group: optically active allene aldehyde ester complexes (+)-**9** and (−)-**9**

To a solution of the semioxamazone (+)-**11** (0.140 g, 0.28 mmol) in acetic acid (5 ml) were successively added pyruvic acid (0.10 ml, 1.2 mmol) and H_2O (0.5 ml). After stirring for 3 h at rt, water (10 ml) was added and the mixture was extracted with ether (3×10 ml). The organic phase was washed with H_2O, then with saturated brine and dried with $MgSO_4$. Evaporation of the solvent and chromatography on SiO_2 (10 g, CH_2Cl_2 with 30% hexane and 5% ether) yielded (+)-**9** [0.078 g, 89%, $[\alpha]_D$=+372 (c=1.5, $CHCl_3$)].

Similarly, from the semioxamazone (−)-**12** (0.150 g, 0.3 mmol), the enantiomeric complex (−)-**9** was obtained [0.087 g, 92%, $[\alpha]_D$=−371 (c=1.1, $CHCl_3$)].

The optical purity of (+)-**9** and (−)-**9**, determined by ^{1}H-NMR in the presence of Eu(hfc)$_3$, was estimated to be >90% (no trace of the other enantiomer was detected, ee=95±5%, limit of precision of the method in this case).

*3.14. Reaction of allene aldehyde complexes with organometallics: synthesis of the secondary alcohols (−)-**13** and (+)-**14***

*3.14.1. Addition of methyllithium to (+)-**3a***

(−)-exo-*(2-3-η-Penta-1,2-dien-4-ol) (η-methylcyclopentadienyl) dicarbonylmanganese (−)-**13*** Methyllithium (0.66 ml, sol 1.67 M in ether, 1.1 mmol) was added dropwise at −78°C to (+)-**3a** (0.240 g, 0.93 mmol, ee >97%) in THF (10 ml). After stirring for 15 min at −78°C, a saturated solution of NH_4Cl (10 ml) was added and the mixture was extracted with ether (2×20 ml). The organic phase was dried with $MgSO_4$, the solvents were evaporated and the residue chromatographed on SiO_2 (20 g, hexane with 30% ether): (−)-**13** (0.250 g, 98%) was obtained as a single diastereomer (NMR, shift reagents).

(−)-**13**: pale yellow oil. $[\alpha]_D$=−116 (c=0.3, $CHCl_3$). IR ($CHCl_3$): ν=3600, 3500–3300 (OH), 1965, 1905 (C≡O). ^{1}H-NMR ($CDCl_3$): δ=1.29 (d, 3H, J=6.0), 1.89 (s, 3H), 2.13 (broad d, 1H, J=4.0), 2.60 (m, 1H), 3.33 (m, 1H), 4.40 (m, 1H), 4.45 (m, 1H), 4.57 (m, 2H), 5.67 (dd, 1H, J=3.0 and 1.0), 6.23 (dd, 1H, J=3.0 and 1.0). Anal. Calcd for $C_{13}H_{15}MnO_3$ (274.20): C, 56.95; H, 5.51. Found: C, 57.26; H, 5.69.

*3.14.2. Addition of n-butylmagnesium bromide to (−)-**3a***

(+)-exo-*(2-3-η-Octa-1,2-dien-4-ol) (η-methylcyclpentadienyl) dicarbonylmanganese (+)-**14*** The complex (−)-**3a** (0.161 g, 0.62 mmol, ee ∼90%) in THF (10 ml) was added dropwise at −20°C to n-butylmagnesium bromide prepared in refluxing ether (8 ml, 30 min) from n-butyl bromide (0.135 ml, 1.25 mmol) and magnesium (0.030 g, 1.25 mmol). After 30 min, a saturated solution of NH_4Cl (10 ml) was added at −20°C and the mixture was extracted with ether (2×15 ml). The organic phase was washed with saturated brine, dried with $MgSO_4$, the solvents evaporated and the residue chromatographed on SiO_2 (10 g, hexane with 20% ether): (+)-**14** (0.117 g, 90%) was obtained as a single diastereomer (NMR, shift reagents).

(+)-**14**: yellow oil. $[\alpha]_D$=+146 (c=0.2, $CHCl_3$). IR ($CHCl_3$): ν=3600 (OH), 1975, 1905 (C≡O). ^{1}H-NMR ($CDCl_3$): δ=1.02 (t, 3H, J=7.0), 1.45 (m, 4H), 1.59 (s, 3H), 1.70 (m, 2H), 1.88 (broad d, 1H, J=4.5), 2.60 (dt, 1H, J=8.0 and 3.0), 3.16 (m, 1H), 3.97 (m, 2H), 4.12 (m, 2H), 5.78 (dd, 1H, J=3.0 and 1.5), 6.37 (dd, 1H, J=3.0 and 1.5). Anal. Calcd for $C_{16}H_{21}MnO_3$ (316.28): C, 60.76; H, 6.69. Found: C, 60.98; H, 6.87.

The enantiomeric excess of (−)-**13** and (+)-**14** was checked by ^{1}H-NMR in the presence of Eu(hfc)$_3$ (molar ratio of shift reagent:complex ∼4:10). (−)-**13** was found to have an ee >97%, but (+)-**14** of only 90%. This correlates with the optical purity of the starting complexes (+)-**3a** and (−)-**3a**, indicating that no racemization occurred.

3.15. Horner–Emmons olefination

*3.15.1. (4*R,E*)-(−)*-exo-*(4-5-η-Methyl-tetradeca-2,4,5-trien-1-oate) (η-methylcyclopentadienyl) dicarbonylmanganese (−)-**15***

Sodium hydride (0.080 g, 3.3 mmol) was added to a solution of methyl dimethylphosphonoacetate (0.667 g, 3.67 mmol) in dry THF (20 ml). After stirring for 30 min at rt, the mixture was cooled to −10°C and the aldehyde complex (−)-**3c** (1.23 g, 3.3 mmol) in THF (20 ml) was added dropwise. After stirring for 12 h at rt, H_2O (20 ml) was added, followed by extraction with ether. The organic phase was washed with a saturated aqueous NaCl solution and dried with $MgSO_4$. After evaporation of the solvents and chromatography on SiO_2 (30 g, hexane with 5% ether), the unreacted starting complex (−)-**3c** (0.125 g, 10%), the complexed *exo-E*-pheromone (−)-**15** (1.005 g, 71%) and the relatively labile complexed *exo-*

Z-derivative **16** (0.195, 14%) were successively obtained. Yields for (−)-**15** and **16**, based on transformed complex (−)-**3c**: 79 and 15%.

(*exo-E*-Pheromone) (methylcyclopentadienyl) dicarbonylmanganese (−)-**15**: orange oil. $[\alpha]_D=-329$ (c=0.25, $CHCl_3$). IR (CCl_4): ν=1980, 1935 (C≡O), 1705 (C=O), 1595 (C=C). ^{1}H-NMR (C_6D_6): δ=0.89 (t, 3H, J=6.5), 1.28–1.34 (m, 10H), 1.40 (s, 3H), 1.40–1.60 (m, 2H), 2.38 (m, 2H), 2.71 (dd, 1H, J=11.0 and 3.0), 3.43 (s, 3H), 3.80 (m, 2H), 3.94 (m, 2H), 5.91 (td, 1H, J=7.0 and 3.0), 6.17 (d, 1H, J=15.0), 6.68 (dd, 1H, J=15.0 and 11.0). Anal. Calcd for $C_{23}H_{31}MnO_4$ (426.44): C, 64.78; H, 7.33. Found: C, 64.41; H, 7.28.

*3.16. Decomplexation: (*R*)-(−)-pheromone (−)-**17***

Anhydrous iron trichloride (1.40 g, 8.6 mmol) in ether (20 ml) was slowly added at −20°C to the complex (−)-**15** (0.70 g, 1.64 mmol) in ether (20 ml). The reaction was monitored by TLC. After total disappearance of the complex, the addition was stopped and H_2O (20 ml) was added. The aqueous phase was extracted with ether and the combined organic extracts were washed with a saturated NaCl solution and dried with $MgSO_4$. After evaporation of the solvent and chromatography on SiO_2 (30 g, hexane with 10% benzene), the pheromone (−)-**17** was obtained [0.325 g, 1.38 mmol, 84%, $[\alpha]_D=-158$ (c=1.4, hexane)]. The spectroscopic data were identical with those reported in the literature.[12,13]

The decomplexation can also be performed with mCPBA (0.452 g complex (−)-**15**, 1.06 mmol and 1.45 g mCPBA of 85% purity, 2 mmol) in CH_2Cl_2 (30 ml) at −78°C (5 min), the yield being slightly better (0.213 g (−)-**17**, 85%).[17]

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