(1*R*,3*R*)-2-Methylene-1,3-dithiolane 1,3-dioxide: a highly reactive and highly selective chiral ketene equivalent in cycloaddition reactions with a broad range of dienes

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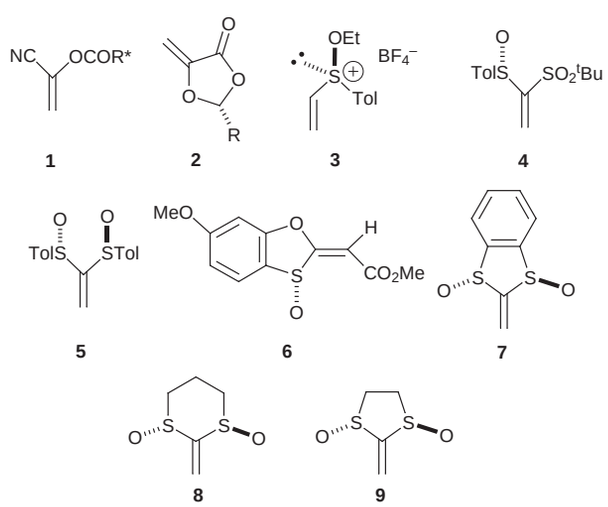
The chiral ketene equivalent *trans*-2-methylene-1,3-dithiolane 1,3-dioxide has been prepared in racemic and enantiomerically pure form in four steps. The key step in the asymmetric synthesis utilised a Modena asymmetric oxidation of 2-benzyloxymethyl-1,3-dithiolane which gave the *trans* bis-sulfoxide with high diastereocontrol (91 : 9 in favour of *trans*) and high enantiocontrol (>97% ee). The ketene equivalent shows high selectivity (>97 : 3) in Diels–Alder reactions with a range of simple dienes (cyclopentadiene, furan, 1-methoxybutadiene, Danishefsky's diene, 1-methoxycyclohexa-1,3-diene) and shows high reactivity as it is able to undergo cycloadditions with notoriously unreactive dienes (cyclohexa-1,3-diene, 90 : 10 selectivity; 2*H*-pyran-2-one, 94 : 6 selectivity). Dihydropyridines also participated in cycloaddition reaction but with only moderate selectivity (73 : 27). The Diels–Alder adducts can be readily deprotected to return the carbonyl group using a two step sequence involving reduction followed by hydrolysis.

Introduction

Ketene equivalents have found widespread use as partners in Diels–Alder reactions for the construction of cyclic, fused and bridged unsaturated ketones.[1] Furthermore, the versatile functionality contained in the products provide useful handles for further manipulation. The current interest in the synthesis of enantiomerically pure compounds has fuelled activity in the design of homochiral ketene equivalents.

Ketene equivalents, **1**, based on the condensation between chiral acid chlorides and pyruvonitrile show low levels of diastereocontrol in their reactions with dienes, but nevertheless have found wide usage in the synthesis of natural products.[2] It has been found that 2-alkyl-5-methylene-1,3-dioxolan-4-ones **2** undergo highly diastereoselective reactions with dienes and are therefore potential ketene equivalents.[3] Sulfoxide-based ketene equivalents have been studied by many groups. However, simple vinyl[4] or acetylenic[5] sulfoxides are poor dienophiles, and show low levels of diastereocontrol, limiting their synthetic use. Kagan[6] found that alkylation of a simple vinyl sulfoxide (*i.e.* alkoxysulfonium salt **3**) gave rise to a much more reactive dienophile which showed high levels of stereocontrol with a range of dienes. The sulfoxonium salt of the Diels–Alder adduct was converted into a carbonyl group in four subsequent steps. Simple vinyl sulfoxides can be made more reactive by the introduction of an additional electron withdrawing group in the 1 position. Carretero[7] has studied the Diels–Alder reaction of (+)-1-*tert*-butylsulfonyl-1-*p*-tolylsulfinylethene **4**. Whilst low levels of stereocontrol were obtained in the absence of Lewis acids, high selectivity was observed in the presence of $Eu(fod)_3$. The sulfinyl-sulfone moiety of the cycloadducts was readily converted into a carbonyl group in one step. Koizumi[8] studied the Diels–Alder reaction of 1,1-bis(*p*-tolylsulfinyl)ethene **5** and found that reaction with cyclopentadiene furnished the cycloadduct but with only moderate diastereoselectivity. Again, the bis-sulfinyl moiety of the cycloadduct was readily converted into a carbonyl group (in one step). Fallis[9] has prepared **6**, which underwent a highly selective Diels–Alder reaction with cyclopentadiene in the presence of Lewis acids. The cycloadduct was converted into norbornenone in four further steps.

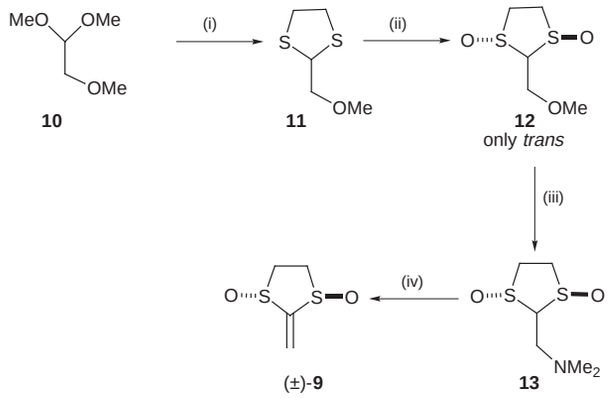


1 **2** **3** **4** **5** **6** **7** **8** **9**

We previously reported on the use of the cyclic alkenyl sulfoxides (±)-**7** and (±)-**8** as potential chiral ketene equivalents and, of the two, (±)-**7** emerged as the more reactive and selective substrate.[10] We have since found that the simpler analogue, (1*R*,3*R*)-2-methylene-1,3-dithiolane 1,3-dioxide, **9**, is a highly reactive and highly diastereoselective ketene equivalent and shows levels of reactivity and diastereoselectivity superior to the cyclic sulfoxides (±)-**7** and (±)-**8**, and all other ketene equivalents currently available. In this paper we describe full details[11] of the preparation of **9** in racemic and enantiomerically pure form, Diels–Alder reactions of **9** with a broad range of dienes, and a method for the conversion of the bis-sulfinyl moiety of the cycloadduct into a carbonyl group.

Synthesis of racemic and enantiomerically pure 9

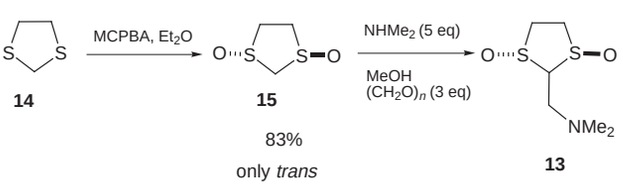
Racemic **9** was prepared as shown in Scheme 1.[12] Transthioketalisation of the commercially available acetal **10** with ethane-1,2-dithiol under acid catalysis[13] gave the methoxymethyl-substituted 1,3-dithiolane **11** in high yield. Oxidation of **11** using MCPBA in Et_2O[14,15] gave exclusively the *trans*



Scheme 1 *Reagents and conditions*: (i) $HSCH_2CH_2SH$, conc. HCl, 0 °C, 6 h, 91%; (ii) MCPBA, Et_2O, 0 °C, 2 h, 84%; (iii) $NHMe_2$, MeCN, 85%; (iv) $EtN(^iPr)_2$, MeI, MeCN, 90%

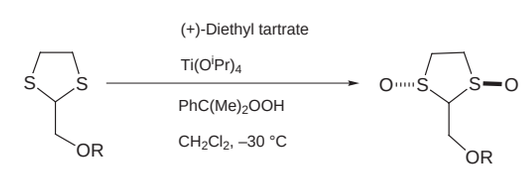
bis-sulfoxide **12** in a very simple experimental process involving direct filtration from the reaction mixture, followed by recrystallisation. Compound **12** was smoothly converted to the dimethylamino-derivative **13** simply by stirring in a solution of dimethylamine in acetonitrile at room temperature. Finally, Hofmann elimination using methyl iodide and Hünig's base at room temperature gave **9** in 90% isolated yield.

An alternative two step method for the preparation of **13** was also developed and is shown in Scheme 2. Oxidation of commercially available 1,3-dithiolane **14** in diethyl ether at 0 °C gave the *trans* dioxide **15** exclusively[15] which again was isolated by simple filtration and recrystallisation in 83% yield. Subsequent Mannich reaction using 3 equivalents of paraformaldehyde and 5 equivalents of dimethylamine at room temperature gave amine **13** in 45% yield. However, the Mannich reaction was found to be somewhat capricious and sensitive to temperature (should be conducted at 25 °C or below).



Scheme 2

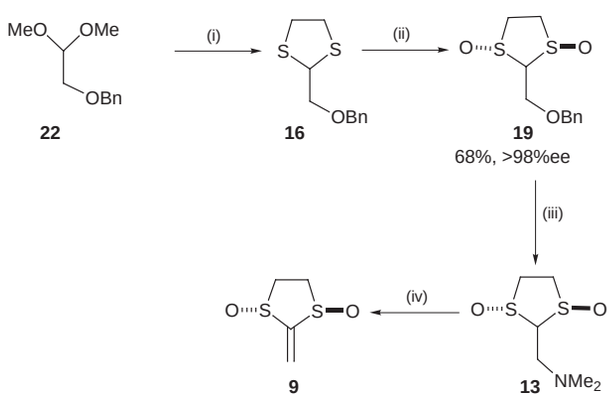
For the preparation of homochiral **9** we considered the application of asymmetric sulfide oxidation and focused on the use of the Modena protocol[16] as we had previously found that this is a slightly stronger oxidising system than that of Kagan (Scheme 3).[17] 1,3-Dithiolanes with a range of substituents in the 2-position were tested in the asymmetric oxidation process using our previously optimised conditions[17] and the results are shown in Table 1 (Scheme 3).



R = Me	**11**	R = Me	**12**
R = Bn	**16**	R = Bn	**19**
R = H	**17**	R = H	**20**
R = Ac	**18**	R = Ac	**21**

Scheme 3

It was found that the nature of the oxygen substituent had a major influence over the yield and enantioselectivity of the oxidation process. A free hydroxy group (entry 3) gave rise to low levels of enantioselectivity; an observation that has also been made by Modena in the asymmetric oxidation of β-hydroxy sulfides.[18] An acetoxy group (entry 4) resulted in decomposition, probably because of the sensitivity of the bis-sulfoxide product towards elimination of acetic acid. Of all the substituents, the benzyl ether (entry 2) was found to give the optimum yield, enantio- and diastereo-selectivity. Indeed, asymmetric oxidation of dithiolane **16** using the Modena protocol gave the (*R*,*R*)-bis-sulfoxide **19** in high yield and as essentially a single enantiomer *before recrystallisation* (*trans*:*cis* 91:9). Optimisation of the oxidation of the benzyl ether **16** led to the discovery that similar yields and selectivities could be achieved with reduced amounts of both catalyst and oxidant (entry 5). Not only is this more efficient but this optimised process makes the work-up of the reaction much easier to carry out. As over-oxidation to the sulfinyl-sulfone also occurred, it was possible that the high selectivity was due, in part, to kinetic resolution.[19] This was shown not to be the case as Modena oxidation of racemic **19** gave a mixture of the sulfinyl-sulfone (50%) and the bis-sulfoxide **19** (50%) which was still racemic. Thus, the very high enantioselectivity is due to an intrinsically highly enantioselective sulfide oxidation process coupled with an enhancement of enantioselectivity as a result of carrying out two asymmetric transformations in one pot and not due to kinetic resolution. The synthesis of the required enantiomerically pure ketene equivalent **9** is shown in Scheme 4.



Scheme 4 *Reagents and conditions*: (i) $HSCH_2CH_2SH$, conc. HCl, 0 °C, 94%; (ii) $PhC(Me)_2OOH$ (2 equiv.), (+)-DET (2 equiv.), $Ti(O^iPr)_4$ (0.5 equiv.), −30 °C, 40 h, CH_2Cl_2, 68%; (iii) $NHMe_2$, MeCN, 85%; (iv) $EtN(^iPr)_2$, MeI, MeCN, 90%

An alternative synthesis based on the asymmetric oxidation of 1,3-dithiolane (*cf.* Scheme 2) was not tested as we had previously found that 1,3-dithiane gave poor asymmetric induction in the Kagan oxidation.[17] The low enantioselectivity is presumably due to the similar size of the groups attached to sulfur. We also tested the commercially available 2-ethoxycarbonyl-1,3-dithiolane in the oxidation process but failed to isolate any bis-sulfoxide. Related oxidations on 2-ethoxycarbonyl-1,3-dithiane showed that the bis-sulfoxide readily decomposed unless it was isolated rapidly in pure form.[17] The instability is believed to be initiated by a Pummerer reaction which is exceptionally facile owing to the acidity of the C-2 proton. 1,3-Dithiolane analogues are even more acidic than 1,3-dithianes[15] and would therefore undergo even more rapid decomposition. This could account for our inability to isolate the bis-sulfoxide.

Diels–Alder reactions with 9

Diels–Alder reactions of **9** with a range of simple dienes were investigated and the results are summarised in Table 2. The effect of solvents on the diastereoselectivity of the Diels–Alder reaction with cyclopentadiene was briefly investigated. We were particularly attracted to the use of EtCN as a solvent as other workers had shown this to be an ideal medium for asymmetric

Table 1 Modena oxidation of 2-substituted-1,3-dithiolanes

Entry	R	*trans* Bis-sulfoxide	Method[a]	*trans* : *cis*	Yield of *trans* (%)	Ee (%)
1	Me (**11**)	**12**	A	79 : 21	66	89[b]
2	Bn (**16**)	**19**	A	91 : 9	70	>98[b]
3	H (**17**)	**20**	A	>95 : 5	46	42[c]
4	Ac (**18**)	**21**	A	—	decomp.	—
5	Bn (**16**)	**19**	B	91 : 9	68	>98[b]

[a] A: 4 : 1 : 1 : 4 ratio of DET : $Ti(O^iPr)_4$: sulfide : peroxide, 18–24 h, −30 °C; B: 2 : 0.5 : 1 : 2 ratio of DET : $Ti(O^iPr)_4$: sulfide : peroxide, 40 h, −30 °C. [b] Ee determined by chiral HPLC (see Experimental section). [c] Ee determined by NMR using chiral shift reagent $Eu(hfc)_3$ after formation of TBDMS ether.

Table 2 Diels–Alder reactions between dienophile **9** and dienes **A**–**D**[a]

Entry	Diene[a]	Lewis acid	*T*/°C[c]	Solvent	*t*	Diels–Alder adducts	Ratio of adducts (a : b)[b]	Yield (%)
1	**A**	—	RT	CH_2Cl_2	24 h	**23a** : **23b**	90 : 10	96
2	**A**	—	RT	EtCN	36 h	**23a** : **23b**	90 : 10	93
3	**A**	$BF_3{\cdot}OEt_2$	−78	CH_2Cl_2	20 min	**23a** : **23b**	95 : 5	81
4	**A**	$BF_3{\cdot}OEt_2$	−78	EtCN	20 min	**23a** : **23b**	>97 : 3	74
5	**B**	—	RT	EtCN	18 h	**24a** : **24b**	>97 : 3	83
6	**C**	—	RT	EtCN	2 h	**25a** : **25b**	>97 : 3	90
7	**D**	—	RT	EtCN	3 days	**26a** : **26b**	76 : 24	64
8	**D**	$BF_3{\cdot}OEt_2$	−78	EtCN	8 h	**26a** : **26b**	86 : 16	53
9	**D**	$SnCl_4$	−78	EtCN	6 h	**26a** : **26b**	>97 : 3	65

[a] **A** = Cyclopentadiene, **B** = 1-methoxybutadiene, **C** = 1-methoxy-3-trimethylsilyloxybutadiene, **D** = Furan. [b] Determined by ^1H NMR integration of crude reaction mixtures. [c] RT = room temperature.

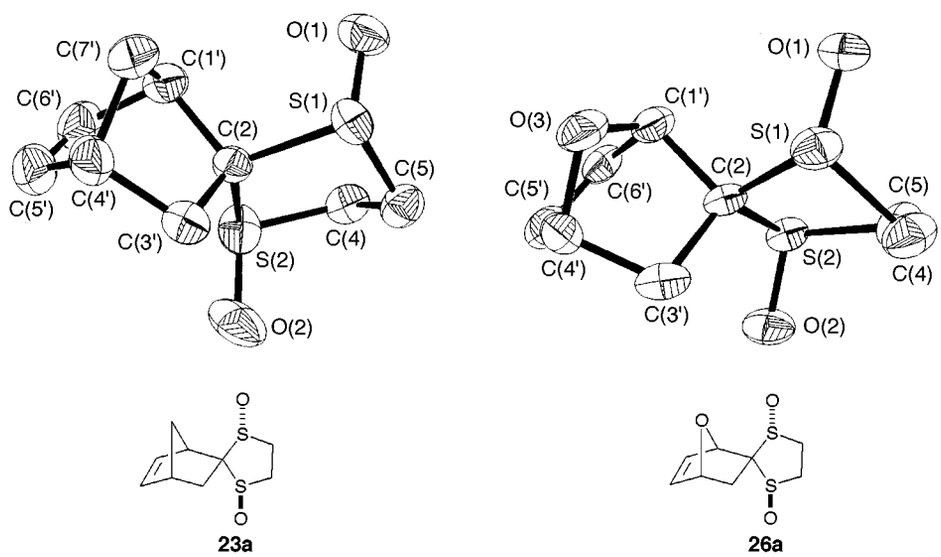
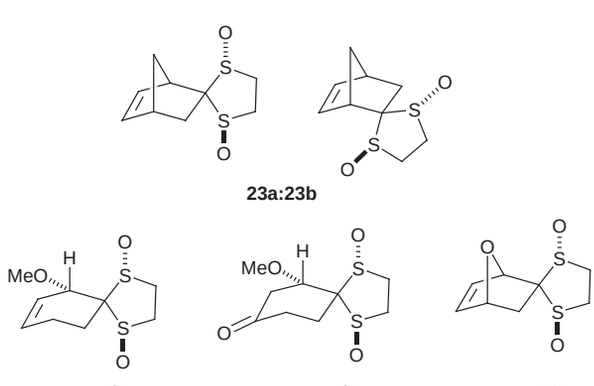


Fig. 1

aldol and cycloaddition processes.[20] At room temperature both CH_2Cl_2 and EtCN gave a 90 : 10 ratio of **23a** : **23b** (entry 1, 2). However, using EtCN at −78 °C, with $BF_3{\cdot}OEt_2$ catalysis, the *adduct* **23a** *was obtained as a single diastereoisomer* and was formed essentially instantaneously (entry 4). Diels–Alder reactions with acyclic dienes also occurred rapidly at room temperature giving *single diastereoisomeric adducts* in excellent yield without the necessity of using Lewis acids (entries 5, 6). Surprisingly, reaction with the much less reactive diene, furan, also occurred readily, and using $SnCl_4$ (entry 9; this was superior to $BF_3{\cdot}OEt_3$, entry 8) catalysis, adduct **26a** was obtained, again as *a single diastereoisomer.* The relative stereochemistries of all major adducts **23a**–**26a** have been determined by X-ray crystallography and are shown in Figs. 1 and 2.[21]

The stereochemical outcome of the Diels–Alder reactions may be rationalised by considering the two possible transition states **TS1** and **TS2**. The preferred formation of **23a** must result from **TS1** being favoured over **TS2**. This is reasonable since **TS2** suffers from non-bonding steric interactions between the vinyl substituent on the diene and the sulfinyl oxygen whereas in **TS1** the vinyl substituent on the diene only interferes with a



lone pair.[22] Electronic factors may also be important in determining the stereochemical outcome of the reaction. Since the interaction of lone pairs of oxygen with π systems is a repulsive one[23] this phenomenon will further destabilise **TS2** relative to **TS1**.

We also investigated the Diels–Alder reaction of dienophile **9**

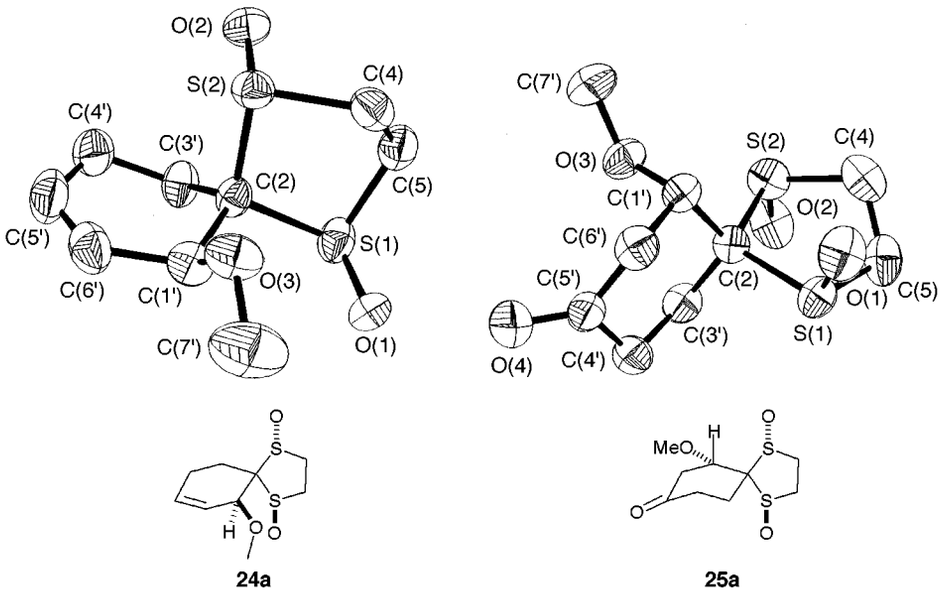
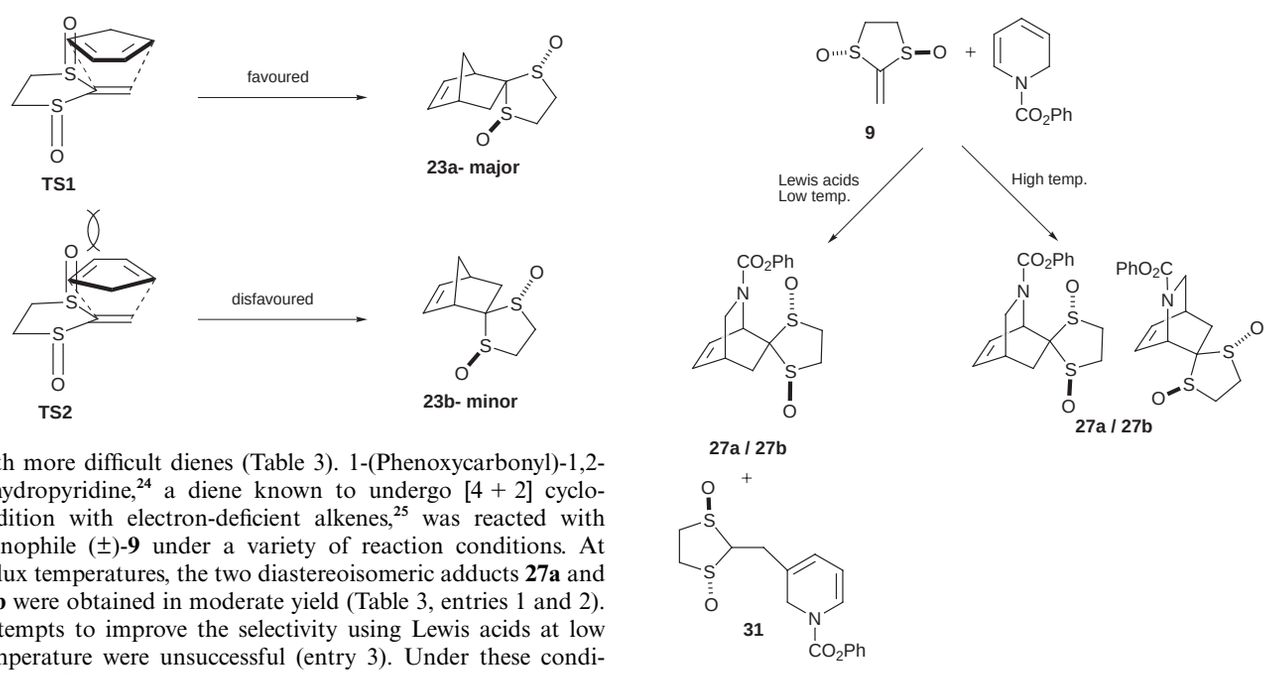


Fig. 2



Scheme 5

with more difficult dienes (Table 3). 1-(Phenoxycarbonyl)-1,2-dihydropyridine,[24] a diene known to undergo [4 + 2] cycloaddition with electron-deficient alkenes,[25] was reacted with dienophile (±)-**9** under a variety of reaction conditions. At reflux temperatures, the two diastereoisomeric adducts **27a** and **27b** were obtained in moderate yield (Table 3, entries 1 and 2). Attempts to improve the selectivity using Lewis acids at low temperature were unsuccessful (entry 3). Under these conditions the Diels–Alder adducts were again obtained as a mixture of diastereoisomers together with a by-product believed to be the Michael addition adduct **31** (Scheme 5), although we were unable to separate **31** from the cycloadducts and could not definitively prove its structure. We are not aware of any Lewis acid mediated cycloadditions with dihydropyridines and indeed there may be an inherent problem with this process.[26] Other Lewis acids tested ($SnCl_4$, $EtAlCl_2$, $Sc(OTf)_3$, $Yb(OTf)_3$) gave a similar mixture of cycloadducts and by-product.

Recrystallisation of the 73:27 mixture of diastereoisomeric adducts (optimum conditions, entry 2) from ethyl acetate afforded pure **27a**, the stereochemistry of which was determined by X-ray crystallography[21] and is shown in Fig. 3.

The cycloaddition reaction of **9** with cyclohexa-1,3-diene was examined under a variety of conditions. At room temperature, no cycloadduct was obtained, even after an extended time period, indicative of the very low reactivity of this diene. Cycloadducts were obtained after the dienophile had been activated by Lewis acids. With $BF_3{\cdot}OEt_2$ at −78 °C, the Diels–Alder adducts **28a** and **28b** were obtained in a 95:5 ratio but in only 26% yield after 6 hours (entry 4). The remaining material was unreacted starting material. At −35 °C (optimum conditions), a higher yield of cycloadducts but with slightly lower selectivity was obtained (entry 5).

1-Methoxycyclohexa-1,3-diene has been used in Diels–Alder reactions[27] and its reactivity with dienophile **9** was investigated under a variety of conditions. At room or elevated temperatures, the cycloadducts **29a** and **29b** were obtained in good yield but with only poor selectivity (entry 7). Using Lewis acids, reactions could be conducted at lower temperature and higher selectivity was obtained (entries 8, 9). The optimum Lewis acid was Et_2AlCl, which gave 97:3 selectivity. However, we again found that using this Lewis acid the Michael addition product was also obtained (40% yield). Reaction with the notoriously unreactive diene, 2*H*-pyran-2-one[28] also occurred, but required refluxing in toluene for 5 days. This gave a 94:6 ratio of cycloadducts **30a**:**30b** in 33% yield with no detectable decarboxylation of the adducts (entry 11). Using Lewis acids such as $BF_3{\cdot}OEt_2$ no cycloaddition occurred.

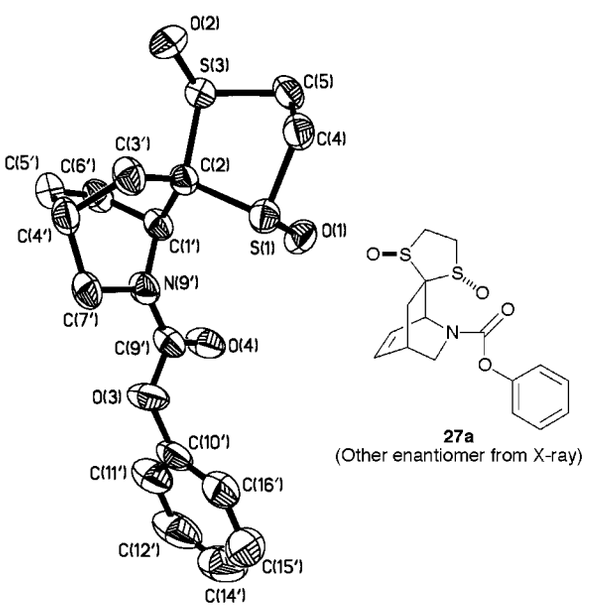
Hydrolysis of cycloadducts

The dithiolane moiety has been readily deprotected using a two

Table 3 Diels–Alder reactions between dienophile **9** and Dienes **E**–**H**[a]

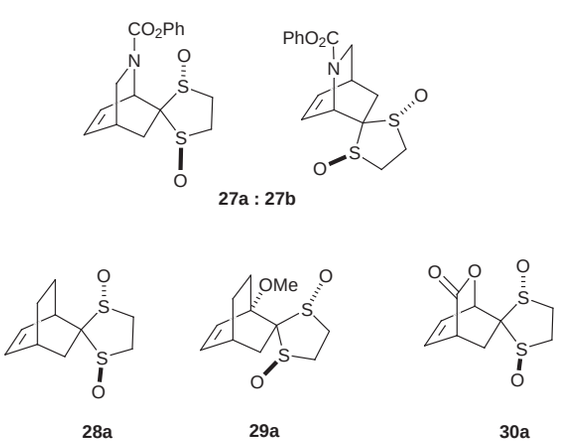
Entry	Diene[a]	Lewis acid	*T*/°C	Solvent	*t*	Diels–Alder adducts	Ratio of adducts (a : b)[b]	Yield (%) (ratio)[c]
1	**E**	—	97	EtCN	4 days	**27a** : **27b**	68 : 32	60 (100 : 0)
2	**E**	—	40	CH_2Cl_2	8 days	**27a** : **27b**	73 : 27	60 (100 : 0)
3	**E**	$BF_3{\cdot}OEt_2$	−78	CH_2Cl_2	2 h	**27a** : **27b**	68 : 32	96 (41 : 59)
4	**F**	$BF_3{\cdot}OEt_2$	−78	CH_2Cl_2	6 h	**28a** : **28b**	95 : 5	26[d]
5	**F**	$BF_3{\cdot}OEt_2$	−35	CH_2Cl_2	24 h	**28a** : **28b**	90 : 10	60
6	**F**	Et_2AlCl	−78	Hexane	16 h	**28a** : **28b**	74 : 26	62
7	**G**	—	97	EtCN	24 h	**29a** : **29b**	59 : 41	77
8	**G**	$BF_3{\cdot}OEt_2$	−78	CH_2Cl_2	2 h	**29a** : **29b**	80 : 20	21[e]
9	**G**	Et_2AlCl	−78	Hexane–CH_2Cl_2	1 h	**29a** : **29b**	>97 : 3	95 (50 : 40)
10	**H**	—	40	CH_2Cl_2	18 days	**30a** : **30b**	54 : 46	29[c]
11	**H**	—	111	Toluene	5 days	**30a** : **30b**	94 : 6	33[e]

[a] **E** = 1-(phenoxycarbonyl)-1,2-dihydropyridine. **F** = cyclohexa-1,3-diene. **G** = 1-methoxycyclohexa-1,3-diene. **H** = 2*H*-pyran-2-one. [b] Ratio of diastereoisomers determined by ^{1}H NMR integration of crude reaction mixture. [c] Ratio of [4 + 2] adducts and Michael addition product. [d] Starting material (60%) was recovered. [e] No starting material was recovered.



27a
(Other enantiomer from X-ray)

Fig. 3



27a : 27b

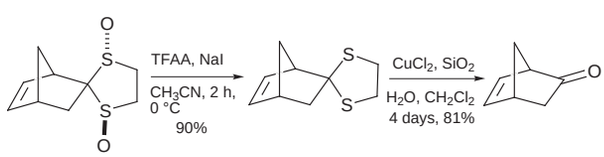
28a **29a** **30a**

step sequence involving reduction followed by hydrolysis and this is demonstrated for the cyclopentadiene adduct **23a** (Scheme 6). A variety of methods were investigated for the reduction of the bis-sulfoxide **23a**[29] (Table 4) and the method using TFAA and NaI[33] (entry 5) gave the highest and most reproducible yield. We had originally reported that reduction using PBr_3 gave high yields of dithiolane **32** but this reaction has proved to be capricious. Finally, hydrolysis of the dithiolane was carried out using $CuCl_2$ on silica gel[34] giving norbornenone

Table 4 Reduction of bis-sulfoxide **23a** to sulfide **32**

Entry	Conditions	Yield 32 (%)
1	PBr_3, CH_2Cl_2, N_2, 0 °C, 1 h[29]	44–90
2	PCl_3, CH_2Cl_2, N_2, 0 °C, 1 h[30]	32
3	Silica chloride,[a] CH_2Cl_2, N_2, 0 °C, 18 h[31]	0
4	$SnCl_2{\cdot}2H_2O$, AcCl, DMF–CH_3CN, N_2, 0 °C, 7 h[32]	66
5	TFAA, NaI, CH_3CN, N_2, 0 °C, 2 h[33]	90

[a] Silica gel + $SOCl_2$.



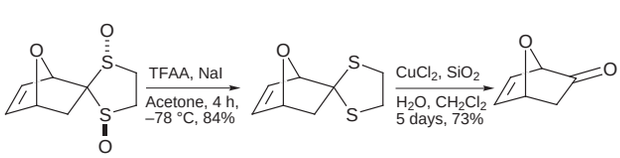
23a **32** **33**

$[\alpha]_D$ +51.9 ($CHCl_3$) $[\alpha]_D$ -29.4 ($CHCl_3$) $[\alpha]_D$ +930 ($CHCl_3$)

>98% ee

Scheme 6

33 in essentially quantitative yield. The enantiomeric excess of norbornenone was determined by chiral GC and was >98%. The deprotection sequence was also applied to the furan Diels–Alder adduct (±)-**26a**, and enone (±)-**35** was obtained in good yield (Scheme 7). This enone has been used extensively in the synthesis of natural products.[31,35]



(±)-26a **34** **35**

Scheme 7

In summary, we have developed a new chiral ketene equivalent which can be readily prepared in racemic and enantiomerically pure forms. The key step in the asymmetric synthesis is a Modena oxidation which gives the bis-sulfoxide in good yield (68%), high diastereoselectivity (91 : 9) and exceptionally high enantioselectivity (>98 : 2). The ketene equivalent shows high selectivity (>97 : 3) in Diels–Alder reactions with a range of simple dienes (cyclopentadiene, furan, 1-methoxybutadiene, Danishefsky's diene, 1-methoxycyclohexa-1,3-diene) and shows high reactivity as it is able to undergo cycloadditions with notoriously unreactive dienes (cyclohexa-1,3-diene, 90 : 10 select-

ivity; 2*H*-pyran-2-one, 94:6 selectivity). Dihydropyridines also participated in cycloaddition reactions but with only moderate selectivity (73:27). The Diels–Alder adducts can be readily deprotected using a two step sequence involving reduction followed by hydrolysis. The broad range of dienes that participate in cycloadditions with our ketene equivalent allows access to a broad range of cyclic, fused and bridged unsaturated ketones.

Experimental

Dry tetrahydrofuran, diethyl ether, dioxane and 1,2-dimethoxyethane were obtained by distillation from benzophenone ketyl radical. Dichloromethane and acetonitrile were distilled from calcium hydride immediately prior to use. Toluene was distilled from $LiAlH_4$ and stored over 4 Å molecular sieves under nitrogen. Pyridine was distilled from calcium hydride and then stored over molecular sieves and under nitrogen until required. $Ti(O^iPr)_4$ and diethyl tartrate were distilled under reduced pressure and stored under nitrogen. Cyclopentadiene was cracked immediately prior to use. All other dienes (furan, 1-methoxybutadiene, 1-methoxy-3-(trimethylsiloxy)buta-1,3-diene, cyclohexa-1,3-diene, 1-methoxycyclohexa-1,3-diene, 2*H*-pyran-2-one) are commercially available. 1-(Phenoxycarbonyl)-1,2-dihydropyridine was prepared as described by Sundberg.[24] Racemic compounds **11**, **12**, **13**, **9** (Scheme 1) were prepared as previously described,[12] and *trans*-1,3-dithiolane 1,3-dioxide **15**[15] was prepared as previously described. Proton and ^{13}C NMR spectra were recorded on a Bruker 250 MHz instrument. Coupling constants are given in Hz. $[a]_D$ Values are given in units of 10^{-1} deg cm^2 g^{-1}. Ether refers to diethyl ether.

Purification of MCPBA

35 g MCPBA (Aldrich 57–86%) was dissolved in 250 ml ether and washed with 3 × 150 ml buffer solution (410 ml 0.1 M NaOH, 250 ml 0.2 M KH_2PO_4 made up to 1 l, pH 7.5). The ether layer was dried over $MgSO_4$ and carefully evaporated under reduced pressure to give *ca.* 17 g pure MCPBA (**CAUTION!** potential explosive).

(1*RS*,3*RS*)-2-(Dimethylaminomethyl)-1,3-dithiolane 1,3-dioxide 13

To *trans*-1,3-dithiolane 1,3-dioxide **15**[15] (0.1 g, 0.7 mmol) was added paraformaldehyde (65 mg, 2.1 mmol) followed by $NHMe_2$ (2.3 ml of 25% solution in MeOH, 3.5 mmol) and the reaction mixture was stirred under nitrogen at room temperature for 11 days. The solvents were removed under reduced pressure and the residue was washed with EtOAc (3 × 3 ml) to separate the product from the starting material. The EtOAc washings were combined and the solvent removed under reduced pressure to give the title compound as a white solid (63 mg, 45%), R_f 0.5 [acetone–methanol (50:50)]; mp 117–119 °C (Found: C, 36.7; H, 6.6; N, 7.05; S, 32.95. $C_6H_{13}NO_2$ requires C, 36.9; H, 6.65; N, 7.15; S, 32.8%); δ_H(250 MHz; $CDCl_3$) 2.4 (6H, s, NMe_2), 2.9 (2H, d, *J* 8.5, –CHCH_2), 3.5–3.8 (4H, m, –CH_2CH_2–), 3.9 (1H, t, *J* 8.5, CHCH$_2$–).

2-Benzyloxymethyl-1,3-dithiolane 16

To a rapidly stirred mixture of concentrated hydrochloric acid (3.2 ml) and ethane-1,2-dithiol (4.33 ml, 51.62 mmol) at 0 °C was added benzyloxyacetaldehyde dimethyl acetal (9.21 g, 46.96 mmol) dropwise over 1.5 hours. After an additional 30 minutes at 0 °C, the reaction mixture was allowed to warm up to room temperature and stirred for a further 4.5 hours. The resulting two-phase mixture was partitioned between water (20 ml) and CH_2Cl_2 (20 ml). The organic phase was separated and the aqueous phase extracted with CH_2Cl_2 (2 × 20 ml). The combined organic phases were washed with water (30 ml), saturated aqueous sodium hydrogen carbonate (30 ml), and brine (30 ml), then dried over $MgSO_4$. Solvent was removed under reduced pressure, and the residue subjected to column chromatography eluting with ethyl acetate–light petroleum (bp 60–80 °C) (5:95). The title compound was obtained as a colourless oil (9.19 g, 86%) (Found: C, 58.2; H, 6.4; S, 28.5. $C_{11}H_{14}OS_2$ requires C, 58.4; H, 6.2; S, 28.3%); ν_{max}/cm^{-1} 2923 and 2854 (CH_2), 1602, 1586 and 1496 (Ar); δ_H(250 MHz; $CDCl_3$) 3.18 (4H, s, CH_2CH_2), 3.56 (2H, d, *J* 7, CHCH_2), 4.59 (2H, s, CH_2Ph), 4.63 (1H, t, *J* 7, CHCH$_2$), 7.24–7.39 (5H, m, Ph); δ_C(63 MHz; $CDCl_3$) 38.06, 51.78, 73.23, 75.19, 127.72, 128.47, 137.96; *m*/*z* 226 (M^+, 15%), 105 (100), 91 (44).

2-Hydroxymethyl-1,3-dithiolane 17

Ethyl 1,3-dithiolane-2-carboxylate (10 g, 56.1 mmol) was dissolved in dry THF (80 ml) under nitrogen. The temperature was reduced to 0 °C and $LiAlH_4$ (1.5 g, 39.5 mmol) was carefully added portionwise to the stirred solution. After 2 hours, the reaction was worked up by dropwise addition of ether at 0 °C until effervescence subsided, followed by dropwise addition of saturated aqueous sodium sulfate until a heavy white precipitate fell out of solution. The solution was filtered, dried over $MgSO_4$, filtered and evaporated under reduced pressure to yield the title compound as a clear yellow oil (7.21 g, 94%), R_f 0.66 (EtOAc); δ_H(250 MHz; $CDCl_3$) 2.25 (1H, br s, OH), 3.23 (4H, s, CH_2CH_2), 3.57 (2H, d, *J* 7.5, CHCH_2), 4.57 (1H, t, *J* 7.5, CHCH$_2$); δ_C(63 MHz; $CDCl_3$) 37.8, 54.7, 66.9.

2-Acetoxymethyl-1,3-dithiolane 18

Alcohol **17** (0.19 g, 1.45 mmol) was dissolved in dry pyridine (1.5 ml) under nitrogen with stirring, and the temperature reduced to 0 °C. Acetic anhydride (0.27 ml, 2.9 mmol) was added dropwise and stirring continued at 0 °C for 1 hour. The reaction mixture was taken up in dichloromethane (20 ml) then washed with cold dilute hydrochloric acid (1 M), saturated aqueous copper sulfate, 10% aqueous $NaHCO_3$, and water. The organic phase was dried over $MgSO_4$, filtered, and the solvent removed *in vacuo*. Column chromatography, eluting with ethyl acetate–light petroleum (bp 60–80 °C) (1:9) gave the title compound as a pale yellow liquid (0.176 g, 68%), R_f 0.25 [10% EtOAc–light petroleum (60–80 °C)]; δ_H(250 MHz; $CDCl_3$) 2.06 (3H, s, OCOCH_3), 3.20 (4H, s, CH_2CH_2), 4.09 2H, d, *J* 7.5, CHCH_2), 4.62 (1H, t, *J* 7.5, CHCH$_2$); δ_C(63 MHz; $CDCl_3$) 20.9, 38.0, 50.5, 67.9, 170.5.

Asymmetric oxidation of 2-methoxymethyl-1,3-dithiolane 11

(+)-Diethyl tartrate (19.3 g, 93.4 mmol) was dissolved in dry dichloromethane (80 ml) under nitrogen, $Ti(O^iPr)_4$ (6.95 ml, 23.4 mmol) added and stirring continued for 30 minutes. A solution of sulfide **11** (3.51 g, 23.4 mmol) in dry dichloromethane (37 ml) was added *via* syringe. The temperature was reduced to −30 °C and the reaction mixture stirred at this temperature for 1 hour. Cumene hydroperoxide (17.3 ml, 93.4 mmol) was slowly added, after which the reaction mixture was stirred at −30 °C for 22 hours. Water (7.5 ml) was then added and the reaction mixture allowed to warm to room temperature. After 1 hour at room temperature, the resulting gel was filtered through a pad of Celite, and washed with more dichloromethane. The dichloromethane solution was dried over $MgSO_4$ then evaporated under reduced pressure. Column chromatography of the residue, eluting with EtOAc–MeOH (gradient 1:0–4:1) gave cumene hydroperoxide and diethyl tartrate, followed by the following compounds.

2-*Methoxymethyl*-1,3-*dithiolane* 1,1,3-*trioxide* as a white solid (209 mg, 4.5%), R_f 0.26 (EtOAc); mp 129–130 °C (EtOAc–hexane); $[a]_D^{22}$ −89 (*c* 0.73 in $CDCl_3$) (Found: C, 30.2; H, 4.9; S, 32.3. $C_5H_{10}O_4S_2$ requires C, 30.3; H, 5.1; S, 32.3%); ν_{max}(KBr)/cm^{-1} 2845 (O–CH_3), 1315, 1160 and 1110 (SO_2), 1050 (S=O); δ_H(250 MHz; $CDCl_3$) (single diastereoisomer) 3.23 (1H, dt, *J* 14 and 5.5, 4-H$_a$), 3.47 (3H, s, CH_3), 3.51 (1H, ddd, *J* 14, 5.5 and 2, 5-H$_a$), 3.64 (1H, ddd, *J* 14, 5.5 and 2, 4-H$_b$), 3.91–4.06 (4H, m, 2-H, CHCH_2 and 5-H$_b$); δ_C(75 MHz; $CDCl_3$) 43.7, 47.1,

59.7, 63.7, 74.1; *m*/*z* (CI) 216 ([M + NH_4]$^+$, 100%), 199 (MH^+, 50).

Next eluted was (1*R*,3*R*)-2-*Methoxymethyl*-1,3-*dithiolane* 1-*oxide* as a yellow oil (46 mg, 1%). R_f 0.15 (EtOAc); $[\alpha]_D^{22}$ +62.5 (*c* 0.48 in $CHCl_3$); ν_{max}(thin film)/cm^{-1} 1048 (S=O); δ_H(250 MHz; $CDCl_3$) 2.78 (1H, ddd, *J* 6.5, 12 and 13.5, 4-H_a), 3.29 (3H, s, 8-H), 3.32–3.47 (3H, m, 4-H_b, 5-H_b and 6-H_a), 3.59–3.73 (2H, m, 5-H_a and 6-H_a), 4.32 (1H, m, 2-H); δ_C(75 MHz; $CDCl_3$) 32.7, 55.6, 59.3, 72.0, 72.6; *m*/*z* (EI) 166 (M^+, 90%), 90 (100), 77 (56), 58 (71) (Found M^+, 166.0115. $C_5H_{10}O_2S_2$ requires *m*/*z*, 166.0122). Chiral HPLC analysis was carried out on a Chiralpak AD column (25 cm × 4.6 mm id) eluting with 95% light petroleum–4% isopropyl alcohol (IPA)–1% diethylamine at 2.0 ml min^{-1} using a UV detector at 220 nm. The (*R*,*R*)-isomer had a retention time (t_r) of 14.6 min while the (*S*,*S*)-isomer had a retention time of 16 min. Ee = 69%.

trans-(1*R*,3*R*)-2-*Methoxymethyl*-1,3-*dithiolane* 1,3-*dioxide* **12** eluted next as a white solid (2.811 g, 66%), R_f 0.3 (10% MeOH–EtOAc); mp 120–121 °C (EtOAc); $[\alpha]_D^{22}$ +191 (*c* 1 in CH_2Cl_2) (Found: C, 32.8; H, 5.3; S, 35.3. $C_5H_{10}O_3S_2$ requires C, 32.95; H, 5.5; S, 35.2%); ν_{max}(KBr)/cm^{-1} 2975, 2930 and 2890 (aliphatic C–H), 2830 (O–Me), 1020 (S=O); δ_H(300 MHz; $CDCl_3$) (single diastereoisomer) 3.43 (3H, s, CH_3), 3.60–3.82 (4H, m, 4-H and 5-H), 3.90–4.10 (3H, m, C*H*CH_2); δ_C(63 MHz; $CDCl_3$) 51.3, 51.8, 59.5, 64.2, 89.5; *m*/*z* (EI) 183 (M^+, 100%). Chiral HPLC analysis was carried out on a Chiralpak AD column (25 cm × 4.6 mm id) eluting with 75% hexane–25% IPA at 1.0 ml min^{-1} using a UV detector at 254 nm. (*R*,*R*)-**12** had a retention time of 15.3 min while (*S*,*S*)-**12** had a retention time of 18.0 min. EE = 89% before recrystallisation, ee >98% after recrystallisation.

cis-2-*Methoxymethyl*-1,3-*dithiolane* 1,3-*dioxide* eluted last as a white solid (0.59 g, 14%), R_f 0.1 (10% MeOH–EtOAc); mp 160–161 °C (EtOAc) (Found: C, 33.25; H, 5.6; S, 35.2. $C_5H_{10}O_3S_2$ requires C, 32.95; H, 5.5; S, 35.2%); ν_{max}(KBr)/cm^{-1} 2920 and 2890 (aliphatic C–H), 1035 (O–CH_3), 1035 (S=O); δ_H(250 MHz; $CDCl_3$) (single diastereoisomer) 3.41–3.55 (2H, m, 4-H_a and 5-H_a), 3.51 (3H, s, 80H), 3.65 (1H, t, *J* 7, 2-H), 3.91–3.77 (2H, m, 4-H_b and 5-H_b), 4.15 (2H, d, *J* 7, 6-H); δ_C(75 MHz; $CDCl_3$) 52.0, 59.8, 63.3; 75.1; *m*/*z* (EI) 182 (M^+, 88%), 106 (100), 77 (82), 58 (100) (Found: M^+, 182.0066. $C_5H_{10}O_3S_2$ requires *m*/*z*, 182.0071).

(1*RS*,3*RS*)-2-Benzyloxymethyl-1,3-dithiolane 1,3-dioxide 19

Sulfide **16** (9.33 g, 41.2 mmol) was dissolved in dry ether (100 ml) under nitrogen and the temperature reduced to 0 °C. A solution of purified MCPBA (15.65 g, 90.7 mmol) in dry ether (250 ml) was slowly added over 45 minutes *via* a dropping funnel. A white precipitate was seen to have formed after 15 minutes. The reaction mixture was stirred for a further 45 minutes at 0 °C, then the white precipitate was filtered and washed with cold ether. Recrystallisation from hot ethyl acetate gave the title compound as white crystals (6.92 g, 65%), R_f 0.1 (EtOAc); mp 120 °C (EtOAc). Data as below.

Asymmetric oxidation of 2-benzyloxymethyl-1,3-dithiolane 16

(+)-Diethyl tartrate (3.0 ml, 9.0 mmol) was dissolved in dry CH_2Cl_2 (15 ml) at room temperature under nitrogen, Ti(O^{i}Pr)$_4$ (0.67 ml, 2.25 mmol) added and the solution stirred for 20 minutes. A solution of sulfide **16** (1.018 g, 4.5 mmol) in dry CH_2Cl_2 (5 ml) was then added, the flask washed with a further 2.5 ml of dry CH_2Cl_2, and the reaction mixture cooled to −38 °C (solid CO_2–acetonitrile bath). After 1 hour, cumene hydroperoxide (1.66 ml, 9 mmol) was added dropwise and the reaction mixture stirred for a further 30 minutes before placing in a commercial freezer (−30 °C internal temperature) for 40 hours, after which time 0.7 ml of water was added. The reaction mixture was then allowed to warm up to room temperature and stirred for 2 hours. The resulting gel was filtered through a pad of Celite to remove the titanium salts, which were thoroughly washed with more dichloromethane. The dichloromethane solution was dried over $MgSO_4$, filtered, and the solvent removed under vacuum. The organic residue (*ca.* 4.5 g) was subjected to flash column chromatography on silica gel, eluting with ethyl acetate–methanol (gradient 1:0 to 4:1). After removal of cumene alcohol and diethyl tartrate, 2-*benzyloxymethyl*-1,3-*dithiolane* 1,1,3-*trixode* eluted first as a white semi-solid (100 mg, 9%), R_f 0.47 (EtOAc); δ_H(250 MHz; $CDCl_3$) (mixture of diastereoisomers) 3.12–3.35 (1H, m, 4-H_a), 3.41–3.65 (2H, m, 4-H_b and 5-H_a), 3.88–4.17 (4H, m, 2-H, 5-H_b and 6-H), 4.48–4.68 (2H, m, 8-H), 7.23–7.49 (5H, m, Ar-H).

(1*R*,2*R*)-2-*Benzyloxymethyl*-1,3-*dithiolane* 1-*oxide* eluted second, and was obtained as a colourless oil (34 mg, 3%), R_f 0.35 (EtOAc); $[\alpha]_D^{22}$ +63 (*c* 0.93 in $CHCl_3$); ν_{max}(thin film)/cm^{-1} 1050 (S=O); δ_H(250 MHz; $CDCl_3$) (single diastereoisomer) 2.80 (1H, ddd, *J* 13.5, 11.5 and 6.5, 4-H_a), 3.4–3.49 (2H, m, 4-H_b and 5-H_b), 3.45 (1H, dd, *J* 11 and 6.5, 6-H_a), 3.71 (1H, dt, *J* 11.5, 11.5 and 5, 5-H_a), 3.82 (1H, dd, *J* 11 and 4, 6-H_b), 4.39 (1H, ddd, *J* 6.5, 4 and 0.5, 2-H), 4.52 (2H, s, CH_2Ar), 7.22–7.36 (5H, m, Ar-H); δ_C(63 MHz; $CDCl_3$) 32.9, 55.6, 69.6, 72.9, 73.6, 127.7, 128.1, 128.6, 137.1; *m*/*z* (EI) 242 (M^+, 11%), 133 (19), 104 (26), 91 (100) (Found: M^+, 242.0437. $C_{11}H_{14}O_2S_2$ requires *m*/*z*, 242.0435).

trans-(1*R*,3*R*)-2-*Benzyloxymethyl*-1,3-*dithiolane* 1,3-*dioxide* **19** eluted next as a white solid (795 mg, 68%), R_f 0.35 (10% MeOH–EtOAc); mp 75–77 °C (^{t}BuOAc); $[\alpha]_D^{22}$ +125.4 (*c* 1.0 in $CHCl_3$) (Found: C, 50.9; H, 5.2; S, 24.8. $C_{11}H_{14}O_3S_2$ requires C, 51.1; H, 5.5; S, 24.8%); ν_{max}(KBr)/cm^{-1} 1024 (S=O); δ_H(250 MHz; $CDCl_3$) 3.56–3.84 (4H, m, 4-H and 5-H), 3.90–4.17 (3H, m, 2-H and 6-H), 4.57 (1H, d, *J* 12, benzylic H_a), 4.65 (1H, d, *J* 12, benzylic H_b), 7.26–7.42 (5H, m, Ar-H); δ_C(63 MHz; $CDCl_3$) 51.3, 51.8, 61.8, 73.9, 89.9, 127.9, 128.2, 128.6, 136.9; *m*/*z* (EI) 259 (MH^+, 98%), 241 (31), 91 (100). Chiral HPLC analysis was carried out on a Chiralpak AD column (25 cm × 4.6 mm id) eluting with 87% light petroleum–12% isopropyl alcohol–1% diethylamine at 2 ml min^{-1} and using a UV detector at 240 mm. (*R*,*R*)-**19** had a retention time of 16.7 min while (*S*,*S*)-**19** had a retention time of 15.8 min. The minor (*S*,*S*)-enantiomer could not be detected before or after recrystallisation.

cis-2-*Benzyloxymethyl*-1,3-*dithiolane* 1,3-*dioxide* eluted last as a white solid (77 mg, 7%), R_f 0.15 (10% MeOH–EtOAc), mp 123–124 °C, ν_{max}(KBr)/cm^{-1} 1039 (S=O); δ_H(250 MHz; $CDCl_3$) 3.37–3.59 (2H, m, 4-H_a and 5-H_a), 3.68 (1H, t, *J* 7, 2-H), 3.74–3.89 (2H, m, 4-H_b and 5-H_b), 4.24 (2H, d, *J* 7, CHCH_2), 4.57 (2H, s, CH_2Ar), 7.23–7.40 (5H, m, Ar-H); δ_C(100 MHz; $CDCl_3$) 51.9, 61.2, 74.3, 75.9, 128.0, 128.5, 137.0; *m*/*z* (EI) 258 (M^+, 28%), 152 (46), 135 (37), 107 (33), 91 (100), 77 (55) (Found: M^+, 258.0378. $C_{11}H_{14}O_3S_2$ requires *m*/*z*, 258.0384).

(1*R*,3*R*)-2-Hydroxymethyl-1,3-dithiolane 1,3-dioxide (−)-20

(+)-Diethyl tartrate (1.71 ml, 10 mmol) was dissolved in dry CH_2Cl_2 (20 ml) at room temperature under nitrogen, Ti(O^{i}Pr)$_4$ (0.74 ml, 2.5 mmol) added and the solution stirred for 20 minutes. A solution of the sulfide **17** (0.34 g, 2.5 mmol) in dry CH_2Cl_2 (10 ml) was then added and the reaction mixture cooled to −35 °C. After 1 hour, cumene hydroperoxide (2.0 ml, 10 mmol) was added and the reaction mixture stirred under nitrogen for 18 hours, after which time 1.3 ml of water was added. The reaction mixture was then allowed to warm to room temperature and stirred for a further 2 hours. The resulting gel was filtered through a pad of Celite to remove the titanium oxide. The dichloromethane solution was dried over Na_2SO_4, filtered and the solvent removed under vacuum. Column chromatography on silica gel, eluting with acetone–ethanol (gradient 1:0–95:5), gave the title compound as a white solid (0.19 g, 46%), R_f 0.2 (acetone); mp 125 °C (MeOH); $[\alpha]_D^{22}$ −173 (*c* 0.075 in H_2O); δ_H(250 MHz, [$^2H_6$]DMSO) 3.4–3.9 (4H, m, 4-H and 5-H), 4.0 (2H, m, CH_2O), 4.1 (1H, m, 2-H), 5.5 (1H, t, *J* 7.5, OH).

(1*R*,3*R*)-2-(Dimethylaminomethyl)-1,3-dithiolane 1,3-dioxide 13
(1*R*,3*R*)-2-Benzyloxymethyl-1,3-dithiolane 1,3-dioxide **19** (2.05 g, 7.92 mmol) was dissolved in a solution of dimethylamine in acetonitrile (25 ml, 0.3 M) at room temperature. The solution was stirred in the dark for 24 hours, after which acetonitrile and excess dimethylamine were evaporated under reduced pressure. Column chromatography (acetone) gave the title compound as a white solid (1.54 g, 100%), mp (^{t}BuOAc) 105.5–106.5; $[\alpha]_D^{22}$ 128.4 (*c* 1.0 in $CHCl_3$) (Found: C, 36.8; H, 6.9; N, 7.2; S, 32.5. $C_6H_{13}NS_2O_3$ requires C, 36.9; H, 6.7; N, 7.2; S, 32.8%); ν_{max}/cm^{-1} 1028 (S=O); δ_H(250 MHz; $CDCl_3$) 2.37 (6H, s, NMe_2), 2.91 (2H, d, *J* 8.5, $CHCH_2$), 3.5–3.83 (4H, m, CH_2CH_2), 3.92 (1H, td, *J* 8.5 and 0.6, $CHCH_2$); δ_C(63 MHz; $CDCl_3$) 45.5, 50.8, 51.3, 52.1, 90.5; *m*/*z* 195 (M^+, 24%), 118 (55), 58 (100).

(1*R*,3*R*)-2-Methylene-1,3-dithiolane 1,3-dioxide 9
Amine **13** (0.53 g, 2.7 mmol) was dissolved in acetonitrile (5 ml) and stirred at room temperature under nitrogen. To the solution was added *N*,*N*-diisopropylethylamine (0.7 g, 5.4 mmol) dropwise *via* a syringe. To the reaction mixture was added methyl iodide (1.9 g, 13.5 mmol). After 2 minutes the reaction mixture turned cloudy. After 18 hours no amine was detected by TLC. To the solution was added dry EtOAc (10 ml) and following filtration the precipitate was washed with EtOAc (4 × 5 ml). The filtrate and EtOAc washings were evaporated *in vacuo* and the residue subjected to flash chromatography [used Sorbsil silica C60 (40–60 μm); use of Merck silica gel resulted in some decomposition and elution of **12** instead of **9**] eluting with acetone to afford the title compound as a white solid (0.37 g, 90%), R_f 0.4 (5% MeOH–Acetone) (Found: C, 32.2; H, 4.0; S, 42.4. $C_4H_6O_2S_2$ requires C, 32.0; H, 4.0; S, 42.6%); $[\alpha]_D^{22}$ −32.6 (*c* 0.043 in $CDCl_3$); ν_{max}/cm^{-1} 1630 (w, C=C), 1030 (S=O); δ_H(250 MHz; $CDCl_3$) 4.0–3.5 (4H, m, 4-H_2 and 5-H_2), 6.9 (2H, s, $=CH_2$); δ_C($CDCl_3$) 51.4, 135.4, 165; *m*/*z* 150 (M^+, 47%), 122 (23), 108 (43), 58 (100).

(1′*R*,3′*R*)-Spiro[bicyclo[2.2.1]hept-2-ene-5,2′-(1,3-dithiolane)] 1′,3′-dioxide 23a
(1*R*,3*R*)-2-Methylene-1.3-dithiolane 1,3-dioxide **9** (104 mg, 0.7 mmol) was dissolved in propionitrile (1.4 ml) and cooled to −78 °C under nitrogen. To this reaction mixture was added $BF_3{\cdot}OEt_2$ (0.17 ml, 1.4 mmol) *via* syringe. After 15 minutes, freshly distilled cyclopentadiene (0.5 ml, 5.5 mmol) was added and the solution stirred at −78 °C for 20 minutes. The reaction was quenched by rapid addition of saturated aqueous $NaHCO_3$ (5 ml). The solution was poured into water (10 ml) and extracted with dichloromethane (3 × 40 ml). The combined organic extracts were dried (over $MgSO_4$), evaporated and subjected to flash chromatography eluting with acetone to afford the title compound as a white solid (0.11 g, 74%). An analytical sample was obtained by recrystallisation from EtOAc to give white cubes, mp 116 °C; R_f 0.4 (acetone) (Found: C, 49.8; H, 5.5; S, 29.4. $C_9H_{12}O_2S_2$ requires C, 50.0; H, 5.55; S, 29.6%); $[\alpha]_D^{22}$ +51.9 (*c* 0.054 in $CHCl_3$); ν_{max}/cm^{-1} 1630 (w, C=C), 1040 (S=O); δ_H(250 MHz; $CDCl_3$) 1.8–2.0 (3H, m, CH_AH_B + CH_2), 2.19 (1H, dd, *J* 9 and 2, CH_AH_B), 3.25 (1H, br s, CH), 3.4–3.5 (4H, m, CH_2CH_2), 4.0 (1H, m, CH), 6.25 (1H, dd, *J* 5.5 and 3, HC=CH), 6.5 (1H, dd, *J* 5.5 and 3, HC=CH); δ_C(63 MHz; $CDCl_3$), 28.8, 42.7, 45.3, 49.9, 50.9, 51.9, 98.4, 133, 141; *m*/*z* 216 (M^+, 5%), 108 (40), 91 (64), 66 (100).

Crystal data for 23a. $C_9H_{12}O_2S_2$; *M* = 216.31, crystallises from ethyl acetate as colourless blocks; crystal dimensions 0.45 × 0.34 × 0.13 mm. Monoclinic, *a* = 9.597(2), *b* = 6.4030(10), *c* = 15.931(3) Å, *β* = 93.37(3)°, *U* = 977.3(3) Å^3, *Z* = 4, D_c = 1.470 Mg m^{-3}, space group $P2_1/c$ (C_{2h}^5, No. 14), Mo-Kα radiation (*λ* = 0.710 73 Å), *μ*(Mo-Kα) = 0.508 mm^{-1}, *F*(000) = 456.

Three-dimensional, room temperature X-ray data were collected in the range 3.5° < 2*θ* < 60° on a Siemens P4 diffractometer by the ω scan method. The 2841 independent reflections (of 3902 measured) for which $|F|/\sigma(|F|) > 4.0$ were corrected for Lorentz and polarisation effects, but not for absorption. The structure was solved by direct methods and refined by full matrix least squares methods on F^2. Hydrogen atoms were included in calculated positions and refined in riding mode. Refinement converged at a final $R = 0.0610$ ($wR_2 = 0.1805$ for all 3902 reflections, 118 parameters, mean and maximum δ/σ 0.000, 0.000), with allowance for the thermal anisotropy of all non-hydrogen atoms. Minimum and maximum final electron density −0.324 and 0.435 e Å^{-3}. A weighting scheme $w = 1/[\sigma^2(F_o^2) + (0.0945P)^2 + 0.00P]$ where $P = (F_o^2 + 2F_c^2)/3$ was used in the latter stages of refinement. Complex scattering factors were taken from the program package SHELXL93[36] as implemented on the Viglen 486dx computer.

(1*R*,4*R*,6*S*)-6-Methoxy-1,4-dithiaspiro[4.5]dec-7-ene 1,4-dioxide 24a
(1*R*,3*R*)-2-Methylene-1,3-dithiolane 1,3-dioxide **9** (60 mg, 0.4 mmol) was dissolved in propionitrile (0.8 ml). To this solution was added 1-methoxybutadiene (0.2 ml, 2 mmol) dropwise *via* syringe. The solution was stirred for 24 hours at room temperature. The solvents and excess reagents were removed *in vacuo* and the residue subjected to flash chromatography eluting with acetone. The title compound was afforded as a white solid (78 mg, 83%). Recrystallisation of an analytical sample gave white plates, mp 147 °C; R_f 0.4 (acetone) (Found: C, 45.8; H, 5.85; S, 27.2. $C_9H_{14}O_3S_2$ requires C, 46.0; H, 6.0; S, 27.35%); $[\alpha]_D^{22}$ +197.2 (*c* 0.072 in $CHCl_3$); ν_{max}/cm^{-1} 1640 (w, C=C); 1040 (S=O); δ_H(250 MHz; $CDCl_3$) 2.2–2.6 (4H, m, C-CH_2CH_2-C), 3.4 (3H, s, OMe), 3.5 (2H, m, S-$CH_AH_BCH_AH_B$-S), 3.6 (2H, m, S-$CH_AH_BCH_AH_B$-S), 4.2 (1H, br s, C*H*OMe), 6.0 (2H, m, HC=CH); δ_C(63 MHz; $CDCl_3$) 22.8, 23.4, 50.1, 52.9, 57.1, 71.7, 92.2, 124.9, 130.0; *m*/*z* 234 (M^+, 19%), 158 (18), 110 (100), 95 (20), 77 (21), 67 (22).

Crystal data for 24a. $C_9H_{14}O_3S_2$; *M* = 234.32, crystallises from ethyl acetate as clear blocks; crystal dimensions 0.66 × 0.35 × 0.15 mm. Monoclinic, *a* = 6.408(2), *b* = 23.631(4), *c* = 7.252(2) Å, *β* = 101.98(2)°, *U* = 1074.7(5) Å^3, *Z* = 4, D_c = 1.448 Mg m^{-3}, space group $P2_1/n$ (a non-standard setting of $P2_1/cC_{2h}^5$, No. 14), Mo-Kα radiation (*λ* = 0.710 73 Å), *μ*(Mo-Kα) = 0.474 mm^{-1}, *F*(000) = 496.

Three-dimensional, room temperature X-ray data were collected in the range 3.0° < 2*θ* < 40° on a Siemens P4 diffractometer by the ω scan method. Of the 1392 reflections measured, all of which were corrected for Lorentz and polarisation effects (but not for absorption), 946 independent reflections exceeded the significance level $|F|/\sigma(|F|) > 4.0$. The structure was solved by direct methods and refined by full matrix least squares methods on F^2. Hydrogen atoms were included in calculated positions and refined in riding mode. Refinement converged at a final $R = 0.0492$ ($wR_2 = 0.1364$, for all 946 unique data 127 parameters, mean and maximum δ/σ 0.000, 0.000), with allowance for the thermal anisotropy of all non-hydrogen atoms. Minimum and maximum final electron density −0.257 and 0.351 e Å^{-3}. A weighting scheme $w = 1/[\sigma^2(F_o^2) + (0.0999P)^2 + 0.000P]$ where $P = (F_o^2 + 2F_c^2)/3$ was used in the latter stages of refinement. Complex scattering factors were taken from the program package SHELXL93[36] as implemented on the Viglen 486dx computer.

(1*R*,4*R*,6*S*)-6-Methoxy-1,4-dithiaspiro[4.5]decan-8-one 1,4-dioxide 25a
(1*R*,3*R*)-2-Methylene-1,3-dithiolane 1,3-dioxide **9** (60 mg, 0.4 mmol) was dissolved in propionitrile (0.8 ml). To this solution was added 1-methoxy-3-(trimethylsiloxy)buta-1,3-diene (0.4 ml, 2 mmol) dropwise *via* syringe. The solution was stirred for 2 hours at room temperature. The solvents and excess reagents were removed *in vacuo* and the residue subjected to flash chromatography eluting with acetone to afford the title compound as a white solid (90 mg, 90%). Recrystallisation of an analytical

sample gave white plates, mp 140.9 °C; R_f 0.4 (acetone) (Found: C, 43.3; H, 5.6; S, 25.6. $C_9H_{14}O_4S_2$ requires C, 43.15; H, 5.6; S, 25.6%); $[\alpha]_D^{22}$ +118.0 (*c* 0.095 in $CHCl_3$); ν_{max}/cm^{-1} 1720 (C=O), 1040 (S=O); δ_H(250 MHz; $CDCl_3$) 1.9 (1H, m, $CH_AH_BCH_2$), 2.6 (3H, m, $CH_AH_BCH_2$), 2.9 (2H, d, *J* 4, CH_2CO), 3.4 (3H, s, OMe), 3.5–4.2 (5H, m, CH_2CH_2-S and CHOMe); δ_C(63 MHz; $CDCl_3$) 22.5, 38.5, 43, 51.0–51.6, 57.6, 92.2, 118.3, 205.3; *m*/*z* 250 (M^+, 15%), 126 (20), 108 (100), 84 (28).

Crystal data for 25a. $C_9H_{14}O_4S_2$; $M = 250.32$, crystallises from ethyl acetate as colourless blocks; crystal dimensions 0.54 × 0.32 × 0.32 mm. Monoclinic, $a = 10.578(4)$, $b = 7.434(2)$, $c = 14.273(4)$ Å, $\beta = 93.47(3)°$, $U = 1120.3(6)$ Å^3, $Z = 4$, $D_c = 1.484$ Mg m^{-3}, space group $P2_1/n$ (a non-standard setting of $P2_1/cC_{2h}^5$, No. 14), Mo-Kα radiation ($\lambda = 0.710\,73$ Å), μ(Mo-Kα) = 0.466 mm^{-1}, $F(000) = 528$.

Three-dimensional, room temperature X-ray data were collected in the range $3.5° < 2\theta < 40°$ on a Siemens P4 diffractometer by the ω scan method. Of the 1511 reflections measured, all of which were corrected for Lorentz and polarisation effects (but not for absorption), 935 independent reflections exceeded the significance level $|F|/\sigma(|F|) > 4.0$. The structure was solved by direct methods and refined by full matrix least squares methods on F^2. Hydrogen atoms were included in calculated positions and refined in riding mode. Refinement converged at a final $R = 0.0343$ ($wR_2 = 0.0920$, for all 1037 unique data 136 parameters, mean and maximum δ/σ 0.000, 0.000), with allowance for the thermal anisotropy of all non-hydrogen atoms. Minimum and maximum final electron density −0.227 and 0.203 e Å^{-3}. A weighting scheme $w = 1/[\sigma^2(F_o^2) + (0.0499P)^2 + 0.7218P]$ where $P = (F_o^2 + 2F_c^2)/3$ was used in the latter stages of refinement. Complex scattering factors were taken from the program package SHELXL93[36] as implemented on the Viglen 486dx computer.

(1*R*,3*R*)-Spiro[1,3-dithiolane-2,5′-(7-oxabicyclo[2.2.1]hept-2-ene)] 1,3-dioxide 26a

(1*R*,3*R*)-2-Methylene-1,3-dithiolane 1,3-dioxide **9** (106 mg, 0.7 mmol) was dissolved in propionitrile (1.4 ml) and cooled to −78 °C under nitrogen. To the solution was added tin(IV) chloride (367 mg, 1.4 mmol) dropwise *via* syringe and the solution stirred for 15 minutes. Freshly distilled furan (238 mg, 3.5 mmol) was added in one portion and the solution stirred at −78 °C for 6 hours. TMEDA (162 mg, 1.4 mmol) was added to the solution at −78 °C and the solution allowed to reach room temperature over 2 hours. The precipitate formed was filtered through Celite. The filter cake was washed with CH_2Cl_2 (10 ml). The solvents were removed *in vacuo* and the residue subjected to flash chromatography eluting with acetone to afford the title compound (100 mg, 65%). Recrystallisation of an analytical sample gave white plates, mp 162.6 °C; R_f 0.4 (acetone) (Found: C, 44.0; H, 4.65; S, 29.1. $C_8H_{10}O_3S_2$ requires C, 44.0; H, 4.6; S, 29.35%); $[\alpha]_D^{22}$ +18.8 (*c* 0.080 in $CHCl_3$); ν_{max}/cm^{-1} 1640 (w, C=C), 1040 (S=O); δ_H(250 MHz; $CDCl_3$) 2.0 (1H, dd, *J* 12 and 4.5, CH_AH_B), 2.2 (1H, d, *J* 12, CH_AH_B), 3.4–3.8 (3H, m, $CH_2CH_AH_B$), 4.1 (1H, m, $CH_2CH_AH_B$), 5.35 (1H, br s, CH), 5.6 (1H, br s, CH), 6.6 (1H, dd, *J* 6 and 2.0, HC=), 6.7 (1H, dd, *J* 6 and 2.0, =CH); δ_C(63 MHz; $CDCl_3$) 28.5, 50.3, 52.3, 77.4, 77.9, 118.3, 132.2, 140.0; *m*/*z* 218 (M^+, 5%), 124 (68), 93 (30), 68 (82), 65 (33), 58 (100).

Crystal data for 26a. $C_8H_{10}O_3S_2$; $M = 218.28$, crystallises from ethyl acetate as clear blocks; crystal dimensions 0.45 × 0.30 × 0.25 mm. Monoclinic, $a = 12.263(2)$, $b = 6.0290(10)$, $c = 13.101(8)$ Å, $\beta = 108.95(3)°$, $U = 916.1(6)$ Å^3, $Z = 4$, $D_c = 1.583$ Mg m^{-3}, space group $P2_1/c$ (C_{2h}^5, No. 14), Mo-Kα radiation ($\lambda = 0.710\,69$ Å), μ(Mo-Kα) = 0.55 mm^{-1}, $F(000) = 456$.

Three-dimensional, room temperature X-ray data were collected in the range $3.5° < 2\theta < 40°$ on a Siemens P4 diffractometer by the ω scan method. The 643 independent reflections (of 843 measured) for which $|F|/\sigma(|F|) > 4.0$ were corrected for Lorentz and polarisation effects, but not for absorption. The structure was solved by direct methods and refined by full matrix least squares methods. Hydrogen atoms were included in calculated positions and refined in riding mode. Refinement converged at a final $R = 0.0530$ ($wR_2 = 0.1529$, 118 parameters, mean and maximum δ/σ 0.002, 0.001), with allowance for the thermal anisotropy of all non-hydrogen atoms. Minimum and maximum final electron density −0.244 and 0.258 e Å^{-3}. A weighting scheme $w = 1/[\sigma^2(F_o^2) + (0.06030P)^2 + 3.257P]$ where $P = (F_o^2 + 2F_c^2)/3$ was used in the latter stages of refinement. Complex scattering factors were taken from the program package SHELXL93[36] as implemented on the Viglen 486dx computer.

(1′*R*,3′*R*)-2-Phenoxycarbonylspiro[2-azabicyclo[2.2.2]oct-5-ene-7.2′-(1,3-dithiolane)] 1′,3′-dioxide 27a/27b

Racemic 2-methylene-1,3-dithiolane 1,3-dioxide **9** (95 mg, 0.63 mmol) was dissolved in CH_2Cl_2 (2 ml) and 1-(phenoxycarbonyl)-1,2-dihydropyridine[24] (190 mg, 0.95 mmol) was added. The solution was refluxed for 8 days. The solvent was then removed and the residue subjected to flash chromatography eluting with acetone–EtOAc (50 : 50). The title compound was afforded as a white solid (130 mg, 60%) as a mixture of diastereoisomers (ratio 73 : 27). Recrystallisation of an analytical sample gave the major diastereoisomer as white plates, R_f 0.4 (acetone); mp 93.2–93.4 °C; ν_{max}/cm^{-1} 1714 (C=O), 1564 (w, C=C), 1040 (S=O); *major isomer*: δ_H(250 MHz; $CDCl_3$) 1.3–1.4 (1H, dd, *J* 13 and 1.5, CH_AH_B), 2.43 (1H, dt, *J* 13 and 2.0, CH_AH_B), 3.0–3.3 (3H, m, CH_2CH_2 and CH), 3.3–3.5 (3H, m, CH_2CH_2 and CH_AH_BN), 4.2 (1H, m, CH_AH_BN), 5.5 (1H, dd, *J* 6.5 and 2.0, CH), 6.7 (2H, m, HC=CH), 7.1–7.4 (5H, m, Ar-H); δ_C(63 MHz; $CDCl_3$) 22.2, 28.1, 46.4, 47.5, 50.1, 52.4, 94.8, 121.5, 121.9, 125.5, 129.2; *m*/*z* 351 (M^+, 18%), 244 (86), 168 (67), 77 (100) (Found: M^+, 351.0609. $C_{16}H_{17}NO_4S_2$ requires *m*/*z*, 351.0599); *minor diastereoisomer*: δ_H(250 MHz; $CDCl_3$) 1.3–1.4 (1H, dd, *J* 13 and 1.5, CH_AH_B), 2.65 (1H, dt, *J* 13 and 2.0, CH_AH_B), 3.0–3.5 (3H, m, CH_2CH_2 and CH), 3.3–3.5 (3H, m, CH_2CH_2 and CH_AH_BN), 4.0–4.5 (1H, m, CH_AH_BN), 5.5 (1H, dd, *J* 6.5 and 2.0, CH), 6.5–7.0 (2H, m, HC=CH), 7.0–7.5 (5H, m, Ar-H). Repeating the reaction with $BF_3{\cdot}OEt_2$ at −78 °C for 1 hour gave **27** with by-product **31** (ratio 41 : 59) in 96% yield. HPLC analysis of **27** and by-products were carried out on a silica column eluting with 70% isopropyl alcohol–light petroleum (bp 60–80 °C) at 1.0 ml min^{-1} and using UV detector at 245 nm. **27a** had a retention time of 20.0 min while **27b** had a retention time of 24.0 min and by-product **31** had retention times of 14.0 and 16.0 min.

Crystal data for 27a. $C_{16}H_{17}NO_4S_2$; $M = 351.43$, crystallises from *tert*-butyl acetate as colourless blocks; crystal dimensions 0.55 × 0.32 × 0.17 mm. Monoclinic, $a = 10.840(4)$, $b = 6.268(5)$, $c = 13.000(5)$ Å, $\beta = 113.14°(2)$, $U = 812.2(8)$ Å^3, $Z = 2$, $D_c = 1.437$ Mg m^{-3}, space group $P2_1$ (C_2^2, No. 4), Mo-Kα radiation ($\lambda = 0.710\,73$ Å), μ(Mo-Kα) = 0.347 mm^{-1}, $F(000) = 368$.

Three-dimensional, room temperature X-ray data were collected in the range $3.5° < 2\theta < 45°$ on a Siemens P4 diffractometer by the ω scan method. Of the 1659 reflections measured, all of which were corrected for Lorentz and polarisation effects (but not for absorption), 1375 independent reflections exceeded the significance level $|F|/\sigma(|F|) > 4.0$. The structure was solved by direct methods and refined by full matrix least squares on F^2. Hydrogen atoms were included in calculated positions and refined in riding mode. Refinement converged at a final $R = 0.0483$ ($wR_2 = 0.1270$ for all 1412 unique data, 208 parameters, mean and maximum δ/σ 0.000, 0.000), with allowance for the thermal anisotropy of all non-hydrogen atoms. Minimum and maximum final electron density −0.505 and 0.388 e Å^{-3}. A weighting scheme $w = 1/[\sigma^2(F_o^2) + (0.1069P)^2 + 0.1055P]$ where $P = (F_o^2 + 2F_c^2)/3$ was used in the latter stages of refinement. Complex scattering factors were taken from the program package SHELXL93[36] implemented on the Viglen 486dx computer.

(1′*R*,3′*R*)-Spiro[bicyclo[2.2.2]oct-2-ene-5,2′-(1,3-dithiolane)] 1′,3′-dioxide 28a/28b

Racemic 2-methylene-1,3-dithiolane 1,3-dioxide **9** (83 mg, 0.55 mmol) was dissolved in CH_2Cl_2 (1.5 ml) and cooled to −78 °C under nitrogen and $BF_3{\cdot}OEt_2$ (0.1 ml, 1.1 mmol) was added. After 15 minutes, cyclohexa-1,3-diene (0.2 ml, 2.2 mmol) was added and the solution stirred at −78 °C for 10 minutes. The mixture was then transferred to a freezer at −32 °C for 24 hours. The reaction was quenched by rapid addition of saturated aqueous $NaHCO_3$ (5 ml). The solution was poured into water (10 ml) and extracted with dichloromethane (3 × 40 ml). The combined organic extracts were dried (over $MgSO_4$), evaporated and subjected to flash chromatography eluting with acetone to afford the title compound as a mixture of diastereoisomers (ratio 90:10) (76 mg, 60%), R_f 0.5 (acetone); ν_{max}(thin film)/cm^{-1} 1655 (w, C=C), 1033 (S=O); *major isomer*: δ_H(250 MHz; $CDCl_3$) 1.2 (1H, dd, *J* 14 and 2.0, CH_AH$_B$), 1.5 (2H, m, CH_2CH$_2$), 2.0 (2H, m, CH$_2$CH_2), 2.4 (1H, m, CH$_A$$H_B$), 2.9 (1H, br s, CH), 3.0–3.5 (4H, m, SCH_2CH_AH$_B$ and C*H*), 4.0 (1H, m, SCH$_2$CH$_A$$H_B$), 6.3 (1H, m, *H*C=), 6.5 (1H, m, =C*H*); δ_C(63 MHz; $CDCl_3$) 20.6, 23.1, 25.0, 38.4, 47.8, 51.1, 64.3, 94.3, 131.7, 138.5; *m*/*z* (EI) 230 (M$^+$, 13%), 155 (31), 126 (36), 108 (60), 80 (100) (Found: M$^+$, 230.0443. $C_{10}H_{14}O_2S_2$ requires *m*/*z*, 230.0435); *minor isomer*: δ_H(250 MHz; $CDCl_3$) 1.2 (1H, dd, *J* 14 and 2.0, CH_AH$_B$), 1.5 (2H, m, CH_2CH$_2$), 2.0 (2H, m, CH$_2$CH_2), 2.4 (1H, m, CH$_A$$H_B$), 2.9 (1H, br s, CH), 3.5–3.0 (4H, m, SCH_2CH_AH$_B$ and C*H*), 4.0 (1H, m, SCH$_2$CH$_A$$H_B$), 6.5 (2H, m, *H*C=C*H*).

(1*S*,1′*R*,3′*R*)-1-Methoxyspiro[(bicyclo[2.2.2]oct-2-ene)-6,2′-(1,3-dithiolane)] 1′,3′dioxide 29a/29b

Racemic 2-methylene-1,3-dithiolane 1,3-dioxide **9** (50 mg, 0.3 mmol) in CH_2Cl_2 (0.3 ml) was cooled to −78 °C under nitrogen and Et_2AlCl (0.3 ml, 0.3 mmol in 1 M hexane solution) was added. After 15 minutes, 1-methoxycyclohexa-1,3-diene (0.18 ml, 1 mmol) was added and the solution stirred at −78 °C for 1 hour. The reaction was quenched by rapid addition of saturated aqueous $NaHCO_3$ (5 ml). The solution was then poured into water (10 ml) and extracted with dichloromethane (3 × 20 ml). The combined organic extracts were dried (over $MgSO_4$), evaporated and subjected to flash chromatography eluting with acetone–EtOAc (60:40) to afford the title compound as a white solid mixture of diastereoisomers (>97:3) (43 mg,. 50%), mp 159.2–159.4 °C; R_f 0.4 (acetone); ν_{max}(KBr)/cm^{-1} 1547 (w, C=C), 1045 (S=O); *major isomer*: δ_H(250 MHz; $CDCl_3$) 1.3 (1H, dd, *J* 2.0 and 13, CH_AH$_B$), 1.55 (1H, m, CH$_A$$H_B$), 1.9–2.0 (4H, m, C$H_2CH_2$), 2.7 (1H, br s, CH), 3.2–3.4 (7H, m, SCH_2CH_2 and OMe), 6.4 (2H, m, *H*C=C*H*); δ_C(63 MHz; $CDCl_3$) 20.7, 25.8, 26.9, 29.0, 48.4, 52.5, 57.8, 81.2, 101.6, 133.1, 134.4; *m*/*z* (EI) 260 (M$^+$, 25%), 185 (60), 108 (100), 77 (54) (Found: M$^+$, 260.0544. $C_{11}H_{16}O_2S_2$ requires *m*/*z*, 260.0540). Conducting the reaction in EtCN in the absence of $BF_3{\cdot}OEt_2$ gave an 80:20 ratio of products. The *minor isomer* had: δ_H(250 MHz; $CDCl_3$) 1.3 (1H, dd, *J* 2.0 and 13, CH_AH$_B$), 1.55 (1H, m, CH$_A$$H_B$), 1.9–2.0 (4H, m, C$H_2CH_2$), 2.7 (1H, br s, CH), 3.2–4.3 (7H, m, SCH_2CH_2 and OMe), 6.4 (1H, m, *H*C=), 6.8 (1H, m, =C*H*).

(1*RS*,3*RS*,1′*RS*,4′*RS*)-Spiro[1,3-dithiolane-2,7′-(2-oxabicyclo[2.2.2]-oct-5-ene]-3′-one 1′,3′-dioxide 30a/30b

Racemic 2-methylene-1,3-dithiolane 1,3-dioxide **9** (50 mg, 0.3 mmol) was dissolved in toluene (0.8 ml) and 2*H*-pyran-2-one (0.07 ml, 0.9 mmol) was added. The solution was refluxed for 8 days. After 8 days, the solvents and excess reagents were removed under reduced pressure and the residue subjected to flash chromatography eluting with acetone. The diastereoisomers (94:6) were afforded as a yellow solid (27 mg, 33%), R_f 0.5 (acetone); mp 84.6–85.2 °C; ν_{max}/cm^{-1} 1768 (C=O), 1725 (w, C=C), 1043 (S=O); *major isomer*: δ_H(250 MHz; $CDCl_3$) 1.52–1.60 (1H, dd, *J* 14 and 2.0, CH_AH$_B$), 2.56–2.64 (1H, dd, *J* 14 and 2.0, CH$_A$$H_B$), 3.4–3.7 (3H, m, C$H_2CH_AH_B$), 3.7–3.8 (1H, m, CH), 4.3 (1H, m, CH_2CH$_A$$H_B$), 5.35 (1H, t, *J* 2.0, CH), 6.8 (2H, m, *H*C=C*H*); δ_C(63 MHz; $CDCl_3$) 20.7, 40.2, 50.6, 51.8, 73.9, 95.3, 131.0, 135.0, 170.5; *m*/*z* (EI) 246 (M$^+$, 27%) 126 (34), 121 (58), 78 (82) (Found: M$^+$, 246.0023. $C_9H_{10}O_4S_2$ requires *m*/*z*, 246.0020); *minor isomer*: δ_H(250 MHz; $CDCl_3$) 1.64–1.68 (1H, dd, *J* 14 and 2.0, CH_AH$_B$), 2.80–2.88 (1H, dd, *J* 14 and 2.0, CH$_A$$H_B$), 3.4–3.7 (3H, m, C$H_2CH_AH_B$), 3.7–3.8 (1H, m, CH), 4.3 (1H, m, CH_2CH$_A$$H_B$), 5.7 (1H, dd, *J* 5 and 2.0, CH), 6.65 (1H, m, *H*C=), 6.8 (1H, m, =C*H*).

(1*R*,4*R*)-Spiro[bicyclo[2.2.1]hept-2-ene-5,2′-(1,3-dithiolane)] 32

To solution of sulfoxide **23a** (200 mg, 0.93 mmol) in acetonitrile (1.5 ml) at 0 °C was added sodium iodide (693 mg, 4.6 mmol) and TFAA (0.77 ml, 5.52 mmol) dropwise over 5 minutes, under nitrogen. After 2 hours, saturated aqueous $Na_2S_2O_3$ was added until the solution turned clear, followed by saturated aqueous $NaHCO_3$ (15 ml). The reaction mixture was allowed to warm up to room temperature and was extracted with CH_2Cl_2 (3 × 20 ml). The combined organic extracts were dried over $MgSO_4$ and evaporated *in vacuo*. The crude sulfide was subjected to flash chromatography eluting with ethyl acetate–light petroleum (bp 60–80 °C) (10:90) and gave the title compound as a colourless liquid (153 mg, 90%), $[a]_D^{22}$ −29.4 (*c* 0.4 in CH_2Cl_2); R_f 0.4 [ethyl acetate–light petroleum (bp 60–80 °C) (10:90)]; ν_{max}/cm^{-1} 2866–2968 (CH), 1614 (w, C=C); δ_H(250 MHz; $CDCl_3$) 1.5 (2H, m, 7-H$_2$), 1.92 (1H, dd, *J* 12.0 and 2.0, 3-H$_a$), 2.40 (1H, dd, *J* 12.0 and 3.0, 3-H$_b$), 2.87 (1H, br s, 1-H), 2.9 (1H, m, 4-H), 3.28 (4H, m, 4′-H$_2$ and 5′-H$_2$), 6.2 (1H, dd, *J* 4.0 and 3.0, 6-H), 6.27 (1H, dd, *J* 4.0 and 3.0, 5-H); δ_C(63 MHz; $CDCl_3$) 39.8 (C-7), 40.6 (C-3), 42.1 (C-4), 47.0 (C-4′), 50.2 (C-5′), 56.9 (C-1), 118.4 (C-2), 135.3 (C-6), 139.0 (C-5); *m*/*z* (EI) 185 (M$^+$, 100%), 125 (42), 118 (45), 105 (48), 89 (74), 57 (88) (Found: M$^+$, 185.0458. $C_9H_{13}S_2$ requires *m*/*z*, 185.0463).

(+)-Norbornenone (bicyclo[2.2.1]hept-5-en-2-one) 33

Dithioketal **32** (45 mg, 0.24 mmol), $CuCl_2$ (320 mg, 2.4 mmol), silica gel (50 mg) and water (0.7 ml) in dichloromethane (4 ml) were refluxed for 4 days. The mixture was then cooled, filtered, diluted with water (5 ml) and extracted with dichloromethane. Drying over $MgSO_4$ and evaporation of the dichloromethane gave a residue which was purified by flash chromatography on silica gel eluting with dichloromethane and gave the ketone as a colourless liquid (21 mg, 81%), $[a]_D^{22}$ +930 (*c* 1.0 in $CHCl_3$) [lit.,[37] +980 (*c* 0.3 in $CHCl_3$)]; R_f 0.3 [ethyl acetate–petrol (10:90)]; δ_H(250 MHz; $CDCl_3$) 1.8–2.0 (2H, m, 7-H$_2$), 3.0 (1H, m, 4-H), 3.25 (1H, br s, 1-H), 6.1 (1H, m, 5-H), 6.55 (1H, dd, *J* 6.0 and 3.0, 6-H). Chiral GC analysis of (+/−)-**33** was carried out on a chiral cyclodextrin α column (30 m, 0.25 mm id), using hydrogen as the carrier gas at a flow rate of 16 PSI, 70 °C isothermal, flame ionisation detection. (+)-**33** had a retention time of 10.50 min while (−)-**33** had a retention time of 10.04. Analysis of the above product showed the enantiomeric excess to be >98%.

(1*RS*,4*RS*)-Spiro[7-oxabicyclo[2.2.1]hept-2-ene-5,2′-(1,3-dithiolane)] 34

This compound was prepared according to the above method using sulfoxide **26a** (97 mg, 0.44 mmol) in acetone (2 ml) at −78 °C, sodium iodide (330 mg, 2.22 mmol) and TFAA (0.37 ml, 2.64 mmol) for 4 hours. The crude material was subjected to flash chromatography eluting with ethyl acetate–light petroleum (bp 60–80 °C) (10:90) and gave the sulfide as a colourless liquid (70 mg, 83%), R_f 0.3 (acetone); ν_{max}(KBr)/cm^{-1} 2999–2863 (CH), 1568 (C=C); δ_H(250 MHz; $CDCl_3$) 2.0 (1H, d, *J* 13, CH_AH$_B$), 2.5 (1H, dd, *J* 13 and 5.5, CH$_A$$H_B$), 3.1–3.4 (4H, m, C$H_2CH_2$), 4.7 (1H, d, *J* 1.1, CH), 5.0 (1H, dd, *J* 5.5 and 1.1, CH), 6.47 (2H, t, *J* 1.0, *H*C=C*H*); δ_C(63 MHz; $CDCl_3$) 39.2, 41.0, 45.8, 66.0, 78.8, 87.5, 134.8, 137.3; *m*/*z* (EI) 187 (M$^+$, 93%), 169 (94), 127 (45), 118 (100), 99 (44), 61 (49) (Found: M$^+$, 187.0251. $C_8H_{11}OS_2$ requires *m*/*z*, 187.0242).

(±)-7-Oxabicyclo[2.2.1]hept-5-en-2-one 35

A mixture of dithioketal **34** (35 mg, 0.18 mmol), $CuCl_2$ (250 mg, 1.88 mmol), silica gel (38 mg) and water (0.5 ml) in dichloromethane (2 ml) was refluxed for 5 days. The mixture was then cooled, filtered, diluted with water (5 ml) and extracted with dichloromethane. Drying ($MgSO_4$) and evaporation of the dichloromethane gave a residue which was purified by flash chromatography on silica gel eluting with acetone–light petroleum (bp 60–80 °C) (40 : 60) and gave the ketone as a yellow oil (15 mg, 73%), R_f 0.5 [acetone–light petroleum (bp 60–80 °C) (40 : 60)]; ν_{max}(KBr)/cm^{-1} 2854–2924 (CH), 1771 (C=O); δ_H(250 MHz; $CDCl_3$) 1.87 (1H, d, *J* 16, CH_AH$_B$), 2.5 (1H, dd, *J* 16 and 4.5, CH$_A$$H_B$), 4.52 (1H, d, *J* 2.0, CH), 5.30 (1H, dd, *J* 4.5 and 1.5, CH), 6.40–6.46 (1H, dd, *J* 5.5 and 2.0, *H*C=), 6.6–6.7 (1H, dd, *J* 5.5 and 1.5, =C*H*); δ_C(63 MHz; $CDCl_3$) 34.0, 79.0, 82.1, 130.6, 142.2, 207.2. Data are in agreement with the literature.[38]

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