New Cyclopropyl Building Blocks for Organic Synthesis, 21[1]

Diels-Alder Reactions of Methyl 2-Chloro-2-cyclopropylideneacetate with Electron-Rich Dienes: Synthesis of Potential Intermediates for Illudin M

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Received April 2, 1993 (revised version February 24, 1994)

Key Words: Cyclopropyl building blocks / Strained compounds / [4 + 2] Cycloaddition / Regioselectivity / Epoxides, regioselective cleavage of

1-Ethoxy- (**8a**) and 1-(trimethylsilyloxy)-1,3-pentadiene (**8b**) cycloadded to 2-chloro-2-cyclopropylideneacetate **6** to give low yields of *endo/exo*-**9a** and -**9b**, respectively. On the other hand, furans **5a–d** added **6** (**5b** and **5d** reacted regioselectively) to afford mixtures of the corresponding [4 + 2] cycloadducts *endo*-**11a–d** and *exo*-**11a–d** in good to high yields. 2-Methyl-5-(trimethylsilyloxy)furan (**5e**) yielded a mixture of the four cycloadducts *endo/exo*-**11e** and *endo/exo*-**12e**, which upon attempted purification on silica gel underwent facile hydrolysis to give bicyclic hemiacetals *endo/exo*-**13** and 4-hydroxycyclo-2-hexen-1-ones *endo/exo*-**14**, respectively. Similarly *endo/exo*-**11f** and *endo/exo*-**12f**, obtained from 2-methoxy-5-methylfuran (**5f**) and **6**, upon hydrolysis in the presence of silica gel gave *endo/exo*-**13** and *endo/exo*-**14**, respectively. The structures of *endo*-**14** and *exo*-**12f** were established by X-ray crystallography. In the presence of florisil, the epoxides *endo*- and *exo*-**16** were formed from trimethylsilyloxy-substituted cycloadducts *endo/exo*-**11e**. Selective reduction of the α-chlorocarboxylate functionality in the cycloadducts *endo*-**11a–d,f** with $LiBH_4$, followed by base-catalyzed cyclization of the resulting chlorohydrins *endo*-**21a–d, f** yielded the corresponding epoxides *endo*-**22a–d,f** in 22–73% overall yield. Under identical conditions, the cycloadducts *exo*-**11a–f** could not be reduced to the corresponding chlorohydrins *exo*-**21a–f**. Regioselective reduction of the acetal epoxide *endo*-**22f** to the tertiary alcohol *endo*-**23f** was achieved with sodium dihydrobis(2-methoxyethoxy)aluminate (Red-Al®). On stirring with moist silica gel, the bicyclic acetals *endo*-**22d,f** and *endo*-**23f** cleanly hydrolysed to the highly substituted spiro[2.5]oct-6-en-5-ones *endo*-**24d,f** (26 and 24% overall yields, respectively, in four steps from **5d,f** and **6**) and *endo*-**25f**, respectively (23% overall yield in five steps from **5f** and **6**).

Methyl 2-chloro-2-cyclopropylideneacetate (**6**), readily prepared in five simple steps[2] from cheaply available trichloroethene, sodium trichloroacetate, and ethene, is a remarkably versatile building block for organic synthesis[3]. Its enhanced tendency to undergo 1,4-additions with various carbon and heteroatom nucleophiles[4,5] as well as its pronounced Diels-Alder reactivity[6] towards acyclic and cyclic dienes has made a number of highly functionalized and thereby synthetically useful spirocyclopropane-anellated intermediates readily accessible. The good regioselectivity in cycloadditions of **6** to unsymmetrically substituted dienes has prompted us to initiate a new synthetic approach to the antibacterial and cytotoxic sesquiterpene illudin M (**1**)[7,8] and structurally related sesquiterpenes like ptaquilosin[9]. Our synthetic strategy for **1**[10] relies on the [2+4] cycloaddition of dienophile **6** to appropriately substituted dienes **5** as one key step to produce a precursor **7** to a cyclohexenone **4** containing all the functionalities of the six-membered ring in **1** (see Scheme 1).

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Recently developed methodology for the anellation of a dimethylcyclopentene ring onto cyclohexenone by photochemical [2+2] cycloaddition of 3,3-dimethylcyclopropene and subsequent acetoxymercuration/elimination[11] might afford **1** via tricycle **2**. Alternatively, an intermolecular Pauson-Khand reaction[12] could be used to attach the functionalized five-membered ring onto the intermediate **7**; further elaboration of **3** should eventually lead to illudin M (**1**). In this report, Diels-Alder reactions of methyl 2-chloro-2-cyclopropylideneacetate (**6**) with 1-ethoxy- and 1-(trimethylsilyloxy)-substituted pentadienes **8a** and **8b** as well as furans **5a-f** followed by appropriate functional group interconversions leading to potential intermediates for illudin M and related sesquiterpenes are described.

Cycloadditions of 6 to 1-Ethoxy- and 1-(Trimethylsilyloxy)-1,3-pentadiene 8a,b

At first, [2+4] cycloadditions of 2-chloro-2-cyclopropylideneacetate **6** to 1-ethoxy- (**8a**) and 1-(trimethylsilyloxy)-1,3-pentadiene (**8b**) were tested. Diene **8a**, obtained from 1,1,3-triethoxypropane by thermal elimination of

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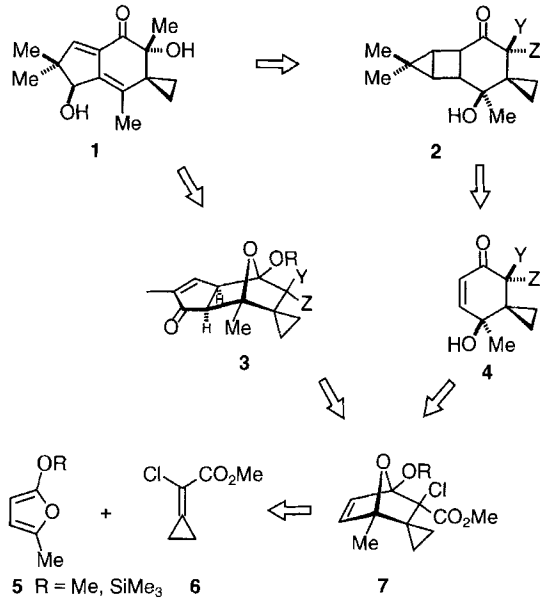
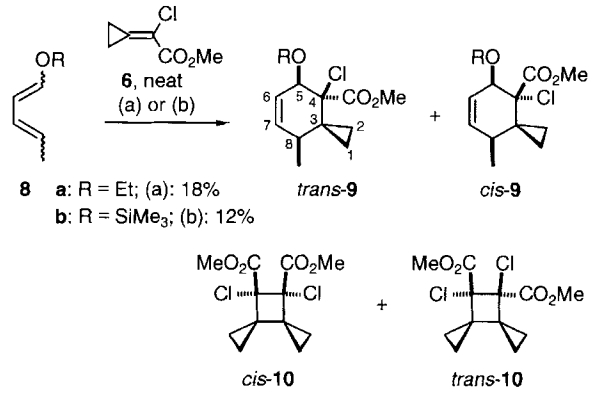
Scheme 1. A new synthetic strategy for the sesquiterpene (±)-illudin M (**1**)[10,11]



Scheme 2. [2 + 4] Cycloaddition of methyl 2-chloro-2-cyclopropylideneacetate (**6**) to 1-oxy-substituted 1,3-pentadienes **8**. The designation *cis/trans* for the products **9** refers to the position of the methoxycarbonyl group relative to the substituents on C-5 and C-8. (a) 80°C, 18 h. – (b) K_2CO_3, 70°C, 24 h



ethanol as a mixture of (*E*,*E*), (*E*,*Z*), (*Z*,*E*), and (*Z*,*Z*) isomers[13], upon heating to 80°C with **6** gave a mixture of products, from which a colorless oil was obtained in 18% yield upon column chromatography over neutral alumina. A multiplet at δ = 4.14 in the ^{1}H-NMR spectrum was assigned to the proton at the ethoxy-substituted C-5 of the cycloadduct *trans*-**9a** which confirmed that cycloaddition had taken place (Scheme 2). As no other cycloadducts could be isolated in pure form, it was difficult to establish the relative configuration at C-4 and C-5 solely on the basis of the ^{1}H-NMR data. The stereoisomer *trans*-**9** would be the preferred one from the most reactive (*E*,*E*) isomer of diene **8a** on the basis of frontier orbital considerations[14]; but the assignment can only be considered as tentative, and it is assumed that the less reactive (*Z*,*E*) isomer of diene **8a** did not give any isolable product under the employed conditions. Except for polymeric material, only small amounts of head-to-head dimers *cis*-**10** and *trans*-**10** of **6**[2b] were also detected (Scheme 2).

1-(Trimethylsilyloxy)-1,3-pentadiene (**8b**) can be prepared as a mixture of all four stereoisomers in different proportions by two reported methods. Tetrakis(triphenylphosphane)ruthenium dihydride-catalyzed isomerization[15] of 1-(trimethylsilyloxy)-2,4-pentadiene gave a 73% yield of the four stereoisomers of **8b** in a 5:2:2:1 ratio, while stannous chloride/triethylamine-assisted silylation of the α,β-unsaturated aldehyde *trans*-2-pentenal with trimethylsilyl chloride[16] yielded a 5:2:2:5 mixture of the isomers, as analyzed by GC. Comparison of the ^{1}H-NMR spectra of the two isomeric mixtures led to the conclusion that the isomer with the longest retention time had (*E*,*E*) configuration. Therefore, the diene mixture of **8b** obtained from *trans*-2-pentenal consisting of about 50% of the (*E*,*E*) isomer was utilized for the cycloaddition reaction with **6**. Heating a 1:2 mixture of **6** and **8b** to 70°C after 24 h afforded only 12% of pure cycloadduct *trans/cis*-**9b** (Scheme 2). Attempts to improve the yield of these cycloadditions by performing the reactions at low temperature in the presence of Lewis acids like titanium tetrachloride[17], boron trifluoride, or tungsten hexachloride were unsuccessful. In all cases extensive polymerization occurred, and cycloadducts could not at all be isolated.

Due to the difficulties encountered in preparing useful amounts of the dienes **8a** or **8b** containing higher proportions of the (*E*,*E*) isomer and because of the low subsequent yields of cycloadducts **9**, attention was turned to furans[18], which due to their rigid cyclic structure in general are better dienes in Diels-Alder reactions.

Cycloadditions of 6 to Furan 5a and Substituted Furans 5b–f

Indeed, unsubstituted furan (**5a**) underwent facile [4 + 2] cycloaddition with neat **6** at 45°C to give the cycloadducts *endo*-**11a** and *exo*-**11a** in a ratio of 1.4:1 in 90% yield (Scheme 3 and Table 1). Similarly, 2-methylfuran (**5b**) afforded the corresponding *endo*-**11b** and *exo*-**11b** as a 1.5:1 mixture in 76% yield. However, 2,5-dimethylfuran (**5c**) reacted much more slowly, and after 120 h at 20°C only around 5% conversion to *endo/exo*-**11c** (2:1) had taken place. This low reactivity of **5c** ist probably due to the steric influence[19] of the second methyl group (compared to **5b**) at C-5, which interacts with the cyclopropyl hydrogens of **6** upon mutual approach and thereby elevates the energy of the transition state. Upon heating **6** in excess of **5c** at 60°C, the reaction was complete within 12 h, and the cycloadducts *endo/exo*-**11c** (2:1) could be isolated in 72% yield (Table 1).

The corresponding cycloadducts *endo*- and *exo*-**11d** of 2-methoxyfuran (**5d**), which is a cyclic ketene acetal, were formed in a 1.2:1 ratio, but turned out to be extremely sensitive to purification by column chromatography on both silica gel and neutral alumina. They apparently underwent facile hydrolytic cleavage and decomposition to give a complex mixture of products. From about 2.5 grams of an al-

most 95% pure product mixture, only a few milligrams of both *endo*- and *exo*-**11d** could be isolated in pure form and identified on the basis of their spectral data.

Scheme 3. [2 + 4] Cycloadditions of **6** to furans **5**. The designation *endo*/*exo* for the products **11**, **12** refers to the position of the methoxycarbonyl group relative to the oxygen bridge. (For details see Table 1)

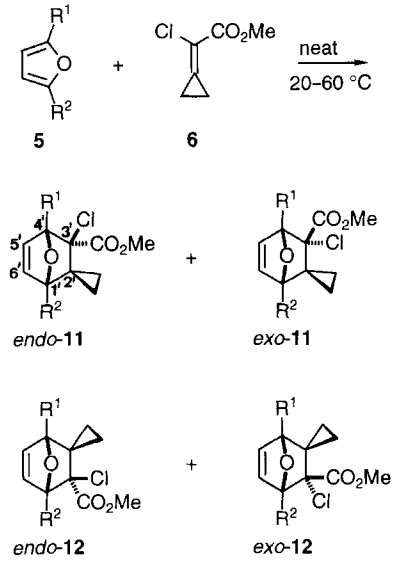


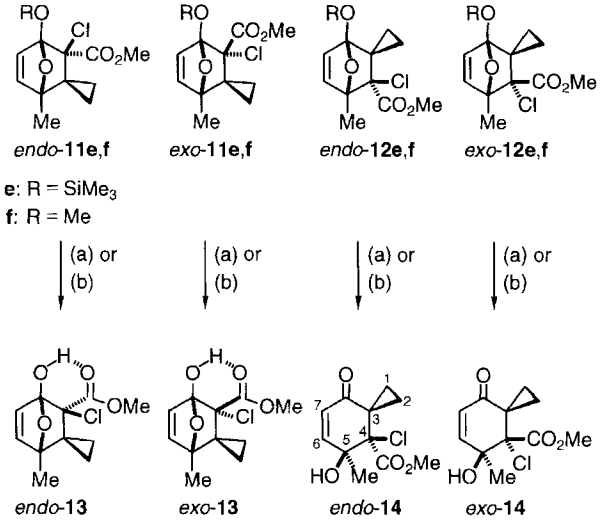
Table 1. Diels-Alder additions of furans **5a–f** to methyl 2-chloro-2-cyclopropylideneacetate (**6**) with formation of *endo*/*exo*-**11** and *endo*/*exo*-**12** (see Scheme 3)

Furan			Temp.	Time	Yield[a]	Product Ratio[b]			
5	R^1	R^2	[°C]	[h]	(%)	*endo*-**11**	*exo*-**11**	*endo*-**12**	*exo*-**12**
a	H	H	45	48	90	1.4	1	–	–
b	Me	H	20	100	76	1.5	1	–	–
c	Me	Me	60	12	72	2	1	–	–
d	OMe	H	20	32	25 (95)[c]	1.2	1	–	–
e	$OSiMe_3$	Me	20	140	8.6 (81)[d]	8	2	1	0.5
f	OMe	Me	20	120	48 (78)[d]	10	3	1	0.3

[a] Combined yields of isolated products, based on consumed **6**. – [b] Taken from ^{1}H-NMR spectra of crude products. – [c] Yield of crude product, purity 95%. – [d] Yield of mixture of isomers.

2-Methyl-5-(trimethylsilyloxy)furan (**5e**)[20] underwent smooth Diels-Alder reaction with **6** at room temperature to give a 81% yield of all four possible cycloadducts *endo*-**11e**, *exo*-**11e**, *endo*-**12e** and *exo*-**12e** (Scheme 3 and Table 1). The ^{1}H-NMR- spectrum of the crude product mixture disclosed a ratio of 8:2:1:0.5 of the respective cycloadducts. Here, too, purification by silica gel chromatography resulted in extensive hydrolytic decomposition. Not a single fraction containing any one of the four cycloadducts in pure could be collected. Only some fractions contained mixtures of the two major products *endo*- and *exo*-**11e** in various proportions according to their ^{1}H-NMR spectra. Repeated chromatography of this mixture gave two new products, which did not show ^{1}H-NMR peaks of a trimethylsilyl group. This clearly indicated that hydrolytic cleavage of the sensitive acetal functionality had taken place. The IR spectrum of the first compound, however, showed only one peak in the carbonyl region at 1765 cm^{-1} due to the ester carbonyl group. An additional peak at 3480 cm^{-1} indicated the presence of a hydroxyl group, which was also confirmed by a broad singlet at δ = 4.26 in the ^{1}H-NMR spectrum. Based on the spectral and analytical data, the two compounds were identified as the bicyclic hemiacetals *endo*- and *exo*-**13**, respectively (Scheme 4). None of the desired cyclohexenones **4** could be isolated from the mixture. The hemiacetals *endo*- and *exo*-**13** are probably stabilized by intramolecular hydrogen bonding[21]. Upon treating the mixture of *endo*- and *exo*-**11e** with moist silica gel or 2 N HCl in dichloromethane, complete hydrolysis to the hemiacetals *endo*- and *exo*-**13** occurred without any polymerization. After stirring the crude mixture of cycloadducts *endo*/*exo*-**11e** and *endo*/*exo*-**12e** with 2 N HCl in dichloromethane, column chromatography yielded four products, two of which were assigned the structures of *endo*- and *exo*-**14**. Apparently, in these regioisomeric 4-hydroxy-2-cyclohexen-1-ones the corresponding hemiacetals cannot be stabilized by intramolecular hydrogen bonding with the ester carbonyl group. This assignment was finally confirmed by an X-ray crystal structure analysis of *endo*-**14** (see Figure 1)[22].

Scheme 4. Hydrolysis of the bicyclic acetal moieties in the cycloadducts **11e,f** and **12e,f**. The designation *endo*/*exo* for non-bridged products relates to the configuration of the corresponding bicyclic acetal, from which it was formed. (a) H_2O/silica gel, CH_2Cl_2. – (b) 2 N HCl, CH_2Cl_2



Considering that the methyl acetals **11f**/**12f** might be less sensitive to hydrolytic cleavage than the trimethylsilyloxy compounds **11e**/**12e**, 2-methoxy-5-methylfuran (**5f**)[23,24] was treated with the ester **6** at room temperature to give a 10:3:1:0.3 mixture of the cycloadducts *endo*-**11f**, *exo*-**11f**, *endo*-**12f**, and *exo*-**12f**, respectively, in 78% yield (Scheme 4). As in the previous cases, hydrolytic cleavage of the cycloadducts upon attempted purification over silica gel and neutral alumina did occur, but small fractions of each of the four cycloadducts could be isolated in pure form and identified on the basis of their spectral data. The major fractions consisted of the four hydrolyzed products *endo*-**13**, *exo*-**13**, *endo*-**14**, and *exo*-**14**.

Attempted chromatographic purification of the mixture of *endo*/*exo*-**11f** and *endo*/*exo*-**12f** over Florisil resulted in the formation of the epoxides *endo*- and *exo*-**16** in 47 and

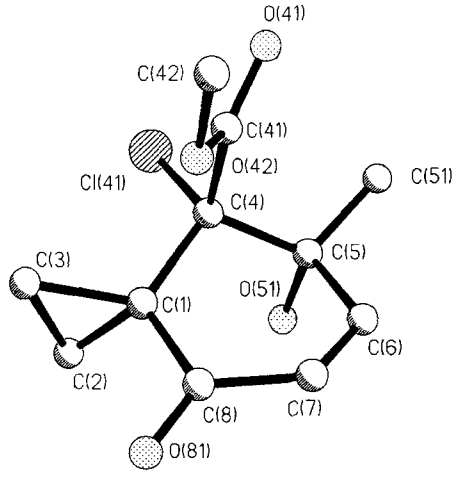
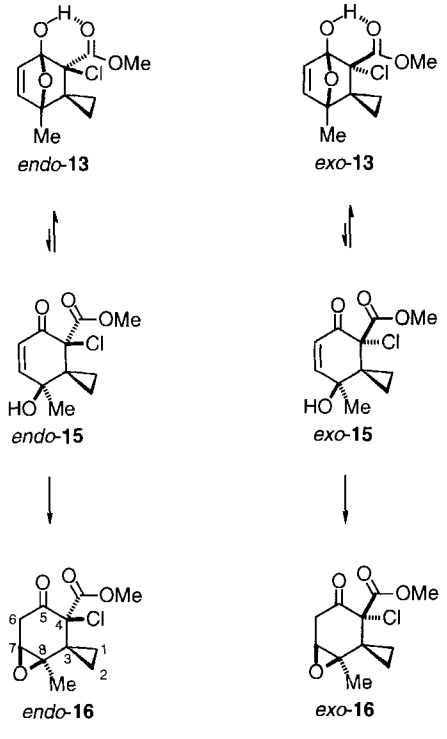


Figure 1. Structure of methyl (4*R**,5*S**)-4-chloro-5-hydroxy-5-methyl-8-oxospiro[2.5]oct-6-ene-4-carboxylate (*endo*-**14**) in the crystal[22]. (The numbering of the atoms does not conform with the IUPAC nomenclature of the molecule)

Scheme 5. The designation *endo*/*exo* for non-bridged compounds **15** relates to the configuration of the corresponding bicyclic acetal, from which it was formed



8% yield, respectively, but the cycloadducts *endo*/*exo*-**11f** and *endo*/*exo*-**12f** could not be isolated in pure form. The epoxides **16** are obviously formed via the intermediate cyclohexenones **15**, which appear to be in an equilibrium with the hemiacetals **13**, but due to the different chemical nature of the Florisil surface, activation of the tertiary hydroxy group at C-5 must take place and lead to an intramolecular Michael addition to the enone moiety in *endo*- and *exo*-**15**. No trace of the epoxides **16** was detected during chromatography over silica gel. Compounds *endo*/*exo*-**11f** and *endo*/*exo*-**12f** are best separated without decomposition when eluted from silica gel with the solvent containing about 3–5% of triethylamine. All four cycloadducts *endo*-**11f**, *exo*-**11f**, *endo*-**12f**, and *exo*-**12f** were thus isolated in 30, 14, 3.0, and 1.4% yield, respectively, when the reaction was carried out on a 71-mmol scale. When run on a 20-mmol scale, isolated yields of *endo*- and *exo*-**11f** were 39 and 19%, respectively. From product mixture comparison it was clear that both *endo*-**11e** and *endo*-**11f** are formed as the major products, but probably due to the greater steric bulk of the trimethylsilyl group *endo* selectivity is higher in the reaction of **5e** with **6**. But because of the easier handling, comparitatively less sensitive *endo*/*exo*-**11f** were preferred for further transformations. All attempts to enhance the *endo* selectivity by performing the cycloaddition reaction between **5f** and **6** in the presence of $TiCl_4$, $SnCl_4$, WCl_6, $(iPrO)_2TiCl_2$, Et_2AlCl, BF_3, or even the mild Lewis acids $LiClO_4$[25] and methyl-bis(2,6-di-*tert*-butyl-4-methylphenoxy)aluminium $[(MAD)_2AlMe]$[26] turned out to be futile due to the extreme sensitivity of methoxymethylfuran **5f** and probably the resulting cycloadducts towards Lewis acids[27]. Experiments carried out with furan **5a** and **6** under high pressure (8–10 kbar)[28] also did not indicate a significant increase in *endo* selectivity[29].

As the cycloadducts arising from the reaction of furans **5a-d** with **6** do not possess the appropriate functionality for further transformations towards illudin M, no proper efforts were made to establish the exact relative configuration of the *endo* and *exo* isomers, which could not simply be deduced from their ^{1}H-NMR spectra because of the absence of protons on the adjacent carbon atoms C-2 and C-3. The major products obtained in all cases were considered to be the kinetically favored products with the *endo* configuration *endo*-**11a-f**. The minor cycloadducts were similarly designated as *exo*-**11a-f**. This assignment is supported by the fact that in all the ^{13}C-NMR spectra the signal of the ester carbonyl group of the minor products appeared at lower field (δ = 0.20–1.40) than that of the major isomers. This difference ought to be due to the deshielding of the bridging oxygen atoms in *exo*-**11a-f**. In order to be absolutely certain, however, an X-ray crystal structure analysis was attempted for the major product from **5f** and **6**. But the crystals started to decompose during the X-ray measurements. Therefore, crystals of the second major compound were used and identified as being those of the *exo* isomer *exo*-**11f** (see Figure 2)[22]. This result in turn confirms that the first major compound indeed is *endo*-**11f** as assigned on the basis of ^{13}C-NMR data.

Interestingly, on treatment with lithium diisopropylamide (LDA), the epoxide *endo*-**16** rearranged[30] back to the hemiacetal *endo*-**13**, which was isolated in 92% yield (Scheme 6). Attempts to prepare the cyclohexenone derivative *endo*-**20** by alkylating the tertiary hydroxide group of the intermediate *endo*-**19**, generated from *endo*-**13** and LDA, with (2-methoxyethoxy)methyl chloride[31] were unsuccessful. Attempts to trap *endo*-**19** by silylation with trimethylsilyl chloride in the presence of triethylamine in DMF[32] or with *tert*-butyldimethylsilyl chloride/imidazole in DMF[33] also failed. On the other hand, direct treatment

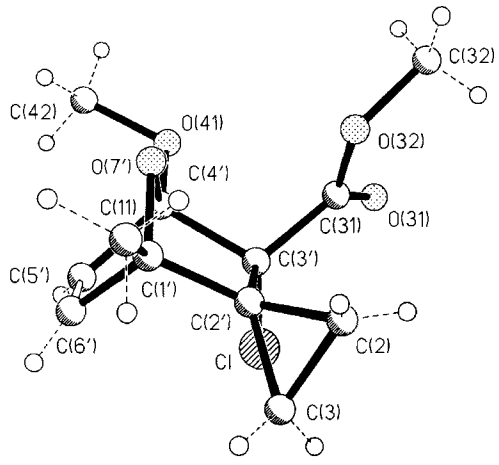
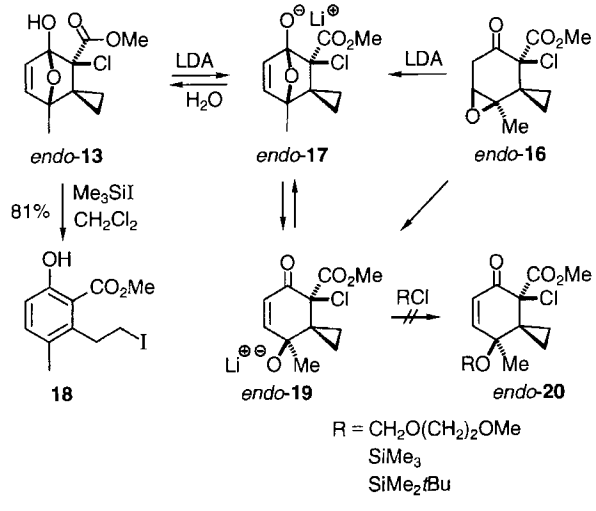


Figure 2. Structure of methyl *exo*-3'-chloro-4'-methoxy-1'-methylspiro-[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]-3'-carboxylate (*exo*-**11f**) in the crystal[22]. (The numbering of the atoms does not conform with the IUPAC nomenclature of the molecule)

of *endo*-**13** with trimethylsilyl iodide in dichloromethane[34] resulted in formation of the phenol derivative **18** apparently after nucleophilic attack of iodide at the spirocyclopropane group. The constitution of **18** was assigned on the basis of its ^{1}H-NMR spectrum with low field doublets at δ = 6.27 and 6.79 (^3J = 9.1 Hz), and a triplet at δ = 3.56.

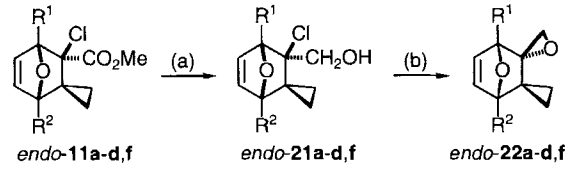
Scheme 6



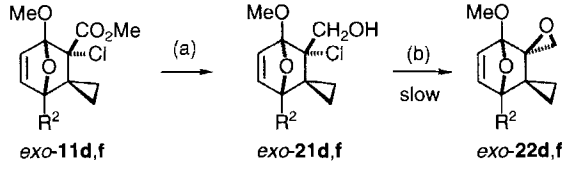
Directed Transformations of [4+2] Cycloadducts Derived from Furans 5 and Cyclopropylideneacetate 6

Because of these failures to obtain cyclohexenone derivatives of the type *endo*-**20**, the α-chloro ester functionality in cycloadducts *endo*-**11** was interconverted to a spiro epoxide group as a potential precursor functionality for the *gem*-hydroxy-methyl grouping in the target molecule **1**. Towards this end, the methoxycarbonyl group in *endo*-**11f** was selectively reduced in over 95% yield with $LiBH_4$[35] in diethyl ether. The resulting chlorohydrin *endo*-**21f** was found to decompose upon standing for a few hours at room temperature and was therefore transformed to the epoxide *endo*-**22f** without purification. Cyclization was readily achieved by treating *endo*-**21f** with a 50% sodium hydroxide solution[36] in the presence of benzyltriethylammonium chloride to give the epoxide *endo*-**22f** in 73% overall yield (Scheme 7), as evidenced by NMR data. Under identical conditions, the cycloadducts prepared from furans **5a-d** and **6** gave the corresponding epoxides *endo*-**22a-d** in 22–73% overall yields (Scheme 7).

Scheme 7. (a) $LiBH_4$, Et_2O, 0°C. – (b) 50% NaOH, THF, benzyltriethylammonium chloride



	R^1	R^2	Overall Yield (%)
a	H	H	57
b	Me	H	66
c	Me	Me	40
d	MeO	H	22
f	MeO	Me	73

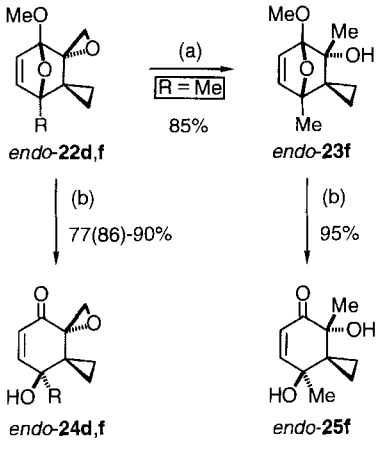


Because of the tedious chromatographic purification of the sensitive cycloadduct *endo*-**11f**, in one test run the crude mixture of cycloadducts *endo*/*exo*-**11f** and *endo*/*exo*-**12f** was subjected to the sequence of reduction and cyclization. Under identical conditions, however, a complex mixture of products was obtained, from which only the epoxide *endo*-**22f** could be isolated in 23% yield. A second product, isolated in less than 0.3% yield, was identified as the epoxide *exo*-**22f** (Scheme 7). When pure *exo*-**11f** was treated with 1.5 equiv. of $LiBH_4$, the sensitive *exo*-chlorohydrin *exo*-**21f** was obtained in 97% crude yield. But its conversion to the corresponding epoxide *exo*-**22f** under the conditions established for *endo*-**21f** was unusually slow, only 50% had reacted after 4 d. Upon prolonged reaction times, side reactions also occurred, and the epoxide *exo*-**22f** could not easily be separated from unreacted chlorohydrin *exo*-**21f**. Similarly, cycloadducts *exo*-**11b,c** did not yield the corresponding epoxides *exo*-**22b,c** under the above standard conditions. By using this reaction sequence, the inseparable mixture of sensitive cycloadducts *endo*- and *exo*-**11d** provided a mixture of *endo*- and *exo*-**22d**, from which only *endo*-**22d** could be isolated in pure form in 22% yield. As the relative configuration of *endo*-**11d** had only been tentatively assigned on the basis of the above mentioned NMR data, the favored reduction of this diastereomer adds support to the stereochemical assignment.

As unsymmetrically substituted epoxides can be regioselectively reduced to alcohols[37], the availability of the epox-

ide *endo*-**22f** is of particular importance for its eventual transformation to illudin M (**1**). The conversion of *endo*-**22f** to the tertiary alcohol *endo*-**23f** could not be achieved with $LiAlH_4$[38], as *endo*-**22f** did not react at all and was recovered quantitatively. However, after stirring at room temperature an equimolar mixture of *endo*-**22f** and sodium dihydridobis(2-methoxyethoxy)aluminate (Red-Al®) in dry toluene[37], the tertiary alcohol *endo*-**23f** was obtained in 85% yield. The ^{1}H-NMR spectrum of the pure compound exhibited two well separated singlets due to the two methyl groups and a broad singlet for the newly formed tertiary hydroxy group.

Scheme 8. The designation *endo/exo* for non-bridged compounds **24**, **25** relates to the configuration of the corresponding bicyclic acetal, from which it was formed. (a) $NaAlH_2(OCH_2CH_2OCH_3)_2$, THF/toluene, 20°C. – (b) H_2O, SiO_2, CH_2Cl_2, 20°C

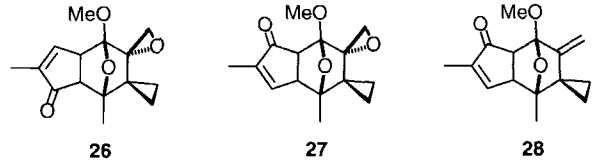


The functionalized bicyclic acetals *endo*-**22d,f** and *endo*-**23f** could easily be converted to the corresponding 4-hydroxy-substituted cyclohexenones *endo*-**24d,f** and *endo*-**25f**, respectively, by treatment with wet silica gel in dichloromethane at room temperature[39] in good to very good yields (Scheme 8).

The ^{13}C-NMR and IR spectra of *endo*-**25f** exhibited peaks at δ = 202 and 1675 cm^{-1}, respectively, which corroborates its existence in the keto form, contrary to the preference for the hemiacetal forms observed for the esters *endo*- and *exo*-**13** due to the intramolecular hydrogen bonding (see above). Additional evidence in favor of the keto form of *endo*-**25f** comes from its electronic spectrum which exhibits an absorption maximum at λ_{max} = 330 nm due to the n-π^* transition of the α,β-enone moiety in the molecule.

Outlook

With an appropriate cyclopentene anellation methodology applied to the highly functionalized cyclohexenones *endo*-**24d,f** and *endo*-**25f**, the further approach to the sesquiterpene illudin M (**1**) and its analogues had been envisaged. The previously reported photochemical [2+2] cycloaddition of 3,3-dimethylcyclopropene with subsequent acetoxymercuration/elimination[12] is hampered by the presence of a sensitive cyclopropyl dicarbinol functionality in *endo*-**25f**. In fact, all attempts to protect the tertiary hydroxy groups in *endo*-**25f** were unsuccessful, and when the unprotected enonediol was irradiated in the presence of excess 3,3-dimethylcyclopropene, a complex mixture was obtained; due to the sensitivity of these polyfunctional molecules, no identifiable products could be isolated from the mixture by chromatographic methods. Alternatively, the five-membered ring can be attached utilizing a Pauson-Khand reaction[13] on bicyclic acetals of type **11** or **22** before the acetal moiety is hydrolyzed[40]. In fact, *endo*-**22f**, when treated with 1.2 equiv. of $Co_2(CO)_8$ and an excess of propyne in toluene at 65°C, gave an isolated yield of 53% of the formal [2+2] cycloadduct **26** along with its regioisomer **27** (12%) and the deoxygenation product **28** (11%) of the latter. It is remarkable that only the regioisomer **27** is deoxygenated by $Co_2(CO)_8$[41]. When the epoxide *endo*-**22f** was treated with only 0.7 equiv. of $Co_2(CO)_8$ in an atmosphere of propyne and carbon monoxide (1:1), only the enones **26** and **27** were obtained in 38 and 44% yield, respectively. The regiochemistry and relative configuration of the cycloadduct **26** was



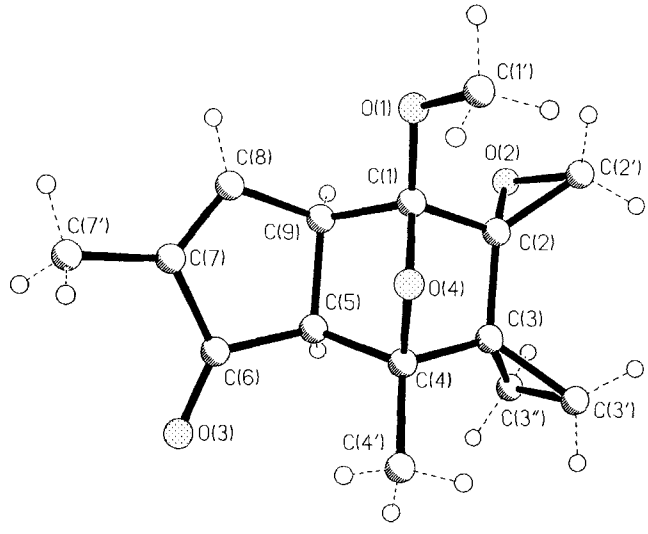


Figure 3. Structure of (±)-1'-methoxy-4',7'-dimethyl-5'-oxodispiro-[cyclopropane-1,8'-*cis,exo*-[10]oxatricyclo[5.2.1.$0^{2,6}$]dec-3-ene-9',2''-oxirane] (**26**) in the crystal[22]. (The numbering of the atoms does not conform with the IUPAC nomenclature of the molecule)

proved by a X-ray crystal structure analysis (see Figure 3).

Compound **26**, which can be prepared from methoxymethylfuran **5f** and cyclopropylideneacetate **6** in four steps with an overall yield of 15%, has all the skeletal features of illudin M[7,8] as well as ptaquilosin[9] and has all the necessary functionalities in place for further elaboration. In addition, highly functionalized spiro[2.5]octenones like **14**, **15** (or their respective hemiacetals **13**), **24**, and **25** are of interest in their own right, as they ought to be physiologically active[9,42].

This work was supported by the *Deutsche Forschungsgemeinschaft* (Me 405/14-1,2,3) and the *Fonds der Chemischen Industrie*. We are grateful to *BASF-Aktiengesellschaft, Bayer AG, Hoechst AG* and *Hüls AG* for generous gifts of chemicals. G. S. S. is indebted to the *Alexander von Humboldt-Stiftung* for a Research Fellowship and S. K. to the *Konrad-Adenauer-Stiftung* for a graduate fellowship (Promotionsstipendium). We acknowledge the help of Dr. *M. Noltemeyer*, Institut für Anorganische Chemie, Universität Göttingen, who kindly determined the crystal structure of compound **26**.

Experimental

^{1}H NMR: Bruker AW 250 (250 MHz), WM 270 (270 MHz), Varian XL-200 (200 MHz); δ = 7.15 for [D_5]benzene, 7.26 for $CHCl_3$. – ^{13}C NMR: Bruker AW 250 (62.89 MHz), WM 270 (67.93 MHz), Varian XL-200 (50.3 MHz); δ = 77.0 for $CDCl_3$, 128.0 for [D_6]benzene. The multiplicities of ^{13}C NMR signals were generally determined with the help of either DEPT or APT techniques and are designated as follows: CH_3, CH = (+) (DEPT and APT), CH_2 = (–) (DEPT and APT), quaternary C = (–) (APT) or (C_{quat}) (DEPT). – IR: Perkin-Elmer 125, 297, 399. – UV/Vis: Varian Cary 219. – MS: Varian MAT 112 with Varian Aerograph 1400 (GC with 25-m fused silica capillary Oribond SE-54, carrier gas He) and Varian MAT 311A (high resolution). – GC analytical: Siemens Sichromat 3 (25-m fused silica capillary CB-SE 54, carrier gas H_2). – M.p.: Melting point apparatus of Wagner & Munz; all values are uncorrected. – Elemental analyses: Mikroanalytisches Laboratorium, Institut für Organische Chemie, Universität Göttingen. – TLC: alumina sheets with UV fluorescence indicator (E. Merck, Silica gel 60 F_{254}; Macherey & Nagel, aluminium oxide BF_{254}). – Column chromatography: 60–230 mesh silica gel from E. Merck, Darmstadt, 60–100 mesh Florisil (E. Merck, Fluka) or aluminium oxide (basic and neutral, respectively, activity III) from Woelm. – Flash chromatography: 200–400 mesh silica gel (E. Merck). – In reactions requiring anhydrous conditions, solvents were dried by distillation under argon or nitrogen from the appropriate drying agent, glassware was flame-dried under reduced pressure and afterwards cooled under a steady stream of argon or nitrogen.

The following compounds were prepared according to literature procedures: Methyl 2-chloro-2-cyclopropylideneacetate (**6**)[2b,c], 1-ethoxy-1,3-pentadiene [mixture of (*E*/*E*), (*E*/*Z*), (*Z*/*E*), and (*Z*/*Z*) isomers] (**8a**)[13], 2-methyl-5-(trimethylsilyloxy)furan (**5e**)[20], and 2-methoxy-5-methylfuran (**5f**)[23,24], 2,4-pentadien-1-ol[43]. – The following abbreviations are used: cpr = cyclopropyl, PE = petroleum ether.

Methyl (4R,5R,8S*)-(±)-4-Chloro-5-ethoxy-8-methylspiro[2.5]oct-6-ene-4-carboxylate* (*trans*-**9a**): A mixture of 325 mg (2.2 mmol) of methyl 2-chloro-2-cyclopropylideneacetate (**6**), 450 mg (4 mmol) of 1-ethoxy-1,3-pentadiene (**8a**) (mixture of isomers as mentioned above), and 20 mg of K_2CO_3 in 2 ml of benzene was heated with stirring at 80°C for 18 h. The solvent was removed in a rotary evaporator, and the residue was chromatographed over 40 g of neutral alumina (*tert*-butyl methyl ether/PE 1:8) to afford 102 mg (18%) of *trans*-**9a**, R_f = 0.36. – IR (film): $\tilde{\nu}$ = 3025 cm^{-1}, 3010, 2910, 2875, 2825, 1725, 1640, 1430, 1365, 1320, 1195, 1160, 1080, 725. – ^{1}H NMR (270 MHz, C_6D_6): δ = 0.13–0.21 (m, 1H, cpr-H), 0.52–0.59 (m, 1H, cpr-H), 0.64 (d, 3H, 8-CH_3), 1.02 (t, 3H, X_3 part of an ABX_3 system, CH_2CH_3), 1.46 (mc, 2H, cpr-H), 2.15 (mc, 1H, 8-H), 3.33 (s, 3H, CO_2CH_3), 3.29–3.38 (m, 1H, A part of the ABX_3 system), 3.45–3.54 (1H, B part of the ABX_3 system), 4.14 (mc, 1H, 5-H), 5.49 (ddd, 1H), 5.75 (ddd, 1H). – MS (70 eV), *m/z* (%): 258 (3) [M^+], 223 (100) [M^+ – Cl], 191 (12), 177 (50), 152 (55), 135 (43), 92 (76). – $C_{13}H_{19}ClO_3$: calcd. 258.1018, found 258.1011 (MS).

1-(Trimethylsilyloxy)-1,3-pentadiene (**8b**). – *Method A:* 5-(Trimethylsilyloxy)-1,3-pentadiene, prepared from 2,4-pentadien-1-ol[43] by trimethylsilylation with chlorotrimethylsilane/bis(trimethylsilyl)amine[28], was isomerized to silyl enol ether **8b** roughly following the procedure described by Suzuki et al.[15]. A solution of 50 mg (0.04 mmol) of tetrakis(triphenylphosphane)ruthenium dihydride and 1.5 g (1 mmol) of the diene in 5 ml of anhydrous toluene was heated at 150°C for 18 h. After cooling to room temp., the mixture was separated from the organometallic dihydride by trap-to-trap distillation. The solvent was removed in vacuo, and the residue was fractionally distilled yielding 1.2 g (73%) of **8b** as a 5:2:2:1 mixture of diastereomers containing 10% of (*E,E*)-**8b** according to GC analysis, b.p. 80°C/60 Torr.

Method B: The enolate of *trans*-2-pentenal was silylated under conditions analogous to those reported by Mukaiyama et al.[16]. To a solution of 8.4 g (100 mmol) of the aldehyde and 10.6 g (105 mmol) of triethylamine was added quickly 120 mg of anhydrous $SnCl_2$ followed by 200 mg of hydroquinone and 13.2 ml (105 mmol) of chlorotrimethylsilane. The reaction mixture was heated at 70°C for 9 h, cooled to 0°C, treated with 30 ml of satd. aqueous $KHCO_3$ solution and filtered. The filtrate was washed successively with 10 ml of 10% aqueous $KHCO_3$ solution and 10 ml of water and dried with Na_2SO_4. The low-boiling components were removed in a rotary evaporator and the resulting residue distilled to afford 12.3 g (79%) of **8b**, b.p. 70°C/60 Torr. GC analysis showed product **8b** to consist of 4 diastereomers in a 1:2:2:5 ratio containing 50% of (*E,E*)-**8b**. – ^{1}H NMR (270 MHz, C_6D_6): δ = 0.03 [s, 9H, $Si(CH_3)_3$], 1.58 (dd, ^4J = 2, ^3J = 5 Hz, 3H, 5-H), 5.24–5.31 (m, ^4J = 1, ^3J = 11 Hz, 1H, 4-H), 5.91 (m, ^3J = 10.5 Hz, 1H, 3-H), 6.20 (ddd, ^3J = 11.2 Hz, 1H, 2-H), 6.50 (dd, 1H, 1-H).

Methyl (4R,5R*,8S*)-(±)-4-Chloro-8-methyl-5-(trimethylsilyloxy)spiro[2.5]oct-6-ene-4-carboxylate* (*trans/cis*-**9b**): A mixture of 330 mg (2.3 mmol) of dienophilic ester **6**, 50 mg of potassium carbonate, and 720 mg (4.6 mmol) of diene **8b** [employing the diastereomeric mixture containing 50% of (*E,E*)-**8b**, thus providing equimolar amounts of **6** and (*E,E*)-**8b**] was heated at 70°C for 24 h. Column chromatography over 160 g of neutral alumina (*tert*-butyl methyl ether/PE 1:4) gave 210 mg of recovered **6** (R_f = 0.69) and 85 mg (12% based on **6**, 34% based on consumed **6**) of cycloadduct *trans/cis*-**9b**, R_f = 0.57. – IR (film): $\tilde{\nu}$ = 3050 cm^{-1}, 3010, 2995, 2980, 2955, 1725, 1595, 1455, 1415, 1370, 1280, 1250, 1170, 720. – ^{1}H NMR (270 MHz, C_6D_6): δ = 0.13 [s, 9H, $Si(CH_3)_3$], 0.04–0.19 (m, 2H, cpr-H), 0.88 (d, 3H, 8-CH_3), 1.03 (m, 1H, 8-H), 1.78 (m, 2H, cpr-H), 3.25 (m, 1H, 5-H), 3.43 (s, 3H, CO_2CH_3), 5.71 (ddd, 1H, 7-H), 6.94 (ddd, 1H, 6-H). – MS (70 eV), *m/z* (%): 267 (100) [M^+ – Cl], 235 (15), 193 (21), 134 (60), 120 (13). – $C_{14}H_{23}ClO_3Si$: calcd. 302.1105, found 302.1112 (MS).

Methyl endo/exo-3'-Chlorospiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]-3'-carboxylate (**11a**): A mixture of 500 mg (3.4 mmol) of ester **6** and 1.5 g (22 mmol) of freshly distilled furan (**5a**) was heated with stirring at 45°C in a sealed tube. After 48 h, excess furan was evaporated in vacuo to give a slightly yellow oil, which consisted of starting material **6** and two further components, the latter in a 1.4:1 ratio according to GC analysis. The oil was chromatographed over 60 g of silica gel (diethyl ether/pentane 1:8). Fraction I (R_f = 0.45): 150 mg of starting ester **6**.

II (R_f = 0.24): 200 mg (39% based on consumed **6**) *exo*-**11a**, m.p. 58°C. – IR (KBr): $\tilde{\nu}$ = 3104 cm^{-1}, 3073, 3028, 3010, 2956, 2848, 1735 (C=O), 1570, 1422, 1213, 974, 815. – ^{1}H NMR (250 MHz, $CDCl_3$): δ = 0.52 (m, 1H, cpr-H), 1.03 (m, 1H, cpr-H), 1.15 (m,

1 H, cpr-H), 1.31 (m, 1 H, cpr-H), 3.69 (s, 3 H, CO_2CH_3), 4.31 (d, ^3J = 1.7 Hz, 1 H), 5.20 (d, ^3J = 1.7 Hz, 1 H), 6.51 (dd, $^3J_{cis}$ = 6.0, ^3J = 1.7 Hz, 1 H), 6.67 (dd, $^3J_{cis}$ = 6.0, ^3J = 1.7 Hz, 1 H). – ^{13}C NMR (62.9 MHz, $CDCl_3$, DEPT): δ = 9.58 (–), 12.94 (–), 35.66 (C_{quat}), 52.57 (+), 74.07 (C_{quat}), 85.50 (+), 88.26 (+), 134.15 (+), 139.86 (+), 168.39 (C_{quat}). – $C_{10}H_{11}ClO_3$ (214.6): calcd. C 55.96, H 5.17, Cl 16.52; found C 55.84, H 5.22, Cl 16.46.

III (R_f = 0.18): 260 mg (51% based on consumed ester **6**) *endo*-**11a**, m.p. 44°C. – IR (KBr): ṽ = 3084 cm^{-1}, 3043, 3020, 3001, 2966, 1735 (C=O), 1573, 1209, 1116, 760. – ^{1}H NMR (250 MHz, $CDCl_3$): δ = 0.63 (m, 1 H, cpr-H), 0.82 (m, 2 H, cpr-H), 1.38 (m, 1 H, cpr-H), 3.82 (s, 3 H, CO_2CH_3), 4.34 (d, ^3J = 1.8 Hz, 1 H), 5.50 (d, ^3J = 1.8 Hz, 1 H), 6.58 (dd, $^3J_{cis}$ = 6.6, ^3J = 1.8 Hz, 1 H), 6.67 (dd, $^3J_{cis}$ = 6.6, ^3J = 1.8 Hz, 1 H). – ^{13}C NMR (62.9 MHz, $CDCl_3$, DEPT): δ = 8.40 (–), 12.16 (–), 35.04 (C_{quat}), 53.08 (+), 71.01 (C_{quat}), 84.78 (+), 85.32 (+), 134.89 (+), 137.38 (+), 169.49 (C_{quat}). – MS (70 eV), *m/z* (%): 214 (0.2) [M$^+$], 179 (25) [M$^+$ – Cl], 155 (18), 119 (37), 91 (100), 68 (88), 59 (33). – $C_{10}H_{11}ClO_3$ (214.6): calcd. C 55.96, H 5.17, Cl 16.52; found C 56.01, H 5.23, Cl 16.46.

Methyl endo/exo-3'-Chloro-4'-methylspiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]-3'-carboxylate (**11b**): A mixture of 2.62 g (32 mmol) of 2-methylfuran (**5b**) and 4.40 g (30 mmol) of ester **6** was stirred at 20°C. After 100 h the crude reaction mixture was chromatographed over 220 g of silica gel (diethyl ether/PE, 1:1) yielding 5.21 g (76%) of *endo/exo*-**11b**. Fraction I (R_f = 0.56): 2.06 g (30%) of *exo*-**11b**. – IR (film): ṽ = 3010 cm^{-1}, 1733, 1445, 1389, 1319, 1272, 1210, 1153. – ^{1}H NMR ($CDCl_3$, 200 MHz): δ = 0.50 (m, 1 H, cpr-H), 0.90–1.25 (m, 3 H, cpr-H), 1.83 (s, 3 H, CH_3), 3.68 (s, 3 H, CO_2CH_3), 4.18 (d, ^3J = 0.5 Hz, 1 H, 1'-H), 6.30 (d, 1 H), 6.63 (m, 1 H). – ^{13}C NMR (50.3 MHz, $CDCl_3$, APT): δ = 9.98 (–), 13.30 (–), 16.10 (+), 37.80 (–), 52.25 (+), 76.30 (–), 84.40 (+), 92.00 (–), 137.60 (+), 139.30 (+), 168.40 (–). – MS (70 eV), *m/z*: 230/228 [M$^+$], 215/213 [M$^+$ – CH_3], 195 [M$^+$ – Cl]. – $C_{11}H_{13}ClO_3$ (228.7): calcd. C 57.78, H 5.73; found C 57.74, H 5.73.

II (R_f = 0.42): 3.16 g (46%) *endo*-**11b**. – IR (film): ṽ = 2890 cm^{-1}, 1733, 1431, 1389, 1320, 1248, 1042. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.53–1.10 (m, 4 H, cpr-H), 1.65 (s, 3 H, CH_3), 3.78 (s, 3 H, CO_2CH_3), 4.18 (d, ^3J = 1.5 Hz, 1 H, 1'-H), 6.29 (d, ^3J = 5.5 Hz, 1 H, 5'-H), 6.55 (dd, ^3J = 1.5, ^3J = 5.5 Hz, 1 H, 6'-H). – ^{13}C NMR (50.3 MHz, $CDCl_3$, APT): δ = 9.61 (–), 13.65 (–), 14.94 (+), 38.00 (–), 53.10 (+), 78.00 (–), 85.00 (+), 93.10 (–), 137.50 (+), 139.40 (+), 169.60 (–). – $C_{11}H_{13}ClO_3$ (228.7): calcd. C 57.78, H 5.73; found C 57.84, H 5.69.

Methyl endo/exo-3'-Chloro-1',4'-dimethylspiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]-3'-carboxylate (**11c**): A stirred mixture of 3.07 g (32 mmol) of 2,5-dimethylfuran (**5c**) and 4.4 g (30 mmol) of ester **6** was heated at 60°C for 12 h. The crude mixture was chromatographed over 230 g of silica gel (diethyl ether/PE, 1:1) to give an overall yield of 5.3 g (72%) of *endo/exo*-**11c**. Fraction I (R_f = 0.56): 1.75 g (24%) of *exo*-**11c**. – IR (film): ṽ = 2983 cm^{-1}, 1733, 1439, 1381, 1320, 1208, 1142. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.18 (m, 1 H, cpr-H), 0.85–1.10 (m, 3 H, cpr-H), 1.20 (s, 3 H, CH_3), 1.76 (s, 3 H, CH_3), 3.65 (s, 3 H, CO_2CH_3), 6.20 (s, 2 H). – ^{13}C NMR (50.3 MHz, $CDCl_3$, APT): δ = 9.70 (–), 10.16 (–), 13.70 (+), 16.10 (+), 40.20 (–), 52.20 (+), 79.80 (–), 86.60 (–), 90.20 (–), 137.90 (+), 142.80 (+), 168.40 (–). – MS (70 eV), *m/z* (%): 244/242 (2/5) [M$^+$], 211 (7), 210 (10), 199 (10), 163 (12), 133 (10), 105 (31), 96 (100), 59 (12). – $C_{12}H_{15}ClO_3$: calcd. 242.0709, found 242.0709 (MS).

II (R_f = 0.44): 3.55 g (48%) of *endo*-**11c**. – IR (film): ṽ = 2993 cm^{-1}, 1735, 1438, 1387, 1323, 1250, 1136, 1039. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.45 (m, 1 H, cpr-H), 0.60 (m, 1 H, cpr-H), 0.80 (m, 1 H, cpr-H), 1.10 (m, 1 H, cpr-H), 1.20 (s, 3 H, CH_3), 1.60 (s, 3 H, CH_3), 3.75 (s, 3 H, CO_2CH_3), 6.26 (AB system, ^3J = 6.6 Hz, 2 H). – ^{13}C NMR (50.3 MHz, $CDCl_3$, APT): δ = 9.33 (–), 9.76 (–), 14.2 (+), 14.9 (+), 40.0 (–), 53.1 (+), 79.8 (–), 87.2 (–), 91.2 (–), 139.5 (+), 140.8 (+), 169.8 (–). – $C_{12}H_{15}ClO_3$ (242.7): calcd. C 59.39, H 6.23; found C 59.30, H 6.18.

Methyl endo/exo-3'-Chloro-4'-methoxyspiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]-3'-carboxylate (**11d**): A mixture of 1.0 g (10.2 mmol) of 2-methoxyfuran (**5d**) and 1.5 g (10.2 mmol) of dienophilic ester **6** was stirred at room temp. for 32 h. The crude product, which was 95% pure according to its ^{1}H-NMR spectrum, was purified by flash chromatography over 150 g of silica gel (diethyl ether/pentane, 1:4 + 3% Et_3N) yielding 425 mg (17%) of *endo*-**11d** (R_f = 0.21, diethyl ether/pentane, 1:4), white solid, m.p. 98°C. – IR (KBr): ṽ = 3105 cm^{-1}, 2996, 2950, 2853, 1739, 1586, 1445, 1433, 1323, 1276, 1226, 1194, 1086, 1032, 1008, 983. – ^{1}H NMR (270 MHz, C_6D_6): δ = 0.00 (m, 1 H, cpr-H), 0.63 (m, 1 H, cpr-H), 0.98 (m, 1 H, cpr-H), 1.30 (m, 1 H, cpr-H), 3.13 (s, 3 H, OCH_3), 3.48 (s, 3 H, CO_2CH_2), 3.62 (d, ^3J = 1.8 Hz, 1 H, 1'-H), 6.13 (dd, ^3J = 1.8, ^3J = 6.2 Hz, 1 H, 6'-H), 6.50 (d, ^3J = 6.2 Hz, 1 H, 5'-H). – ^{13}C NMR (67.9 MHz, C_6D_6, DEPT): δ = 10.28 (–), 13.49 (–), 39.62 (C_{quat}), 51.64 (+), 54.38 (+), 76.00 (C_{quat}), 79.85 (+), 115.32 (C_{quat}), 134.00 (+), 141.32 (+), 166.35 (C_{quat}). – MS (CI), *m/z* (%): 247/245 [M$^+$ + 1], 231, 209, 195, 177. – $C_{11}H_{13}ClO_4$ (244.7): calcd. C 54.00, H 5.36; found C 54.10, H 5.31.

II: 210 mg (8%) of *exo*-**11d**, R_f = 0.12 (diethyl ether/pentane, 1:4), light yellow oil. – ^{1}H NMR (270 MHz, C_6D_6): δ = 0.10 (m, 1 H, cpr-H), 0.68 (m, 1 H, cpr-H), 0.75 (m, 1 H, cpr-H), 0.88 (m, 1 H, cpr-H), 3.33 (s, 3 H, OCH_3), 3.47 (s, 3 H, CO_2CH_3), 3.70 (d, ^3J = 1.8 Hz, 1 H, 1'-H), 6.12 (dd, ^3J = 1.8, ^3J = 6.2 Hz, 1 H, 6'-H), 6.28 (d, ^3J = 6.2 Hz, 1 H, 5'-H). – ^{13}C NMR (67.9 MHz, C_6D_6, DEPT): δ = 9.77 (–), 14.02 (–), 39.23 (C_{quat}), 52.71 (+), 54.44 (+), 77.19 (C_{quat}), 80.34 (+), 118.24 (C_{quat}), 134.61 (+), 140.25 (+), 168.00 (C_{quat}). – $C_{11}H_{13}ClO_4$ (244.7): calcd. C 54.00, H 5.36; found C 54.13, H 5.39.

Methyl endo/exo-3'-Chloro-1'-methyl-4'-(trimethylsilyloxy)spiro-[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]3'-carboxylate (**11e**) *and Methyl endo/exo-3'-Chloro-4'-methyl-1'-(trimethylsilyloxy)spiro[cyclopropane-1,3'-[7]oxabicyclo[2.2.1]hept-5-ene]-3'-carboxylate* (**12e**): A mixture of 1.5 g (10 mmol) of dienophilic ester **6**, 2.1 g (12 mmol) of 2-methyl-5-(trimethylsilyloxy)-furan (**5e**), and 0.5 ml of Et_3N was stirred at 20°C for 140 h. According to its ^{1}H-NMR spectrum, the crude product mixture (3.5 g) consisted mainly of the four possible cycloadducts in a ratio of 8:2:1:0.5; an attempted separation by column chromatography turned out to be quite difficult due to their extremely facile hydrolytic decomposition on alumina as well as on silica gel. When the crude reaction mixture was subjected to column chromatography over 200 g of silica gel (diethyl ether/pentane, 1:10 + 2% Et_3N) 222 mg (7%) of *endo*-**11e** (R_f = 0.7) and 50 mg (1.6%) of a mixture of *endo/exo*-**11e** (2:1) was obtained but no trace of *endo/exo*-**12e** could be isolated.

endo-**11e**: ^{1}H NMR (250 MHz, C_6D_6): δ = 0.22 [s, 9 H, $Si(CH_3)_3$], 0.50 (m, 1 H, cpr-H), 1.21 (m, 2 H, cpr-H), 1.41 (m, 1 H, cpr-H), 1.86 (s, 3 H, CH_3), 3.09 (s, 3 H, CO_2CH_3), 6.19 (d, ^3J = 5.5 Hz, 1 H), 6.32 (d, ^3J = 5.5 Hz, 1 H). – ^{13}C NMR (62.9 MHz, C_6D_6, DEPT): δ = 1.29 [+, 3 C, $Si(CH_3)_3$], 10.18 (–), 10.67 (–), 16.84 (+), 40.20 (C_{quat}), 51.82 (+), 79.75 (C_{quat}), 86.20 (C_{quat}), 108.05 (C_{quat}), 138.65 (+), 142.18 (+), 168.66 (C_{quat}). – $C_{14}H_{21}ClO_4Si$ (316.9): calcd. C 53.07, H 6.68, Cl 11.19; found C 53.15, H 6.70, Cl 11.12.

exo-**11e**: ^{1}H NMR (250 MHz, C_6D_6): δ = 0.00 (m, 1 H, cpr-H), 0.37 [s, 9 H, $Si(CH_3)_3$], 0.76–0.98 (m, 2 H, cpr-H), 0.86 (s, 3 H,

CH_3), 1.14 (m, 1H, cpr-H), 3.11 (s, 3H, CO_2CH_3), 5.95 (d, ^3J = 5.4 Hz, 1H), 6.58 (d, ^3J = 5.4 Hz, 1H).

Methyl endo/exo-3'-Chloro-4'-hydroxy-1'-methylspiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]-3'-carboxylate (**13**), *Methyl (4R*,5S*)-(±)-4-Chloro-5-hydroxy-5-methyl-8-oxospiro[2.5]oct-6-ene-4-carboxylate* (*endo*-**14**), *and Methyl (4S*,5S*)-(±)-4-Chloro-5-hydroxy-5-methyl-8-oxospiro[2.5]oct-6-ene-4-carboxylate* (*exo*-**14**): A solution of 9.0 g (28.4 mmol) of the mixture of cycloadducts *endo/exo*-**11e** and *endo/exo*-**12e**, as obtained from **5e** and **6**, in 10 ml of CH_2Cl_2 was treated with 1 ml of 2 N HCl, and after having been stirred for 4 h at 18°C, the mixture was diluted with 100 ml of diethyl ether. The resulting solution was washed with three portions of satd. aqueous Na_2CO_3 solution (10 ml each) and dried with Na_2SO_4. The solvent was evaporated in vacuo to give 6.9 g of an oil which was purified by column chromatography over 400 g of neutral alumina (PE/diethyl ether, 2:1) to afford four products. Fraction I (R_f = 0.66): 3.3 g (48%) of *endo*-**13**, m.p. 156°C. – IR (KBr): $\tilde{\nu}$ = 3480 cm^{-1}, 3100, 3010, 2990, 2960, 2860, 1765, 1615, 1470, 1455, 1440, 1395, 1370, 1355, 1315, 1210, 1190, 1145, 1030, 985. – ^1H NMR (270 MHz, C_6D_6): δ = 0.41 (mc, 1H, cpr-H), 0.57 (mc, 2H, cpr-H), 0.86 (mc, 1H, cpr-H), 1.00 (s, 3H, CH_3), 3.26 (s, 3H, OCH_3), 4.26 (s, 1H, OH), 5.44 (d, ^3J = 5.3 Hz, 1H, 6'-H), 6.51 (d, ^3J = 5.3 Hz, 1H, 5'-H). – MS (70 eV), *m/z* (%): 231/229 (1/3) [$M^+ - CH_3$], 209 (48) [$M^+ - Cl$], 177 (9), 149 (23), 147 (18), 137 (26), 105 (12), 97 (100), 77 (18), 69 (21), 59 (24). – $C_{11}H_{13}ClO_4$ (244.7): calcd. C 53.99, H 5.36; found C 54.03, H 5.39.

II (R_f = 0.51): 0.84 g (12%) of *exo*-**13**, m.p. 173°C. – ^1H NMR (270 MHz, C_6D_6): δ = 0.49–0.57 (m, 3H, cpr-H), 0.73 (m, 1H, cpr-H), 1.00 (s, 3H, CH_3), 3.28 (s, 3H, CO_2CH_3), 3.79 (s, 1H, OH), 5.40 (d, ^3J = 5.2 Hz, 1H, 6'-H), 6.51 (d, ^3J = 5.2 Hz, 1H, 5'-H). – $C_{11}H_{13}ClO_4$ (244.7): calcd. C 53.99, H 5.36; found C 53.87, H 5.43.

III (R_f = 0.18): 0.19 g (2.7%) of *exo*-**14**, m.p. 162°C. – ^1H NMR (270 MHz, C_6D_6): δ = 0.84 (mc, 1H, cpr-H), 1.17 (mc, 2H, cpr-H), 1.37 (s, 3H, CH_3), 1.88 (mc, 1H, cpr-H), 3.09 (s, 3H, CO_2CH_3), 5.08 (s, 1H, OH), 5.75 (d, ^3J = 10.5 Hz, 1H, 6-H), 6.59 (d, ^3J = 10.5 Hz, 1H, 7-H). – $C_{11}H_{13}ClO_4$ (244.7): calcd. C 53.99, H 5.36; found C 54.14, H 5.35.

IV (R_f = 0.07): 0.42 (6%) of *endo*-**14**, m.p. 150°C. – ^1H NMR (270 MHz, C_6D_6): δ = 1.17–1.31 (m, 2H, cpr-H), 1.38 (s, 3H, CH_3), 1.39–1.54 (m, 2H, cpr-H), 3.06 (s, 3H, CO_2CH_3), 5.91 (d, ^3J = 9.3 Hz, 1H, 6-H), 6.13 (d, ^3J = 9.3 Hz, 1H, 7-H). – MS (70 eV), *m/z* (%): 244 (2) [M^+], 214 (16), 212 (48), 177 (17), 169 (33), 160 (30), 149 (23), 137 (15), 84 (42), 77 (30), 55 (25), 51 (25), 43 (100) [$C_2H_3O^+$]. – $C_{11}H_{13}ClO_4$ (244.7): calcd. C 53.99, H 5.36; found C 54.11, H 5.37.

X-Ray Structure Analysis of endo-**14**[22]: Colorless crystal, size 0.15 × 0.23 × 0.21 mm^3, space group $P_{ca}2_1$, *a* = 1419.1(2), *b* = 682.8(1), *c* = 2354.7(3) pm, α = 90, β = 90, γ = 90°, *Z* = 8, *V* = 2282 · 10^6 pm^3, 1223 structural amplitudes, 360 variables, 2° ≤ Θ ≤ 65°, Cu-K_α four-circle diffractometer Enraf-Nonius CAD 4-SDP. – Direct methods were used to solve the structure with all atoms except H from *E* map, program MULTAN. – The measured crystal was disordered. The asymmetric unit contained two independent molecules, which had a common center of symmetry. This center of symmetry could not be transformed into a crystal center of symmetry. Because of the high correlation, refinement was difficult, and the resulting bonding parameters were not very accurate. It converged to R = 0.062 and R_w = 0.060, anyway, and confirmed the structure as (7*S**,8*R**)-**14**.

Methyl endo/exo-3'-Chloro-4'-methoxy-1'-methylspiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]-3'-carboxylate (*endo/exo*-**11f**) *and Methyl endo/exo-3'-Chloro-1'-methoxy-4'-methylspiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]-3'-carboxylate* (*endo/exo*-**12f**): A mixture of 8.0 g (71 mmol) of 2-methoxy-5-methylfuran (**5f**) and 10.4 g (71 mmol) of dienophilic ester **6** was stirred at 20°C for 120 h. Four products could be isolated by column chromatography on 500 g of silica gel (pentane/diethyl ether/triethylamine, 100:25:1). Fraction I (R_f = 0.70, pentane/diethyl ether, 1:1): 5.52 g (30%) of *endo*-**11f**, m.p. 129°C. – IR (KBr): $\tilde{\nu}$ = 3075 cm^{-1}, 3020, 2992, 2980, 2830, 1745, 1595, 1450, 1395, 1330, 1280, 1250, 1230, 1055, 995, 865, 735. – ^1H NMR (270 MHz, C_6D_6): δ = 0.01 (m, 1H, cpr-H), 0.84 (m, 1H, cpr-H), 0.90 (s, 3H, CH_3), 0.94 (m, 2H, cpr-H), 3.15 (s, 3H, OCH_3), 3.49 (s, 3H, CO_2CH_3), 6.01 (d, ^3J = 5.5 Hz, 1H), 6.54 (d, ^3J = 5.5 Hz, 1H). – ^{13}C NMR (67.9 MHz, C_6D_6, DEPT): δ = 9.84 (–), 10.41 (–), 14.01 (+), 42.35 (C_{quat}), 49.6 (C_{quat}), 51.92 (+), 54.16 (+), 78.01 (C_{quat}), 82.04 (C_{quat}), 134.54 (+), 144.53 (+), 168.25 (C_{quat}). – $C_{12}H_{15}ClO_4$ (258.7): calcd. C 55.71, H 5.84; found C 55.67, H 5.89.

II (R_f = 0.55): 2.56 g (14%) of *exo*-**11f**. – ^1H NMR (270 MHz, C_6D_6): δ = 0.07 (m, 1H, cpr-H), 0.69 (m, 1H, cpr-H), 0.88 (m, 2H, cpr-H), 0.91 (s, 3H, CH_3), 3.33 (s, 3H, OCH_3), 3.45 (s, 3H, CO_2CH_3), 5.94 (d, ^3J = 5.56 Hz, 1H), 6.30 (d, ^3J = 5.56 Hz, 1H). – ^{13}C NMR (50.3 MHz, C_6D_6, APT): δ = 10.10 (–), 10.32 (–), 14.55 (+), 42.09 (–), 53.32 (+), 54.79 (+), 79.38 (–), 83.00 (–), 116.82 (–), 135.55 (+), 143.8 (+), 168.8 (–), .

III (R_f = 0.38): 0.57 g (3%) of *endo*-**12f**. – ^1H NMR (270 MHz, C_6D_6): δ = 0.50 (m, 1H, cpr-H), 0.74 (m, 2H, cpr-H), 0.92 (m, 1H, cpr-H), 1.05 (s, 3H, CH_3), 3.03 (s, 3H, OCH_3), 3.08 (s, 3H, CO_2CH_3), 6.11 (d, ^3J = 5.5 Hz, 1H), 6.40 (d, ^3J = 5.5 Hz, 1H).

IV (R_f = 0.19): 0.26 g (1.4%) of *exo*-**12f**. – ^1H NMR (270 MHz, C_6D_6): δ = 0.58 (m, 1H, cpr-H), 0.69 (m, 1H, cpr-H), 0.81 (s, 3H, CH_3), 1.41 (m, 2H, cpr-H), 2.96 (s, 3H, OCH_3), 3.05 (s, 3H, CO_2CH_3), 6.06 (d, ^3J = 5.5 Hz, 1H), 6.18 (d, ^3J = 5.5 Hz, 1H).

When the cycloaddition was carried out on a smaller scale (20 mmol), 2.04 g (39%) of *endo*-**11f** and 1.0 g of *exo*-**11f** were isolated from 3.0 g (20 mmol) of **6** and 2.41 g of **5f** after 5.5 d at 20°C.

X-Ray Structure Analysis of exo-**11f**[22]: Colorless crystal, size 0.14 × 0.28 × 0.47 mm^3, space group $P\bar{1}$, *a* = 781.3(1), *b* = 835.1(1), *c* = 982.2(1) pm, α = 88.40(1), β = 88.57(1), γ = 73.90(1)°, *Z* = 2, *V* = 618 · 10^6 pm^3, 2074 structural amplitudes, $I > 3\sigma(I)$, 2° ≤ Θ ≤ 70°, Cu-K_α, four-circle diffractometer Enraf-Nonius CAD 4-SDP. – Direct methods to solve the structure with MULTAN program, R = 0.44, R_w = 0.043. Selected bond distances [pm]: C1'–C2' 154.0(5), C2'–C2 150.0(5), C2'–C3 149.9(5), C2–C3 149.4(6), C2'–C3' 153.2(4), C3'–C4' 154.4(5), C4'–C5' 151.5(5), C5'–C6' 131.9(6), C6'–C1' 151.5(6), C1'–C11 149.5(6), C3'–C31 153.2(5), C3'–C1 179.1(3); selected bond angles [°]: C1–C3'–C31 106.0(2), C1'–C2'–C3' 103.0(3), C2'–C3'–C4' 100.1(3), C1'–O7'–C4' 96.7(2), C1'–C6'–C5' 107.5(3), C4'–C5'–C6' 104.6(4), C3'–C4'–C5' 107.3(3).

General Procedure for the Hydrolysis of Acetals endo/exo-**11f** *and endo/exo*-**12f** *to Hemiacetals endo/exo*-**13** *and Enonens endo/exo*-**14**

a) *endo*-**13**: To a mixture of 3 g of silica gel and 5 ml of CH_2Cl_2 was added with stirring 0.3 ml of water and subsequently a solution of 26 mg (0.1 mmol) of *endo*-**11f** in 1 ml of CH_2Cl_2. After 1.5 h the mixture was diluted with 10 ml of diethyl ether, the silica gel was washed with two additional 10-ml portions of diethyl ether and the solvent removed in a rotary evaporator to afford 23 mg (93%) of *endo*-**13**.

b) *exo*-**13**: Hydrolysis of 26 mg (0.1 mmol) of *exo*-**11f** according to the general procedure yielded 22 mg (90%) of *exo*-**13**.

c) *endo*-**14**: According to the procedure described above 13 mg (0.05 mmol) of *endo*-**12f** was hydrolyzed to give 10.5 mg (86%) of *endo*-**14**.

d) *exo*-**14**: 13 mg (0.05 mmol) of *exo*-**12f** was hydrolyzed to afford 11 mg (92%) of *exo*-**14**.

Methyl (4S,7S*,8R*)-(±)-4-Chloro-7,8-epoxy-8-methylspiro[2.5]octane-4-carboxylate* (*endo*-**16**) *and Methyl (4R*,7S*,8R*)-(±)-4-Chloro-7,8-epoxy-8-methylspiro[2.5]octane-4-carboxylate* (*exo*-**16**): 3.0 g (11.6 mmol) of cycloadducts *endo/exo*-**11f** and *endo/exo*-**12f** [crude mixture resulting from the reaction of 2-methoxy-5-methylfuran (**5f**) and ester **6**] was subjected to column chromatography over 50 g of florisil (PE/diethyl ether/ethyl acetate, 20:6:3) to give only 0.3 g of two separate fractions, *endo/exo*-**11f** and *endo/exo*-**12f**, respectively. Two more fractions could be isolated, when the eluent was changed to pure diethyl ether. Fraction I: 1.4 g (47%) of *endo*-**16**, m.p. 123°C. – IR (KBr): $\tilde{\nu}$ = 3070 cm^{-1}, 2990, 2940, 1765, 1725, 1410, 1370, 1335, 1265, 1160, 1120, 1090, 1030, 1010, 940. – ^1H NMR (270 MHz, C_6D_6): δ = 0.56 (mc, 1H, cpr-H), 0.69 (m, 1H, cpr-H), 0.89 (m, 2H, cpr-H), 1.00 (s, 3H, CH_3), 2.39 (dd, ^2J = 18.2, ^3J = 11.8 Hz, 1H, 6-H), 2.91 (dd, ^3J = 18.2, ^3J = 2 Hz, 1H, 7-H), 3.27 (s, 3H, CO_2CH_3), 3.45 (dd, ^2J = 11.8, ^3J = 2 Hz, 1H, 6-H). – ^{13}C NMR (67.9 MHz, C_6D_6, DEPT): δ = 11.13 (–), 12.02 (–), 20.00 (+), 31.91 (–), 39.71 (C_{quat}), 47.31 (–), 52.63 (+), 70.78 (C_{quat}), 85.67 (C_{quat}), 169.51 (C_{quat}), 174.31 (C_{quat}). – MS (70 eV), *m/z* (%): 209 (100) [M^+ – Cl], 181 (94), 177 (75), 149 (67), 138 (56), 121 (26), 79 (65), 77 (63). – $C_{11}H_{13}ClO_4$ (244.7): calcd. C 53.99, H 5.36; found C 54.06, H 5.42.

II: 0.23 g (8%) of *exo*-**16**. – ^1H NMR (270 MHz, C_6D_6): δ = 0.34 (m, 2H, cpr-H), 0.53 (m, 1H, cpr-H), 0.69 (s, 3H, CH_3), 1.31 (mc, 1H, cpr-H), 2.79–2.94 (mc, ^2J = 28.0, ^3J = 18.0, ^3J = 6.5 Hz, 2H, AB part of an ABX system, 6-H), 3.07 (s, 3H, CO_2CH_3), 3.19 (dd, ^3J = 18.0, ^3J = 6.5 Hz, 1H, X part of an ABX system, 7-H). – $C_{11}H_{13}ClO_4$ (244.7): calcd. C 53.99, H 5.36; found C 53.88, H 5.47.

endo-**13**: To a solution of lithium diisopropylamide [1 mmol, prepared from 0.16 ml (1.1 mmol) of diisopropylamine and 0.68 ml (1 mmol) of a 1.5 M solution of *n*BuLi in hexane in 15 ml of anhydrous diethyl ether at −78°C] was added a solution of 250 mg (1.0 mmol) of epoxide *endo*-**16** in 5 ml of anhydrous diethyl ether. After stirring for 4 h, the mixture was allowed to warm to ambient temp. and washed with two 3-ml portions of satd. aqueous NaCl solution. The organic solution was dried with Na_2SO_4 and the solvent evaporated in vacuo yielding 231 mg (92%) of *endo*-**13**. For spectral data see above.

Methyl 6-Hydroxy-2-(2-iodoethyl)-3-methylbenzoate (**18**): To a stirred solution of 90 mg (0.35 mmol) of *endo*-**13** in 10 ml of anhydrous CH_2Cl_2, kept at 0°C, was added 0.060 ml (0.42 mmol) of iodotrimethylsilane. After 1 h the mixture was diluted with 5 ml of a satd. aqueous $NaHSO_3$ solution and 5 ml of diethyl ether. The layers were separated and the aqueous phase extracted with three portions of diethyl ether (5 ml each). The combined organic layers were dried with Na_2SO_4 and evaporated to give 95 mg (81%) of **18**, yellow oil. – IR (film): $\tilde{\nu}$ = 3400 cm^{-1} (OH), 3095, 2995, 2980, 1765, 1610, 1505, 1470, 1445, 1280, 1130, 1110, 1030, 980, 885. – ^1H NMR (270 MHz, C_6D_6): δ = 1.88 (s, 3H, CH_3), 3.05 (t, ^3J = 8.2 Hz, 2H), 3.22 (s, 3H, CO_2CH_3), 3.56 (t, ^3J = 8.2 Hz, 2H), 6.27 (d, ^3J = 9.1 Hz, 1H), 6.79 (d, ^3J = 9.1 Hz, 1H).

General Procedure for the Conversion of Cyclic α-Chloro Esters endo- and exo-**11a–d,f** *to their Epoxides endo*-**22a–d,f** *and exo*-**22d,f** *via Chlorohydrins endo*-**21a–d,f** *and exo*-**21d,f** *as Intermediates*

a) *endo-3'-Chloro-3'-(hydroxymethyl)spiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]* (*endo*-**21a**) *and endo-Dispiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene-3',2''-oxirane]* (*endo*-**22a**): To a suspension of 122 mg (5.5 mmol) of $LiBH_4$ in 15 ml of anhydrous diethyl ether/CH_2Cl_2 (1:1) was added dropwise at 0°C a solution of 800 mg (3.7 mmol) of cycloadduct *endo*-**11a** in 14 ml of dry Et_2O/CH_2Cl_2 (1:1). The mixture was stirred under nitrogen at 20°C for 1 h, then 25 mg of $LiBH_4$ was added and the mixture stirred at room temp. for an additional 2.5 h. Then it was poured into 40 ml of a satd. aqueous NaCl solution. The mixture was extracted with five portions of diethyl ether (30 ml each), the combined organic layers were washed with 20 ml of satd. aqueous NaCl solution and dried with $MgSO_4$ for 1 h. The solvent was evaporated in vacuo to give 637 mg (92%) of crude *endo*-**21a**, 350 mg of which was used in the next step without any further purification. An aliquot of 42 mg of *endo*-**21a** was chromatographed over 4 g of silica gel (diethyl ether/pentane, 1:2) to give a small amount of recovered starting material *endo*-**11a** (R_f = 0.43) and 35 mg (77%) of chlorohydrin *endo*-**21a** (R_f = 0.2), m.p. 89°C. – IR (KBr): $\tilde{\nu}$ = 3420 cm^{-1} (OH), 3030, 3003, 2933, 1457, 1423, 1190, 924, 658. – ^1H NMR (250 MHz, $CDCl_3$): δ = 0.68 (m, 3H, cpr-H), 1.03 (m, 1H, cpr-H), 2.23 (dd, 1H, OH), 3.61 (dd, 1H), 3.82 (dd, 1H), 4.29 (s, 1H), 5.25 (s, 1H), 6.54 (dd, 1H), 6.66 (dd, 1H). – ^{13}C NMR (62.9 MHz, $CDCl_3$, DEPT): δ = 7.51 (–), 8.49 (–), 32.38 (C_{quat}), 68.76 (–), 75.81 (C_{quat}), 83.29 (+), 86.07 (+), 135.09 (+), 136.41 (+). – MS (70 eV), *m/z* (%): 188/186 (0.3/0.4) [M^+], 170/168 (7) [M^+ – H_2O], 157 (17). – $C_9H_{11}ClO_2$ (186.6): calcd. C 57.93, H 5.94, Cl 19.01; found C 57.63, H 6.05, Cl 19.24.

To 90 ml of a well-stirred 50% aqueous solution of NaOH was added a solution of 595 mg (3.2 mmol) of crude *endo*-**21a** in 20 ml of THF and 270 mg of benzyltriethylammonium chloride. The mixture was stirred at ambient temp. for 5 d. Although TLC (SiO_2, diethyl ether/pentane, 1:2) still indicated a small amount of starting material, the reaction was terminated at this time, because of competitive formation of side products. The reaction mixture was taken up in 80 ml of ice/water, extracted with six portions of diethyl ether (25 ml each), and the combined organic layers were washed with 20 ml of satd. aqueous NaCl solution and dried with $MgSO_4$. The solvent was removed in a rotary evaporator, and the resulting residue was purified by column chromatography on 50 g of flash silica gel (diethyl ether/pentane, 1:2, with 2% Et_3N added) yielding 40 mg of impure *endo*-**22a** and 276 mg (57% overall based on *endo*-**11a**) of pure epoxide *endo*-**22a** (R_f = 0.3), white solid, m.p. 91°C. – ^1H NMR (250 MHz, $CDCl_3$): δ = 0.29 (m, 1H, cpr-H), 0.56 (m, 2H, cpr-H), 0.74 (m, 1H, cpr-H), 2.59 (AB system, δ_A = 2.42, δ_B = 2.75, ^2J = 3.8 Hz, 2H, epoxide-H), 4.42 (bs, 1H), 4.61 (bs, 1H), 6.51 (dd, ^3J = 5.9, ^3J = 1.6 Hz, 1H), 6.72 (dd, ^3J = 5.9, ^3J = 1.6 Hz, 1H). – ^{13}C NMR (62.9 MHz, $CDCl_3$, DEPT): δ = 5.48 (–), 6.64 (–), 24.41 (C_{quat}), 45.50 (–), 67.20 (C_{quat}), 83.56 (+), 83.80 (+), 132.91 (+), 139.27 (+). – MS (70 eV), *m/z* (%): 150 (0.8) [M^+], 149 (6), 121 (43), 107 (35), 103 (13), 94 (29), 91 (76), 77 (100), 68 (57), 65 (55), 53 (38), 51 (46). – $C_9H_{10}O_2$ (150.2): calcd. C 71.98, H 6.71; found C 71.83, H 6.69.

b) *endo-4'-Methyldispiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene-3',2''-oxirane]* (*endo*-**22b**): According to the general procedure 2.1 g (9.1 mmol) of *endo*-**11b** was reduced with 325 mg (17.9 mmol) of $LiBH_4$. After 7 h crude chlorohydrin *endo*-**21b** was isolated and directly used in the following reaction to afford, after 48 h of vigorous stirring and purification by column chromatography over silica gel (PE/ether, 1:1), 982 mg (66%) of epoxide *endo*-**22b** (R_f = 0.46) as a white solid, m.p. 63–64°C. – IR (KBr): $\tilde{\nu}$ = 2999 cm^{-1}, 1498, 1448, 1390, 1328, 1293, 1169, 1122. – ^1H NMR (200 MHz, C_6D_6): δ = −0.98 (m, 1H, cpr-H), 0.10 (m, 1H, cpr-H), 0.46 (m, 1H, cpr-H), 0.55 (m, 1H, cpr-H), 1.26 (s, 3H, CH_3), 1.92 (d, ^2J = 4.6 Hz, 1H, epoxide-H), 2.10 (d, ^2J = 4.6 Hz, 1H, epoxide-H), 3.93 (d, ^3J = 1.1 Hz, 1H, 1'-H), 5.90 (d, ^3J = 5.5 Hz, 1H, 5'-H), 6.23 (dd, ^3J = 5.5, ^3J = 1.1 Hz, 1H, 6'-H). – ^{13}C

NMR (50.3 MHz, C_6D_6, APT): δ = 6.0 (−), 7.9 (−), 12.6 (+), 26.0 (−), 45.1 (−), 68.5 (−), 83.5 (+), 87.7 (−), 137.5 (+), 140.1 (+). − MS (70 eV), *m/z* (%): 164 (3) [M^+], 163 (4) [$M^+ - 1$], 149 (7) [$M^+ - CH_3$], 122 (14), 121 (64), 108 (29), 91 (32), 77 (41), 65 (15), 43 (100). − $C_{10}H_{12}O_2$ (164.2): calcd. C 73.15, H 7.37; found C 73.04, H 7.27.

c) *endo-1',4'-Dimethyldispiro[cyclopropane-1,2'-[7]oxabicyclo-[2.2.1]hept-5-ene-3',2''-oxirane]* (*endo*-**22c**): After 7 h of stirring at 0°C and ensuing workup, a mixture of 484 mg (2.0 mmol) of cycloadduct *endo*-**11c** and 70 mg (3.9 mmol) of $LiBH_4$ gave crude chlorohydrin *endo*-**21c** which was subjected to basic phase-transfer conditions immediately. After 48 h and column chromatography over silica gel (diethyl ether/PE, 1:1), 142 mg (40%) of epoxide *endo*-**22c** (R_f = 0.41) was obtained as a white solid, m.p. 45−46°C. − IR (KBr): ṽ = 3060 cm^{-1}, 1269, 900, 743. − ^1H NMR (200 MHz, C_6D_6): δ = 0.00 (m, 2H, cpr-H), 0.55 (m, 2H, cpr-H), 1.02 (s, 3H, CH_3), 1.30 (s, 3H, CH_3), 1.89 (d, ^2J = 4.4 Hz, 1H, epoxide-H), 2.11 (d, ^2J = 4.4 Hz, 1H, epoxide-H), 5.91 (d, ^3J = 6.0 Hz, 1H), 6.12 (d, ^3J = 6.0 Hz, 1H). − MS (70 eV), *m/z*: 163 [$M^+ - CH_3$], 147, 135, 121. − $C_{11}H_{14}O_2$ (178.2): calcd. C 74.13, H 7.92; found C 73.29, H 7.71.

d) *endo/exo-4'-Methoxydispiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene-3',2''-oxirane]* (*endo/exo*-**22d**): A mixture of 3.67 g (15 mmol) of crude *endo/exo*-**11d** (1.2:1 mixture of isomers as mentioned above) and 600 mg (33 mmol) of $LiBH_4$ was stirred in anhydrous diethyl ether at −10°C. The reaction mixture was allowed to warm to 0°C over a period of 7 h, and the resulting mixture of crude chlorohydrins *endo/exo*-**21d** was used in the preparation of epoxides *endo/exo*-**22d**, of which only the *endo* isomer could be isolated in pure form by column chromatography over silica gel (diethyl ether/PE, 1:1). *exo*-**22d** (R_f = 0.31) was found, but could not really be purified (yield less than 1%). Thus 297 mg (22% based on *endo*-**11d**) of *endo*-**22d** (R_f = 0.39) was obtained. − IR (film): ṽ = 2986 cm^{-1}, 1449, 1328, 1293, 1259, 1227. − ^1H NMR (200 MHz, C_6D_6): δ = −0.92 bis +0.58 (m, 4H, cpr-H), 2.10 (d, ^2J = 4.4 Hz, 1H, epoxide-H), 3.17 (d, ^2J = 4.4 Hz, 1H, epoxide-H), 3.31 (s, 3H, OCH_3), 3.86 (d, ^3J = 1.0 Hz, 1H, 1'-H), 6.32 (m, ^3J = 6.2, ^3J = 1.0 Hz, 2H). − ^{13}C NMR (50.3 MHz, C_6D_6, APT): δ = 3.80 (−), 10.66 (+), 28.54 (−), 46.15 (−), 53.80 (+), 67.34 (−), 79.86 (+), 111.56 (−), 133.72 (+), 140.90 (+). − MS (70 eV), *m/z*: 180 [M^+], 165 [$M^+ - CH_3$], 137, 121, 93, 91, 79, 77.

e) *endo-3'-Chloro-3'-(hydroxymethyl)-4'-methoxy-1'-methylspiro-[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]* (*endo*-**21f**) *and endo-4'-Methoxy-1'-methyldispiro[cyclopropane-1,2'-[7]oxabicyclo-[2.2.1]hept-5-ene-3',2''-oxirane]* (*endo*-**22f**): Following the general procedure 1.9 g (7.4 mmol) of *endo*-**11f** was reduced within 7 h to 1.6 g (94%) of crude chlorohydrin *endo*-**21f** as a colorless oil, which because of its considerable instability was almost immediately subjected to the next reaction. − ^1H NMR (270 MHz, C_6D_6): δ = −0.23 (m, 1H, cpr-H), 0.75 (mc, 1H, cpr-H), 0.81−0.90 (m, 2H, cpr-H), 0.85 (s, 3H, CH_3), 1.88 (bs, 1H, OH), 3.25 (d, ^2J = 11.9 Hz, 1H, CH_2OH), 3.37 (s, 3H, OCH_3), 3.51 (d, ^2J = 11.9 Hz, 1H, CH_2OH), 5.84 (d, ^3J = 5.7 Hz, 1H), 5.88 (d, ^3J = 5.7 Hz, 1H). − ^{13}C NMR (67.9 MHz, C_6D_6, DEPT): δ = 6.88 (−), 9.46 (−), 13.69 (+), 39.72 (C_{quat}), 53.94 (+), 66.67 (−), 82.20 (C_{quat}), 82.49 (C_{quat}), 113.83 (+), 132.46 (+). − From 1.60 g (6.9 mmol) of *endo*-**21f** was obtained 1.05 g (78%) of epoxide *endo*-**22f** (R_f = 0.56) after the reaction mixture had been stirred for 48 h under basic conditions as described above and the product purified by column chromatography over 50 g of silica gel (pentane/diethyl ether/triethylamine, 50:25:1). M.p. 197°C. − IR (KBr): ṽ = 3050 cm^{-1}, 3045, 2990, 2960, 2935, 2840, 1570, 1440, 1425, 1385, 1315, 1230, 1180, 1125, 1055, 1010, 975, 965, 860, 835. − ^1H NMR (270 MHz, C_6D_6): δ = −0.02 (mc, 1H, cpr-H), 0.12 (mc, 1H, cpr-H), 0.34 (mc, 1H, cpr-H), 0.59 (mc, 1H, cpr-H), 1.01 (s, 3H, CH_3), 2.11 (d, ^2J = 5.0 Hz, 1H, epoxide-H), 3.16 (d, ^2J = 5.0 Hz, 1H, epoxide-H), 3.35 (s, 3H, OCH_3), 6.13 (d, ^3J = 5.6 Hz, 1H), 6.35 (d, ^3J = 5.6 Hz, 1H). − ^{13}C NMR (67.9 MHz, C_6D_6, DEPT): δ = 3.99 (−), 6.65 (−), 14.68 (+), 31.73 (C_{quat}), 46.90 (−), 53.65 (+), 68.50 (C_{quat}), 82.25 (C_{quat}), 110.41 (C_{quat}), 134.54 (+), 143.69 (+). − MS (70 eV), *m/z* (%): 194 (6) [M^+], 179 (11) [$M^+ - CH_3$], 164 (13), 151 (23), 149 (14), 135 (66), 107 (35), 105 (81), 93 (33), 91 (100), 79 (70), 77 (74). − $C_{11}H_{14}O_3$ (194.2): calcd. C 68.02, H 7.26; found C 68.09, H 7.31.

f) *endo/exo*-**22f**: 7.00 g (38.6 mmol) of *endo/exo*-**11f** (mixture of isomers of not precisely known composition obtained after column chromatography as described above) was reduced with 1.80 g (82.6 mmol) of $LiBH_4$. After 7 h the resulting chlorohydrins were immediately converted into the corresponding epoxides under conditions as described above, affording 1.18 g (23% based on the total amount of diasteromeric starting material used) of *endo*-**22f** (spectral data are given above) and 13 mg (0.3%) of *exo*-**22f**. − ^1H NMR (200 MHz, C_6D_6): δ = −0.95 (m, 2H, cpr-H), 0.55 (m, 2H, cpr-H), 1.00 (s, 3H, CH_3), 1.92 (d, ^2J = 4.4 Hz, 1H, epoxide-H), 2.54 (d, ^2J = 4.4 Hz, 1H, epoxide-H), 3.53 (s, 3H, OCH_3), 6.09 (m, ^3J = 6.2 Hz, 2H).

g) *exo-3'-Chloro-3'-(hydroxymethyl)-4'-methoxy-1'-methylspiro-[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]* (*exo*-**21f**) *and exo-4'-Methoxy-1'-methyldispiro[cyclopropane-1,2'-[7]oxabicyclo-[2.2.1]hept-5-ene-3',2''-oxirane]* (*exo*-**22f**): A solution of 626 mg (2.4 mmol) of *exo*-**11f** in 7 ml of dry ether/dry dichloromethane (4:1) was added with stirring at ambient temp. to a suspension of 79 mg (3.6 mmol) $LiBH_4$ in 10 ml of dry ether. The mixture was stirred for an additional 2 h, then poured into 40 ml of a satd. NaCl solution and the aqueous phase extracted with ether (5 × 80 ml). The combined organic layers were dried with Na_2SO_4 and the solvent evaporated under reduced pressure to give 541 mg (97%) of crude chlorohydrin *exo*-**21f** as an oil. − ^1H NMR (250 MHz, C_6D_6): δ = −0.02 bis +0.05 (m, 1H, cpr-H), 0.50−0.63 (m, 1H, cpr-H), 0.64−0.75 (m, 1H, cpr-H), 0.79 (s, 3H, 1'-CH_3), 0.84−0.99 (m, 1H, cpr-H), 2.94 (dd, ^3J = 7.1, ^3J = 5.7 Hz, 1H, OH), 3.21 (s, 3H, OCH_3), 3.92 (dd, ^2J = 11.6, ^3J = 5.7 Hz, 1H, CH_2OH), 4.07 (dd, ^2J = 11.6, ^3J = 5.7 Hz, 1H, CH_2OH), 5.94 (d, ^3J = 5.7 Hz, 1H), 6.21 (d, ^3J = 5.7 Hz, 1H).

Crude *exo*-**21f** (520 mg, 2.2 mmol) in 12 ml of THF was stirred with 50 ml of a 50% aqueous NaOH solution in the presence of 135 mg of benzyltriethylammonium chloride for 4 d. Then the mixture was poured into 50 ml of ice/water, the aqueous phase was extracted with ether (5 × 70 ml), the combined ethereal layers were dried with Na_2SO_4, and the solvent was evaporated under reduced pressure. The residue was chromatographed over silica gel (13 cm in a 4 × 30-cm column, elution with PE/ether, 8:1, with 0.5% Et_3N) to give 233 mg of a 1:1 mixture of *exo*-**21f** and *exo*-**22f**. − ^1H NMR (250 MHz, C_6D_6) of *exo*-**22f** (from the spectrum of the mixture): δ = −0.04 bis +0.12 (m, 2H, cpr-H), 0.50−0.74 (m, cpr-H), 1.01 (s, 3H, 1'-CH_3), 2.34 (AX system, δ_A = 2.13, δ_X = 2.55, $^2J_{AX}$ = 4.7 Hz, 2H, epoxide-H), 3.49 (s, 3H, OCH_3), 6.04 (d, ^3J = 5.7 Hz, 1H), 6.10 (d, ^3J = 5.7 Hz, 1H).

(1'S,3'R*,4'R*)-3'-Hydroxy-4'-methoxy-1',3'-dimethylspiro[cyclopropane-1,2'-[7]oxabicyclo[2.2.1]hept-5-ene]* (*endo*-**23f**): A stirred solution of 150 mg (0.77 mmol) of epoxide *endo*-**22f** in 20 ml of anhydrous THF was treated with 0.40 ml of a 3.5 M sodium dihydridobis(2-methoxyethoxy)aluminate (Red Al®) solu-

tion in toluene. The mixture was kept at 20°C under nitrogen for 24 h and poured into 30 ml of a satd. aqueous NaCl solution. The layers were separated, and the aqueous phase was extracted with three portions of diethyl ether (150 ml each). The combined organic layers were washed with 50 ml of satd. aqueous NaCl solution and dried with $MgSO_4$. Evaporation of the solvent followed by chromatography of the residue over 15 g of silica gel (pentane/diethyl ether/triethylamine, 50:25:1) afforded 129 mg (85%) of alcohol *endo*-**23f** (R_f = 0.19), m.p. 155°C. – IR (KBr): $\tilde{\nu}$ = 3490 cm^{-1}, 3430 (OH), 3050, 2970, 2950, 2915, 2825, 1580, 1445, 1440, 1375, 1310, 1220, 1170, 1150, 1115, 1095, 1040, 1010, 970, 920, 855. – ^1H NMR (270 MHz, C_6D_6): δ = −0.12 (mc, 1H, cpr-H), 0.48 (m, 3H, cpr-H), 0.90 (s, 3H, CH_3), 1.33 (s, 3H, CH_3), 1.53 (bs, 1H, OH), 3.43 (s, 3H, OCH_3), 6.06 (d, ^3J = 5.6 Hz, 1H), 6.23 (d,^3J = 5.6 Hz, 1H). – ^{13}C NMR (67.9 MHz, C_6D_6, DEPT): δ = 5.09 (−), 5.57 (−), 14.61 (+), 21.78 (+), 53.72 (+), 40.56 (C_{quat}), 77.61 (C_{quat}), 81.69 (C_{quat}), 114.97 (C_{quat}), 133.74 (+), 143.50 (+). – MS (70 eV), *m/z* (%): 196 (1.2) [M^+]. – $C_{11}H_{16}O_3$ (196.2): calcd. C 67.32, H 8.22; found C 67.29, H 8.28.

(3S,7S*)-7-Hydroxy-1-oxadispiro[2.0.2.4]dec-8-en-10-one* (*endo*-**24d**): To a mixture of 0.3 ml of water, 6 ml of dichloromethane, and 4 g of silica gel, which had been stirred for 5 min, was added 27 mg (0.15 mmol) of acetal *endo*-**22d**. After an additional 2 h, the silica gel was separated by filtration and washed with three portions of diethyl ether (35 ml each). Concentration in vacuo followed by filtration through 3 g of silica gel (diethyl ether/PE, 1:1) afforded 22 mg (90%) of enone *endo*-**24d**, R_f = 0.35. – ^1H NMR (200 MHz, C_6D_6): δ = −0.79 (m, 2H, cpr-H), 0.22 (m, 2H, cpr-H), 1.0 (bs, 1H, OH), 2.01 (d, ^2J = 6.7 Hz, 1H, epoxide-H), 2.53 (d, ^2J = 6.7 Hz, 1H, epoxide-H), 2.78 (d, 1H), 5.63 (d, ^3J = 10.7 Hz, 1H), 6.05 (dd, ^3J = 10.7 Hz, 1H). – $C_9H_{10}O_3$ (166.2): calcd. C 65.05, H 6.07; found C 64.92, H 6.01.

(3S,7S*)-7-Hydroxy-7-methyl-1-oxadispiro[2.0.2.4]dec-8-en-10-one* (*endo*-**24f**): Acetal *endo*-**22f** (58 mg, 0.3 mmol) was added to a mixture of 0.3 ml of water, 8 ml of CH_2Cl_2, and 6 g of silica gel, that had been stirred for 5 min beforehand. After 2 h of stirring, the silica gel was separated by filtration and washed with four portions of diethyl ether (35 ml each). Evaporation of the solvent gave 46 mg (86%) of enone *endo*-**24f**, which could be obtained as white crystals by filtration through a short column of silica gel (diethyl ether/PE, 1:1, R_f = 0.5), yield 41 mg (77%), m.p. 83–84°C. – ^1H NMR (200 MHz, C_6D_6): δ = −0.6 (m, 4H, cpr-H), 0.75 (s, 3H, CH_3), 1.1 (bs, 1H, OH), 1.72 (d, ^2J = 6.2 Hz, 1H, epoxide-H), 2.80 (d, ^2J = 6.2 Hz, 1H, epoxide-H), 5.58 (d, ^3J = 10.0 Hz, 1H), 5.97 (d, ^3J = 10.0 Hz, 1H). – MS (70 eV), *m/z* (%): 181 (2) [M^+ + 1], 180 (12) [M^+], 165 (49) [$M^+ - CH_3$], 150 (38), 107 (26), 91 (37), 77 (34), 69 (26), 55 (33), 43 (100). – $C_{10}H_{12}O_3$: calcd. 180.0786, found 180.0786 (MS).

(4R,8S*)-4,8-Dihydroxy-4,8-dimethylspiro[2.5]oct-6-en-5-one* (*endo*-**25f**): To a mixture of 0.3 ml of water, 5 ml of CH_2Cl_2, and 3 g of silica gel was added 60 mg (0.3 mmol) of acetal *endo*-**23f** after 5 min of stirring. After an additional 1.5 h, the silica gel was separated by filtration and washed with three portions of diethyl ether (30 ml each). The solvent was evaporated in vacuo to afford 51 mg (95%) of enone *endo*-**25f**, m.p. 173°C. – IR (KBr): $\tilde{\nu}$ = 3420 cm^{-1} (OH), 3090, 3015, 2960, 2930, 1675 (C=O), 1630 (C=C), 1465, 1450, 1410, 1380, 1365, 1290, 1260, 1165, 1125, 1105, 1050, 1020, 960, 925, 910, 900, 820. – ^1H NMR (270 MHz, C_6D_6): δ = 0.23 (mc, 1H, cpr-H), 0.34 (mc, 1H, cpr-H), 0.63 (s, 3H, CH_3), 0.80 (mc, 1H, cpr-H), 1.03 (mc, 1H, cpr-H), 1.58 (s, 3H, CH_3), 1.78 (bs, 1H, OH), 3.70 (bs, 1H, OH), 5.79 (d, ^3J = 8.9 Hz, 1H), 6.12 (d, ^3J = 8.9 Hz, 1H). – ^{13}C NMR (67.9 MHz, C_6D_6, DEPT): δ = 3.51 (−), 8.13 (−), 26.81 (+), 27.80 (+), 32.40 (C_{quat}), 70.62 (C_{quat}), 73.77 (C_{quat}), 123.86 (+), 152.14 (+), 202.89 (C_{quat}). – MS (70 eV), *m/z* (%): 182 (3) [M^+], 164 (9) [$M^+ - H_2O$], 149 (7), 121 (89), 98 (69), 93 (46), 79 (22), 77 (43), 55 (100), 53 (44). – UV (methanol): λ_{max} (ε) = 330 nm (89). – $C_{10}H_{14}O_3$ (182.2): calcd. C 65.91, H 7.74; found C 65.96, H 7.69.

(1'R,2'R*,6'S*,7'S*,9'S*)-(±)-1'-Methoxy-4',7'-dimethyl-5'-oxodispiro[cyclopropane-1,8'-cis,exo-[10]oxatricyclo[5.2.1.0^{2,6}]-dec-3-ene-9',2"-oxirane]* (**26**), *(1'R*,2'S*,6'S*,7'S*,9'S*)-(±)-1'-Methoxy-4',7'-dimethyl-3'-oxodispiro[cyclopropane-1,8'-cis,exo-[10]oxatricyclo[5.2.1.0^{2,6}]dec-4-ene-9',2"-oxirane]* (**27**), *and 1'-Methoxy-4',7'-dimethyl-9'-methylene-3'-oxospiro[cyclopropane-1,8'-cis,exo[10]oxatricyclo[5.2.1.0^{2,6}]dec-4-ene]* (**28**): *Variant A:* A solution of 253 mg (0.74 mmol, 0.7 equiv.) of octacarbonyldicobalt $[Co_2(CO)_8]$ in 8 ml of dry toluene was stirred in the dark under an atmosphere of propyne at room temp. for 4.5 h, then – after formation of the propynecobalt complex – a solution of 205 mg (1.06 mmol) of the epoxide *endo*-**22f** in 4 ml of dry toluene was added. After the mixture had been stirred for 3 h at 65°C under an atmosphere of propyne and CO (1:1), 1 ml of triethylamine was added, the mixture was cooled to room temp., concentrated under reduced pressure, and the residue chromatographed (column 3 × 30 cm, 13 cm of silica gel 60–230 mesh). The major fraction of the cobalt complexes was eluted with 600 ml of pentane (containing 0.5% Et_3N). Then 300 ml of pentane/ether (5:1), 300 ml of pentane/ether (2:1), and finally 800 ml of pentane/ether (1:1) were used to elute the two cycloadducts in crude, but separate fractions. These solutions were exposed to daylight, until their color had almost disappeared (ca. 3 d). Solution A contained the more polar and solution B the less polar component. After filtration the solutions were concentrated and again subjected to chromatography. Solution A [column 2 × 30 cm, 5 cm of silica gel (60–230 mesh), eluting with pentane/ether, 15:1, with 0.5% Et_3N] gave 104 mg (38%) of **26** as a white solid, R_f = 0.56 (pentane/ether, 1:1), m.p. 109°C. – IR (KBr): $\tilde{\nu}$ = 2962 cm^{-1}, 2924, 2865, 1698 (CO), 1640, 1446, 1392, 1328, 1188, 1119, 1043, 924. – ^1H NMR (250 MHz, C_6D_6): δ = −0.06 bis +0.06 (m, 2H, cpr-H), 0.32–0.43 (m, 1H, cpr-H), 0.60–0.74 (m, 1H, cpr-H), 1.15 (s, 3H, 7'-CH_3), 1.62 (dd, ^4J = 1.5, ^5J = 1.5 Hz, 3H, 4'-CH_3), 2.36 (AX-system, δ_A = 2.03, δ_X = 2.68, $^2J_{AX}$ = 4.4 Hz, 2H, 3"-H), 2.54 (d, ^3J = 5.6 Hz, 1H, 6'-H), 3.19 (s, 3H, OCH_3), 3.60 (m, 1H, 2'-H), 6.99 (m, 1H, olefin-H, 3'-H). – ^{13}C NMR (62.9 MHz, $CDCl_3$): δ = 4.49 (−, C-Cpr), 9.62 (−, C-Cpr), 10.42 (+), 13.77 (+), 32.36 (C_{quat}, C-Cpr), 48.02 (+), 49.00 (−, C-3"), 53.45 (+), 56.38 (+), 66.34 (C_{quat}), 81.35 (C_{quat}), 107.81 (C_{quat}), 145.75 (C_{quat}, C-olefin, C-4'), 154.85 (+, C-olefin, C-3'), 205.99 (C_{quat}, C=O). – MS (70 eV), *m/z* (%): 262 (6) [M^+], 247 (5) [$M^+ - CH_3$], 161 (18), 146 (57), 91 (48), 43 (100). – $C_{15}H_{18}O_4$ (262.3): calcd. C 68.68, H 6.92; found C 68.70, H 6.95.

Solution B (column 2 × 30 cm, 5 cm of silica gel 60–230 mesh, eluting with pentane/ether, 4:1, with 0.5% Et_3N) gave 121 mg (44%) of **27** as a white solid, R_f = 0.23 (pentane/ether 1:1, m.p. 104–105°C. – IR (KBr): $\tilde{\nu}$ = 3059 cm^{-1}, 2925, 2855, 1703 (CO), 1641, 1443, 1390, 1325, 1293, 1255, 1114, 1082, 1043, 908. – ^1H NMR (250 MHz, C_6D_6): δ = −0.04 bis +0.10 (m, 2H, Cpr-H), 0.37–0.50 (m, 1H, Cpr-H), 0.58–0.70 (m, 1H, Cpr-H), 0.74 (s, 3H, 7'-CH_3), 1.67 (dd, ^4J = 1.5, ^5J = 1.5 Hz, 3H, 4'-CH_3), 2.43 (AX-system, δ_A = 2.04, δ_X = 2.82, $^2J_{AX}$ = 4.5 Hz, 2H, 3"-H), 2.73 (m, 1H, 6'-H), 3.27 (d, ^3J = 5.5 Hz, 1H, 2'-H), 3.33 (s, 3H, OCH_3), 6.50 (m, 1H, olefin-H, 5'-H). – ^{13}C NMR (62.9 MHz, C_6D_6): δ = 4.39 (−, C-Cpr), 9.05 (−, C-Cpr), 10.49 (+), 13.80 (+), 31.37 (C_{quat}, C-Cpr), 49.25 (−, C-3"), 51.35 (+), 52.05 (+), 53.49 (+), 67.83 (C_{quat}), 80.09 (C_{quat}), 108.23 (C_{quat}), 146.30 (C_{quat}, C-olefin, C-4'), 153.32 (+, C-olefin, C-5'), 203.95 (C_{quat}, C=O). –

MS (70 eV), *m/z* (%): 262 (22) [M^+], 247 (8) [$M^+ - CH_3$], 244 (21) [$M^+ - H_2O$], 203 (56), 159 (91), 91 (72), 43 (100). – $C_{15}H_{18}O_4$ (262.3): calcd. C 68.68, H 6.92; found C 68.53, H 7.02.

Variant B: A solution of 1.06 g (3.1 mmol, 1.2 equiv.) of $Co_2(CO)_8$ in 22 ml of dry toluene was stirred in the dark under an atmosphere of propyne at room temp. for 5 h. A solution of 501 mg (2.6 mmol) of *endo*-**22f** in 3 ml of dry toluene was added, and the mixture was stirred under an atmosphere of propyne for an additional 4 h at 65°C. After the mixture had cooled down to room temp., and 1 ml of Et_3N had been added, it was concentrated and the residue chromatographed (column 4 × 30 cm, 19 cm of silica gel 60–230 mesh). The major fraction of the cobalt complexes was eluted with 1 l of pentane (containing 0.5% of Et_3N), and the cycloadducts were collected in separate fractions eluting with pentane/ether (5:1), pentane/ether (2:1), and finally pentane/ether (1:2). The fractions containing the cycloadducts were concentrated under reduced pressure to a volume of 1 l and the solution exposed to daylight for 2 d. After filtration the solution was evaporated and the residue chromatographed again (column 3 × 30 cm, 12 cm of silica gel, eluent 900 ml of pentane/ether, 2:1, with 0.5% Et_3N, then 400 ml of pentane/ether, 1:1), to give three fractions. Fraction I: 360 mg (53%) of **26**. – II: 77 mg (12%) of the deoxygenation product **28**, white solid, R_f = 0.35 (pentane/ether, 1:1), m.p. 113°C. – IR (KBr): $\tilde{\nu}$ = 2926 cm^{-1}, 2854, 1703 (CO), 1460, 1393, 1330, 1260, 1129, 1017, 988, 877, 848, 804. – ^1H NMR (250 MHz, C_6D_6): δ = 0.21–0.52 (m, 3H, Cpr-H), 0.72 (s, 3H, 7′-CH_3), 0.84–0.95 (m, 1H, Cpr-H), 1.66 (dd, ^4J = 1.5, ^5J = 1.5 Hz, 3H, 4′-CH_3), 2.57 (m, 1H, 6′-H), 2.61 (d, ^3J = 5.4 Hz, 1H, 2′-H), 3.40 (s, 3H, OCH_3), 4.15 (s, 1H, olefin-H), 4.74 (s, 1H, olefin-H), 6.49 (m, 1H, olefin-H, 5′-H). – ^{13}C-NMR (62.9 MHz, $CDCl_3$): δ = 10.51 (+), 11.70 (–, C-Cpr), 13.22 (+), 15.01 (–, C-Cpr), 34.35 (C_{quat}, C-Cpr), 52.41 (+), 53.04 (+), 55.01 (+), 79.90 (C_{quat}), 96.57 (–, C-olefin), 110.70 (C_{quat}), 146.22 (C_{quat}, C-olefin), 152.89 (C_{quat}, C-olefin), 153.52 (+, C-olefin), 202.59 (C_{quat}, C=O). – MS (70 eV), *m/z* (%): 246 (82) [M^+], 231 (45) [$M^+ - CH_3$], 203 (52), 171 (39), 143 (35), 91 (44), 43 (100). – $C_{15}H_{18}O_3$ (246.3): calcd. C 73.15, H 7.37; found C 73.05, H 7.38.

III: 73 mg (11%) of **27**.

X-Ray Structure Analysis of Compound **26**[22]: Colorless crystal, size 0.7 × 0.7 × 0.3 mm^3, space group *Cc*, *a* = 11051.0(10), *b* = 9150.0(10), *c* = 12963.0(10) pm, α = 90, β = 93.6, γ = 90°, *Z* = 4, *V* = 13081 · 10^6 pm^3, 1698 independent reflections, of which 1657 were observed [$F > 3\sigma(F)$], Mo-K_α (λ = 71.073 pm), Siemens-Stoe AED 2 diffractometer, temperature 293 K. Direct methods were used to solve the structure (SHELXTL PLUS, PC version). It converged to R = 0.040 and R_w = 0.048.

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