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Chiral pyridine *N*-oxides derived from monoterpenes as organocatalysts for stereoselective reactions with allyltrichlorosilane and tetrachlorosilane

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ABSTRACT

The synthesis of enantiomerically pure C_2-symmetric dipyridylmethane ligands and related *N*,*N*′-dioxides is reported. A procedure for the synthesis of a few new enantiomerically pure C_2-symmetric pyridine *N*-oxides and the preparation of four pyridine *N*-oxides with oxygen and nitrogen atoms as further coordinating elements in the heterocycle framework is described. All compounds were prepared from naturally occurring monoterpenes. These new compounds were assessed as organocatalysts in two different reactions, namely the allylation of aldehydes with allyltrichlorosilane that afforded homoallylic alcohols in good yields and up to 85% ee and the stilbene oxide opening by the addition of tetrachlorosilane that gave chlorohydrin in quantitative yield and up to 70% ee.

1. Introduction

The replacement or the co-existence of metal-based catalysts with equally efficient metal-free counterparts is a very attractive field of research. In addition, there are possible future applications of non-toxic, low cost and more environmentally friendly promoters on industrial scale with obvious benefits from the environmental and economic point of view.[1] In this context, the chemistry of penta and/or hexavalent silicon compounds has recently attracted much attention because of the possibility to develop organocatalyzed enantioselective reactions.[2]

The coordination of a Lewis base to a tetracoordinated silicon atom leads to hypervalent silicate species of increased Lewis acidity at the silicon centre. As a consequence, such extracoordinated organosilicon compounds become very reactive carbon nucleophiles or hydride donors with a strong electrophilic character at silicon and an enhanced capability to transfer a formally negatively charged group to an acceptor.[3] Among Lewis basic catalysts,[4] a class of compounds that deserve special attention are chiral *N*-oxides derived from tertiary amines.[5] The high nucleophilicity of the oxygen in *N*-oxides, coupled with a high affinity of silicon for oxygen represent ideal properties for the development of synthetic methodology based on nucleophilic activation of organosilicon reagents. The most popular examples in chiral *N*-oxide derivatives are those with a pyridine (or quinoline-type) scaffold that are able to activate trichlorosilanes and catalyze a number of reactions such as allylation of aldehydes, aldol condensations and ring opening of epoxides.[5]

Although a variety of chiral pyridine *N*-oxide derivatives are able to perform these transformations with a high level of stereocontrol, they were often synthesized according to long and tedious procedures, sometimes also involving a resolution step. Furthermore, a difficult-to-control stereogenic element such as a stereogenic axis in the catalyst is often required to achieve high levels of stereocontrol. Therefore, the search for new, readily available and efficient chiral organocatalysts for the reaction of trichlorosilyl compounds is still very active.

On this basis, we have undertaken the preparation of chiral organocatalysts, from naturally occurring and easily available monoterpenes, containing two pyridine rings connected by a proper tunable spacer. In this context, we have recently reported the synthesis of chiral dipyridines with an isopropylidene backbone between two pyridine rings.[6,7] The preliminary results obtained by the C_2-symmetric dipyridylmethane ligands **1**–**4** (Fig. 1) and their

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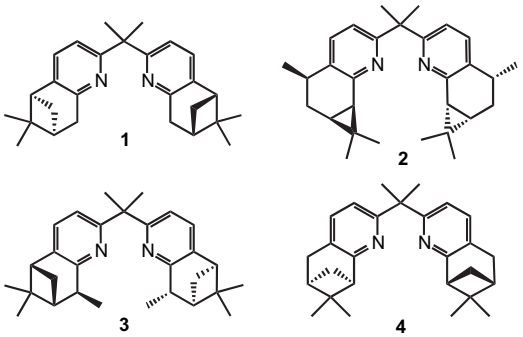


Figure 1. C_2-symmetric dipyridylmethane ligands **1**–**4**.

derivatives in the enantioselective palladium-catalyzed allylic alkylation of 1,3-diphenylprop-2-enyl acetate with dimethyl-malonate,[6a] copper-catalyzed cyclopropanation of styrene with ethyl diazoacetate[6b] and enantioselective addition of allyltrichlorosilane to aldehydes have also been described.[7]

Herein, we wish to report full experimental details for the preparation of the ligands **1**–**4** and related *N*,*N*′-dioxides (Scheme 1). A procedure for the synthesis of a few new enantiomerically pure C_2-symmetric pyridine *N*-oxides (Schemes 2–4) and the preparation of four pyridine *N*-oxides with oxygen and nitrogen atoms as further coordinating elements in the heterocycle framework is also described (Schemes 5 and 6). All these new compounds have been assessed as organocatalysts in two reactions involving trichlorosilyl compounds: the allylation of aldehydes with allyltrichlorosilane and the opening of *meso*-epoxides by addition of tetrachlorosilane.

2. Results and discussion

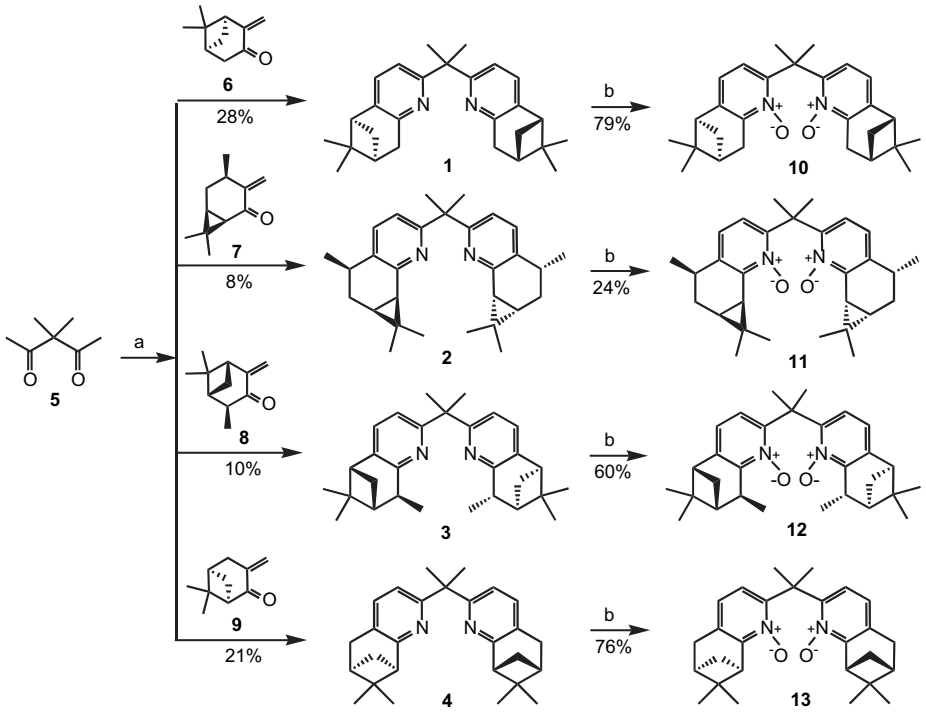
In considering possible synthetic pathways to dipyridylmethane ligands of type **1**–**4**, we decided that the most direct approach to these ligands could have been the tandem one-pot synthesis of the two pyridine rings by a double Michael addition of the dianion of 3,3-dimethylpentane-2,4-dione **5** to an α-methylene ketone, followed by pyrido-anellation of the formed unisolated 1,5-dicarbonyl intermediates. This strategy has been firstly examined in order to prepare the dipyridylmethane **1**.

Thus, the lithium dienolate of the diketone **5**, generated in THF by treatment with lithium diisopropylamide (LDA) at −78 °C for 2 h, was treated at −78 °C with the Michael acceptor (−)-pinocarvone (**6**),[8] obtained in turn from (+)-α-pinene, and the resulting reaction mixture was allowed to slowly reach room temperature. Ammonium acetate and acetic acid were added, THF was then distilled off over a 3 h period and finally, the mixture was heated at 120 °C for 3 h. This one-pot process afforded the dipyridylmethane **1** in 28% yield.

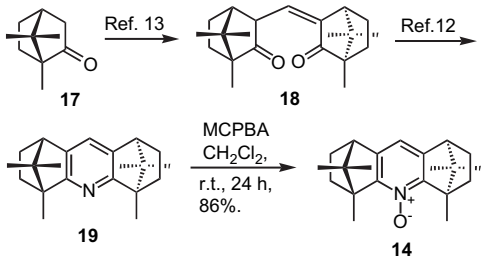
With the desired dipyridylmethane **1** in hand, this protocol was extended to other more sterically hindered α-methylene ketones (Scheme 1). Thus, the application of this protocol to α-methylene ketones **7**,[9] **8**[10] and **9**,[11] obtained from (+)-3-carene, (−)-*iso*-pinocampheol and (+)-α-pinene, afforded the related dipyridylmethanes **2**, **3** and **4** in 8, 10 and 21% yield, respectively (Scheme 1). The overall yield of **1** and **4** was comparable, but it was much lower for the other two ligands **2** and **3**, probably due to the instability of the cyclopropane ring and the steric hindrance of carbonyl groups that determines a reduction of their ability to undergo the aza-anellation step.

It is worth mentioning that although the overall yield of the process is low, this procedure represents a straightforward way to obtain C_2-symmetric dipyridylmethane ligands. Oxidation of **1**–**4** with 3-chloroperbenzoic acid (2.6 equiv) in CH_2Cl_2 at room temperature for 24 h afforded the corresponding *N*,*N*′-dioxides **10**–**13** (24–79% yield) (Scheme 1).

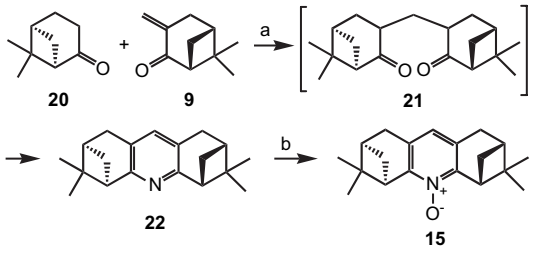
Then, we considered that the synthesis of enantiomerically pure C_2-symmetric pyridine *N*-oxides was worthy of investigation. In fact, although some examples of pyridine *N*-oxides without additional coordinating elements have been reported in organocatalyzed reactions based on trichorosilane reagents, none of them possess C_2-symmetry.[5] Thus, pyridine *N*-oxides **14**, **15** and **16** were prepared (Fig. 2).



Scheme 1. Synthesis of dipyridylmethane ligands **1**–**4** and *N*-oxides **10**–**13**. Reactions: (a) (i) LDA, THF, −78 °C, 2 h, then α-methylene ketone (**2**–**5**), −78 °C to slowly rt, (ii) NH_4OAc, AcOH, THF, reflux, 5 h; (b) MCPBA (2.3 equiv), CH_2Cl_2, rt, 24 h.



Scheme 2. Synthesis of pyridine *N*-oxide **14**.



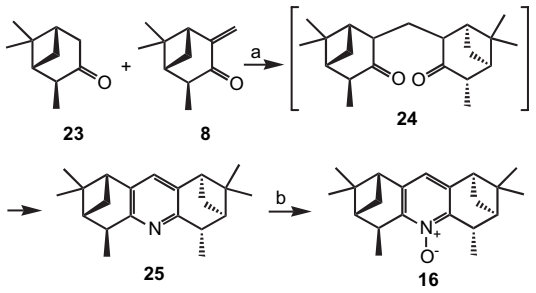
Scheme 3. Synthesis of pyridine *N*-oxide **15**. Reactions: (a) (i) **20**, LDA, THF, −40 °C then 9, −40 °C to rt, (ii) NH_4OAc, AcOH, 70 °C, 3 h, then 120 °C, 3 h, 31% overall; (b) MCPBA, CH_2Cl_2, rt, 24 h, 89%.

The preparation of the C_2-symmetric pyridine *N*-oxide **14** has previously been reported by Kotsuki (Scheme 2).[12] Their synthesis is hinged upon the pyrido-anellation with NH_4OAc and $Cu(OAc)_2$ in propionic acid of the diketone **18** that was in turn obtained by reaction of (+)-camphor **17** with potassium metal in DMF[13] (37% overall yield). The *N*-oxide **14** was finally prepared in 86% yield by oxidation of **19** with MCPBA in CH_2Cl_2.

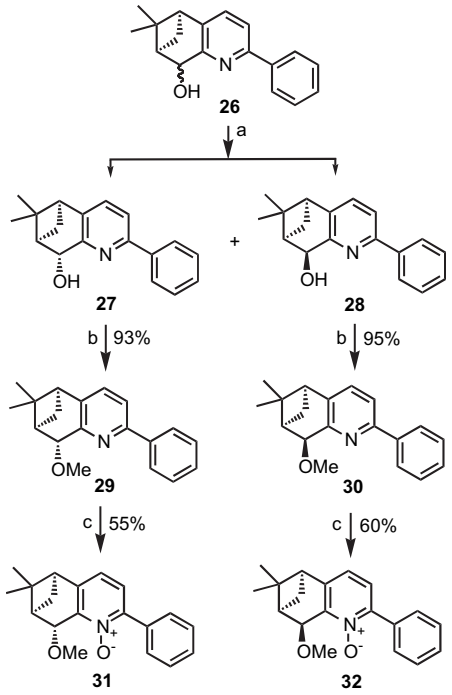
This procedure represents an interesting way to obtain C_2-symmetric pyridines such as **14**, but is restricted to ketones such as camphor **17** with only an α-enolizable position. To overcome these limitations, we have developed a one-pot process that is based on the Michael addition of the enolate of a ketone to an α-methylene ketone, followed by pyrido-anellation of the formed unisolated 1,5-dicarbonyl intermediate. This strategy has firstly been pursued to obtain the pyridine **22** (Scheme 3).

Thus, conjugate addition of the lithium enolate of (+)-nopinone **20**, generated by treatment with LDA at −40 °C for 2 h, with the α-methylene ketone **9** (from −40 °C to room temperature) gave the 1,5-dicarbonyl intermediate **21** that was not isolated, but directly converted into the pyridine **22** (31% overall yield) by treatment with the ammonium acetate/acetic acid system (120 °C, 3 h).

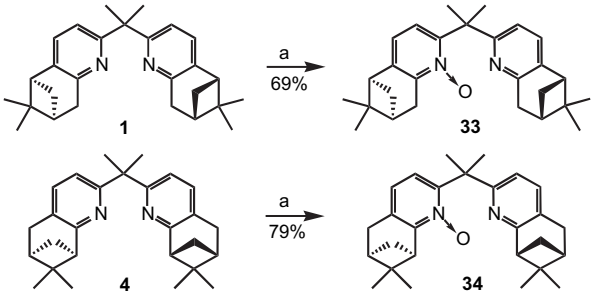
According to this protocol, the pyridine **25** was prepared by reaction of the ketone **23** with the unsaturated ketone **8** (Scheme 4). Unfortunately in this case the yield of **25** was very low (8%). From the pyridines **22** and **25**, the related *N*-oxides **15** and **16**, respectively, were obtained in high yields (89 and 97%) by oxidation with an excess of MCPBA in CH_2Cl_2 (Schemes 3 and 4).



Scheme 4. Synthesis of pyridine *N*-oxide **16**. Reaction: (a) (i) **23**, LDA, THF, −40 °C, then 8, −40 °C to rt, (ii) NH_4AcO, AcOH, 70 °C, 3 h, then 120 °C, 3 h, 8%; (b) MCPBA, CH_2Cl_2, rt, 24 h, 97%.



Scheme 5. Synthesis of pyridine *N*-oxides **31** and **32**. Reactions: (a) chromatographic separation; (b) NaH, THF, rt, then MeI; (c) MCPBA, CH_2Cl_2, rt, 24 h.



Scheme 6. Synthesis of pyridine *N*-oxides **33** and **34**. Reactions: (a) MCPBA (0.2 equiv), CH_2Cl_2, rt, 24 h.

Then, deciding to investigate the catalytic activity of pyridine *N*-oxides bearing an additional coordinating element in the heterocycle framework, the new enantiomerically pure pyridine *N*-oxides **31**,**32** and **33**,**34** with potentially coordinating ethereal oxygen and pyridine nitrogen, respectively, were prepared.

The synthesis of **31** and **32** starts from a 3:1 mixture of the epimeric alcohols **26**, differing in the configuration at C8, that was previously prepared by von Zelewsky[14] (Scheme 5). Careful flash chromatography of **26** gave pure diastereomers **27** and **28**, which were then treated separately with the sodium hydride/methyl iodide system to afford the 8-methoxytetrahydroquinolines **29** and **30** in quantitative yields. Finally, the oxidation of these quinolines

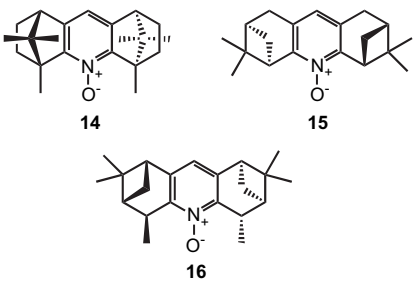


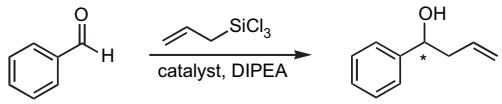
Figure 2. C_2-symmetric pyridine *N*-oxides **14**–**16**.

with an excess of MCPBA in CH_2Cl_2 produced the pyridine *N*-oxides **31** and **32** in 55 and 60% yield, respectively (Scheme 5).

The *N*-monoxide **33** (69% yield) and **34** (79% yield) were also prepared from the parent dipyridylmethane **1** and **4** by oxidation with MCPBA (Scheme 6). However, in this case, in order to increase the selective *N*-monoxide formation, a large excess of dipyridylmethane (5 equiv) with respect to MCPBA (1 equiv) was used and the unconverted starting material and the product were separated by flash chromatography.

The catalytic activity and stereodifferentiating ability of the new pyridine *N*-oxide derivatives were then examined in the allylation of aldehydes[15] and opening of *meso*-epoxides.[16]

Initially, the asymmetric addition of allyltrichlorosilane to benzaldehyde, which is used as a testing ground for new chiral nucleophilic catalysts, was examined (Scheme 7). In a typical procedure, 0.1 mol equiv of catalyst, 1.2 mol equiv of allyltrichlorosilane and 3 mol equiv of DIPEA in acetonitrile were reacted for 48 h at different temperatures. Isolated yields and ees, as determined by HPLC, are collected in Tables 1 and 2. The absolute configuration was assigned to the predominant isomer of the obtained homoallylic alcohol on the basis of its optical rotation.



Scheme 7. Addition of allyltrichlorosilane to benzaldehyde promoted by pyridine *N*-oxides.

First, the catalytic efficiency of pyridine *N*-oxides was investigated and the results are reported in Table 1. The data show clearly that the related pyridine *N*-oxides **14**, **15** and **16** are not good promoters of the addition of allyltrichlorosilane to benzaldehyde at low temperature. The sterically hindered *N*-oxide **14** catalyzed the reaction only at room temperature in fair yield, but no enantioselectivity was observed (entries 1 and 2). Also compound **16** was quite ineffective in promoting the reactions, whereas best results were obtained with catalyst **15** that was able to afford the homoallylic alcohol with 42% ee at −40 °C, albeit low yielding (entry 3). The product was isolated in improved yield and slightly increased enantioselectivity by employing tetrabutylammonium iodide as additive (31% yield and 48% ee), whereas a decrease of the enantioselectivity was produced by running the reaction at 0 °C (entries 4 and 5).

Modest results were also obtained with pyridine *N*-oxides **31** and **32** bearing the methoxy group as a potentially chelating element for the silicon atom (entries 8 and 9). Still more worse results were found with *N*-oxides **33** and **34** bearing a pyridine nitrogen as further coordinating element (entries 10 and 11).

Table 1
Allylation reaction promoted by *N*-oxides **14**–**16**, and **31**–**34**

Entry[a]	Catalyst	Temp (°C)	Yield[b] (%)	ee[c] (%)	Configuration[d]
1	**14**	0	n.r.	—	—
2[d]	**14**	25	65	<5	n.d.
3	**15**	−40	23	42	*S*
4[e]	**15**	−40	31	48	*S*
5[d]	**15**	0	51	37	*S*
6	**16**	−40	n.r	—	—
7[e]	**16**	−40	11	15	*R*
8	**31**	0	21	35	*S*
9	**32**	0	17	12	*R*
10	**33**	0	n.r	—	—
11	**34**	0	21	7	*S*

[a] Typical experimental conditions: 0.1 mol equiv of catalyst, 1.2 mol equiv of allyltrichlorosilane, 3 mol equiv of DIPEA, CH_3CN, 67 h.
[b] Yields of isolated products.
[c] As determined by HPLC on a chiral stationary phase; yields and ee are average of duplicate experiments.
[d] Reaction time: 40 h.
[e] Reaction runs in the presence of 1 mol/equiv of $Bu_4N^+I^-$ as additive.

Table 2
Allylation reaction promoted by *N*,*N*′-dioxides **10**–**13**[a]

Entry	Catalyst	Temp (°C)	Time (h)	Yield[b] (%)	Ee[c] (%)[c]	Configuration[d]
1	**10**	0	72	30	4	*S*
2	**11**	0	72	24	30	*S*
3	**12**	0	72	22	35	*S*
4	**13**	−40	67	37	85	*S*
5	**13**	0	67	58	83	*S*
6	**13**	25	67	97	77	*S*
7[e]	**13**	0	67	98	64	*S*

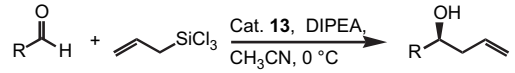
[a] The reaction was carried out at 0.3 mmol scale in CH_3CN (2 ml) with allyl(trichloro)silane (1.2 equiv), catalyst (10 mol %), DIPEA (3 equiv) for 60 h.
[b] Isolated yields after flash chromatography.
[c] Determinated by HPLC on a Chiracel OD column (hexane/isopropanol 95:5; flow rate 0.8 ml/min; λ 220 nm): t_R=10.4 min, t_S=11.3 min.
[d] Assigned by comparison of optical rotation.
[e] Reaction run in CH_2Cl_2.

More interesting results were obtained with dipyridylmethane *N*,*N*′-dioxides **10**–**13**. The data related to the catalytic ability of these catalysts to promote the addition of allyltrichlorosilane to benzaldehyde are collected in Table 2.[7]

Among the C_2-symmetric dipyridylmethane *N*,*N*′-dioxides **10**–**13**, compound **13** performed the reaction much better than its congeners. In fact, already at 0 °C it was able to produce in 58% yield and 83% ee the homoallylic alcohol, the enantiomeric excess of which was increased to 85% by running the allylation at −40 °C. Interestingly, raising the temperature to 25 °C brought about a higher yield (98%) with only a slight decrease of the enantioselectivity (77% ee, entry 6). A solvent change from MeCN to CH_2Cl_2 led to a quantitative yield, but with a negative effect on the enantioselectivity (entry 7 vs 5). Finally, the use of other solvents (toluene, DME and THF) led to lower yields and enantiomeric excesses.

Having identified catalyst **13** as the most efficient one, its use was extended to the addition of allyltrichlorosilane to other aromatic aldehydes (Table 3). The reported data show that ees equal to or greater than 70% and yields constantly higher than 58% could be obtained (entries 1–5).

Table 3
Allylation of aldehydes with allyltrichlorosilane using **13**[a]



Entry	R	Yield[b] (%)	ee[c](%)	Configuration[d]
1	Ph	58	83	*S*
2	*p*-$O_2NC_6H_4$	68	70	*S*
3	*p*-$MeOC_6H_4$	65	80	*S*
4	2-Thiophenyl	60	75	*S*
5	3-Thiophenyl	61	73	*S*
6	Ph–CH=CH	41	18	*S*
7	Ph–CH_2CH_2	46	4	*S*

[a] The reaction was carried out at 0.3 mmol scale in CH_3CN (2 ml) with allyl(trichloro)silane (1.2 equiv), catalyst (10 mol %), DIPEA (3 equiv) at 0 °C for 60 h.
[b] Isolated yields after flash chromatography.
[c] Determinated by HPLC on a chiral column.
[d] Assigned by comparison of optical rotation.

These results show that an electron-withdrawing group at the *para*-position of benzaldehyde exhibits a negative impact on the enantioselectivity (entry 2), whereas the substrate bearing an electron-donating group at the *para*-position does not seem to affect the stereoselectivity (entry 3). Marginal difference in selectivity and yield was observed for the two isomeric thiophene-carboxaldehydes (entries 4 and 5) showing the compatibility of the new

catalyst in the reaction with heteroaromatic systems. Finally, both α,β-unsaturated and saturated aldehydes such as cinnamaldehyde and dihydrocinnamaldehyde, respectively, afforded the corresponding homoallylic alcohols with low enantiomeric excesses (entries 6 and 7).

The results point out, once again, that in the asymmetric allylation of aldehydes with allyltrichlorosilanes the efficiency of the process, for *N*-oxide based catalysts, depends both on the possibility to have a bis-chelation to the silicon centre and on the chelate ring size of silicon in the hypothesized transition state. These considerations stand out comparing a homogeneous series of *N*-monoxides and *N*,*N*′-dioxides derived from bipyridine and dipyridylmethane ligands. Thus, bipyridine *N*-monoxide **35a**[17] (Fig. 3) (87% ee at −40 °C) is more stereoselective than bipyridine *N*,*N*′-dioxide **35b**[17] (41% ee at −90 °C), which is in turn a better catalyst than dipyridylmethane *N*-monoxide **34** (no activity at −40 °C), but less selective than dipyridylmethane *N*,*N*′-dioxide **13** (85% ee at −40 °C) that shows similar selectivity of **35a**. In other words, in the case of bidentate Lewis bases, in the dipyridine series it seems that ligands forming an even-membered chelate ring (**35a** and **13**) are more stereoselective than those generating an odd-membered ring (**35b** and **34**).

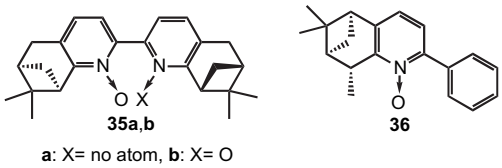


Figure 3. Dipyridine *N*-monoxide **35a**, *N*,*N*′-dioxide **35b** and pyridine *N*-oxide **36**.

Concerning catalysts **31** and **32**, it should be noted these epimers, which differ in the C_8 configuration, behave as pseudoenantiomers. In fact, they give opposite configuration of the allylic alcohol, indicating that the steric control of the reaction depends chiefly on the stereogenic centre bonded to the oxygen, though in the catalyst **32** the other stereocentres are in a mismatching relation with the one in the C_8. Moreover, since catalyst **31** affords the product with the same (*S*)-configuration and similar level of stereodifferentiation (41% ee) of the related *N*-oxide **36**[18] (Fig. 3) in which a methyl group replaces a methoxy group in the C_8, it is likely to exclude with **31** and **32** the involvement of silicon coordination by the methoxy group in the reaction course.

On the basis of these observations and previous studies from other groups on *O*-based bidentate ligands,[15] a possible transition state model **C** compatible with the stereoselection observed for the new organocatalysts such as **13** is proposed in Figure 4, as a working hypothesis for future studies.

While the enantioselective allylation of aldehydes with allylchlorosilanes is the reaction that has most exploited pyridine *N*-oxide derivatives as chiral catalysts, the ring opening of *meso*-epoxides has received much less attention.[5] In fact only a few catalysts, shown in Figure 5, have been used in this process.[19]

On this basis, the new pyridine and dipyridine *N*-oxides were tested as metal-free catalysts in the ring opening of *meso*-epoxides

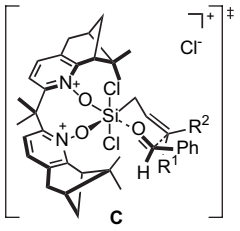


Figure 4. Proposed transition state for allylation catalyzed by **13**.

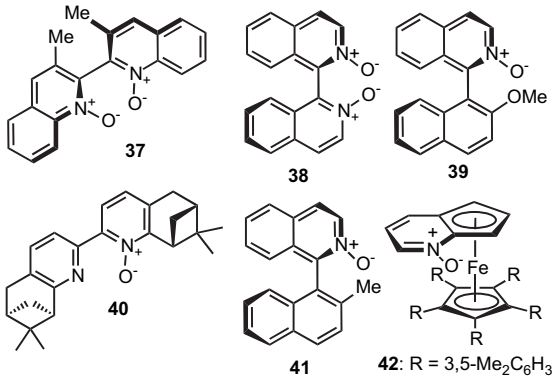
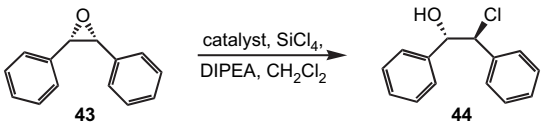


Figure 5. Pyridine *N*-oxide derivatives used in opening of *meso*-epoxides.

by addition of tetrachlorosilane in CH_2Cl_2. In particular, as a model for the evaluation of catalytic activity of all new *N*-oxides, the opening of *cis*-stilbene oxide was examined (Scheme 8). The reaction was performed at −78 °C in the presence of DIPEA, to give the corresponding chlorohydrin **44**[20] in yields and enantioselectivities, which are reported in Table 4.



Scheme 8. Enantioselective opening of *cis*-stilbene oxide.

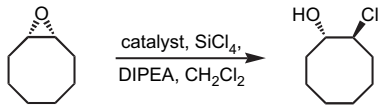
Pyridine *N*-oxides **14**–**16** gave **44** in high yield, but with poor enantioselectivity (entries 1–3). Also for this transformation compound **17** gave better results than its congeners, affording the product with the modest asymmetric induction of 37% ee (entry 2).

Table 4
Ring opening of *cis*-stilbene oxide by addition of tetrachlorosilane

Entry[a]	Catalyst	Yield[b] (%)	ee[c] (%)
1	**14**	77	<5
2	**15**	83	37
3	**16**	95	<5
4	**33**	50	<5
5	**34**	47	<5
6	**10**	100	<5
7	**11**	71	7
8	**12**	100	70
9	**13**	91	38
10[d]	**12**	100	67
11[e]	**12**	91	37

[a] Typical experimental conditions: 0.1 mol equiv of catalyst, 1 mol equiv of tetrachlorosilane, and 3 mol equiv of DIPEA, CH_2Cl_2, −78 °C, 18 h.
[b] Yields of isolated products.
[c] As determined by HPLC on a chiral stationary phase; yields and ee are average of duplicate experiments.
[d] Reaction runs with 20% mol/equiv of catalyst.
[e] Reaction runs in the presence of proton sponge as a base.

Catalysts **33** and **34** gave acceptable yields of the chlorohydrin **44** (47–50%), which however showed to be in both cases a racemic compound (entries 4 and 5). These results were very disappointing, considering that the pyridine *N*-oxide **40**, differing from **34** by a carbon spacer between the two pyridine rings, produced the opening of cyclooctene epoxide **45** to the corresponding chlorohydrin **46** in 85% ee (Scheme 9), although this catalyst was considerably less efficient with other substrate types.[21] Once again it appears that the chelate ring size of silicon plays a basic role in determining the efficiency of the process.



45 46

Scheme 9. Enantioselective opening of cyclooctene epoxide.

Contrasting results were obtained with dipyridine *N*,*N*′-dioxides **10**–**13**. In fact, while all catalysts effected the transformation with excellent yields, only compound **12** showed to be a moderately effective stereodifferentiating catalyst, affording the chlorohydrin **44** in quantitative yield and 70% ee after 18 h at −78 °C in CH_2Cl_2 (entries 8). Unfortunately, any attempt to improve the stereochemical efficiency of **12** by increasing the catalyst loading or by changing the base did not lead to any positive effect (entries 10 and 11).

Having determined that compound **12** was the best catalyst in the opening of *cis*-stilbene oxide, its ability to promote the cleavage of cyclooctene epoxide with $SiCl_4$ was also examined. The related chlorohydrin was obtained in 52% yield and 40% ee after 20 h at −20 °C.

3. Conclusion

In conclusion, a successful approach to the synthesis of enantiomerically pure C_2-symmetric dipyridylmethane ligands is described. Full experimental details for their preparation and that of the related *N*,*N*′-dioxides are reported. A procedure for the synthesis of a few new enantiomerically pure C_2-symmetric pyridine *N*-oxides and the preparation of four pyridine *N*-oxides with oxygen and nitrogen atoms as further coordinating elements in the heterocycle framework are also described. All compounds were prepared from naturally occurring monoterpenes.

These new compounds have been assessed as organocatalysts in two different reactions involving trichlorosilyl compounds. In the allylation of benzaldehyde with allyltrichlorosilane the corresponding homoallylic alcohol has been obtained in modest to good yields and up to 85% ee. In the ring opening of *cis*-stilbene oxide by addition of tetrachlorosilane at −78 °C, the corresponding chlorohydrin has been obtained in generally very high yield and enantioselectivity up to 70%. It has been demonstrated that in both reactions, *N*,*N*′-dioxide derivatives act, without a doubt, better than the corresponding mono *N*-oxide or other prepared pyridine *N*-oxide derivatives.

4. Experimental

4.1. General methods

TLC was performed on Merck silica gel 60 TLC plates F_{254} and visualized using UV or phosphomolibdic acid. Flash chromatography was carried out on silica gel (230–400 mesh).

All reagents and solvents were purchased from Aldrich and used as-received. Low boiling petroleum ether was the fraction collected between 40 and 60 °C. THF was distilled from sodium-benzophenone ketyl and degassed thoroughly with dry nitrogen directly before use. Melting points were determined on a Büchi 510 capillary apparatus and are uncorrected. The NMR spectra were obtained with a Varian VXR-300 spectrometer at 300 for ^1H and 75.4 MHz for ^{13}C. Chemical shifts are reported in parts per million downfield from internal Me_4Si in $CDCl_3$. Optical rotations were measured with a Perkin–Elmer 241 polarimeter in a 1 dm tube. Elemental analyses were performed on a Perkin–Elmer 240B analyser.

3,3-Dimethylpentane-2,4-dione **5** was prepared from pentane-2,4-dione.[22] (−)-Pinocarvone **6** was obtained by oxidation of (+)-α-pinene (98% pure, 91% ee by GLC, Aldrich).[8] (1*R*,4*S*)-1,7,7-Trimethyl-3-methylenebicyclo[2.2.1]heptan-2-one **7**, (1*R*,4*S*,5*R*)-4,6,6-trimethyl-2-methylenebicyclo[3.1.1]heptan-3-one **8** and (1*R*,5*R*)-6,6-dimethyl-3-methylenebicyclo[3.1.1]heptan-2-one **9** were prepared from (+)-3-carene,[9] (−)-*iso*-pinocampheol (98% pure, 95% ee by GLC, Aldrich),[10] and (−)-β-pinene (99% pure, Aldrich),[11] respectively.

(5*S*,7*R*,8*R*)- and (5*S*,7*R*,8*S*)-2-Phenyl-8-hydroxy-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinoline (**27** and **28**, respectively) were prepared as a mixture of epimers at C8[12] and then obtained as pure diastereomers by flash chromatography (petroleum ether/ethyl acetate=85/15).

4.2. Synthesis of the pyridine ligands

*4.2.1. 2-Bis[(5R,5R)-5,7-methano-7,7-dimethyl-5,6,7,8-tetrahydroquinolin-2-yl]propane **1***

A solution of 3,3-dimethylpentan-2,4-dione (1.410 g, 11.0 mmol) in anhydrous THF (6 ml) was added dropwise at a cooled (−78 °C) solution of lithium diisopropylamide (22.0 mmol) in anhydrous THF (44 ml). The resulting solution was stirred at −78 °C for 2 h and then a solution of (−)-pinocarvone **6** (0.71 g, 0.01 mol) in THF (3 ml) was added dropwise at −78 °C. After 15 min at −78 °C, the solution was allowed to reach slowly room temperature (overnight) and then poured into a mixture of ammonium acetate (8.5 g, 0.11 mol) and acetic acid (33 ml). The flask was connected with a distillation head and the THF was distilled off over a 3 h period and then the mixture was heated at 120 °C for 3 h. Most part of the acetic acid was removed under reduced pressure and the residue was taken up with H_2O (500 ml) and extracted with ethyl ether (3×50 ml). The organic phase was separated and extracted with 10% HCl (3×20 ml). The acid phase was basified with 10% NaOH solution and then extracted with ethyl ether (3×50 ml). The organic phase was dried on anhydrous Na_2SO_4, the solvent was evaporated and the residue was purified by flash chromatography (petroleum ether/ethyl acetate=98/2) to give **1**: 1.08 g (28%); mp 161 °C; $[\alpha]_D^{20}$ +63.2 (*c* 1.1, $CHCl_3$); ^1H NMR: δ 7.04 (d, 2H, *J*=7.8 Hz), 6.73 (d, 2H, *J*=7.8 Hz), 3.07 (d, 4H, *J*=2.7 Hz), 2.72–2.60 (m, 4H), 2.40–2.30 (m, 2H), 1.77 (s, 6H), 1.38 (s, 6H), 1.27 (d, 2H, *J*=8.8 Hz), 0.63 (s, 6H). ^{13}C NMR: δ 165.1, 155.1, 138.1, 132.7, 117.7, 47.4, 46.0, 40.3, 39.4, 36.6, 31.9, 28.9, 26.0, 21.3. Anal. Calcd for $C_{27}H_{34}N_2$: C, 83.89; H, 8.87; N, 7.75. Found: C, 83.99; H, 8.84; N, 7.77.

*4.2.2. 2-Bis[(5R,7R,8S)-7,8-methano-5,9,9-trimethyl-5,6,7,8-tetrahydroquinolin-2-yl]propane **2***

Following the above procedure using (1*R*,4*R*,6*S*)-4,7,7-trimethyl-3-methylenebicyclo[4.1.0]heptan-2-one, compound **2** was obtained and purified by flash chromatography (petroleum ether/ethyl acetate=8/2) oil; 0.45 (8%); $[\alpha]_D^{20}$ −26.5 (*c* 0.61, $CHCl_3$); ^1H NMR: δ 7.26 (d, 2H, *J*=6 Hz), 6.78 (d, 2H, *J*=6 Hz), 2.92–2.81 (m, 2H), 2.21–2.13 (m, 2H), 1.80 (d, 2H, *J*=6.3 Hz), 1.77 (s, 6H), 1.36–1.22 (m, 4H), 1.23 (s, 6H), 1.19 (d, 6H, *J*=5.4 Hz), 0.62 (s, 6H). ^{13}C NMR: δ 164.7, 155.4, 134.8, 131.3, 118.4, 47.2, 32.3, 30.3, 28.7, 28.1, 27.0, 23.7, 23.0, 18.1, 16.3. Anal. Calcd for $C_{29}H_{38}N_2$: C, 84.01; H, 9.24; N, 6.76. Found: C, 84.00; H, 9.26; N, 6.75.

*4.2.3. 2-Bis[(5R,7R,8S)-5,7-methano-6,6,8-trimethyl-5,6,7,8-tetrahydroquinolin-2-yl]propane **3***

Following the above procedure using (1*R*,2*S*,5*R*)-2,6,6-trimethyl-4-methylenebicyclo[3.1.1]heptan-3-one, compound **3** was obtained and purified by flash chromatography (petroleum ether/ethyl acetate=98/2) oil; 0.80 g (10%); $[\alpha]_D^{20}$ −11.9 (*c* 1.2, $CHCl_3$); ^1H NMR: δ 7.00 (d, 2H, *J*=7.8 Hz), 6.73 (d, 2H, *J*=7.8 Hz), 3.18–3.08 (m, 2H), 2.70–2.63 (m, 2H), 2.54–2.44 (m, 2H), 2.14–2.07 (m, 2H), 1.79 (s, 6H), 1.39 (s, 6H), 1.33 (d, 6H, *J*=7.2 Hz), 1.27 (d, 2H, *J*=9.6 Hz), 0.64 (s, 6H). ^{13}C NMR: δ 165.0, 158.8, 137.9, 132.3, 117.7, 47.6, 46.8, 46.7, 41.3, 38.8, 28.7, 26.3, 20.9, 18.2. Anal. Calcd for $C_{29}H_{38}N_2$: C, 84.01; H, 9.24; N, 6.76. Found: C, 84.12; H, 9.21; N, 6.73.

4.2.4. 2-Bis[(6R,8R)-6,8-methano-7,7-dimethyl-5,6,7,8-tetrahydroquinolin-2-yl]propane **4**

Following the above procedure using (1*R*,5*R*)-6,6-dimethyl-3-methylenebicyclo[3.1.1]heptan-2-one, compound **4** was obtained after flash chromatography (petroleum ether/ethyl acetate=98/2), 0.89 (21%), mp 136–137 °C; $[\alpha]_D^{20}$ −44.4 (*c* 1.2, $CHCl_3$); ^{1}H NMR: *δ* 7.23 (d, 2H, *J*=7.8 Hz), 6.80 (d, 2H, *J*=7.8 Hz), 2.96 (t, 2H, *J*=5.7 Hz), 2.87 (d, 4H, *J*=2.4 Hz), 2.72–2.62 (m, 2H), 2.32–2.24 (m, 2H), 1.75 (s, 6H), 1.40 (s, 6H), 1.28 (d, 2H, *J*=6.9 Hz), 0.65 (s, 6H). ^{13}C NMR: *δ* 164.6, 163.7, 134.8, 126.4, 118.8, 50.3, 47.3, 40.2, 39.0, 30.9, 28.8, 26.0, 21.1. Anal. Calcd for $C_{27}H_{34}N_2$: C, 83.89; H, 8.87; N, 7.75. Found: C, 83.75; H, 8.85; N, 7.73.

4.2.5. (2R,4R,5R,7R)-Bis(2,4,5,7-methano)-3,3,6,6-tetramethyl-1,2,3,4,5,6,7,8-octahydroacridine **22**

A solution of (+)-nopinone (1,38 g, 0.01 mol) in anhydrous THF (3 ml) was added dropwise at a cooled (−40 °C) solution of lithium diisopropylamide (10.0 mmol) in anhydrous THF (50 ml). The resulting solution was stirred at −40 °C for 2 h and then a solution of (1*R*,5*R*)-6,6-dimethyl-3-methylenebicyclo[3.1.1]heptan-2-one **9** (0.01 mol) in THF (3 ml) was added dropwise at −40 °C. After 15 min at −40 °C, the solution was allowed to reach slowly room temperature (overnight) and then poured into a mixture of ammonium acetate (7.71 g, 0.10 mol) and acetic acid (30 ml). The flask was connected with a distillation head and THF was distilled off over a 3 h period and then the mixture was heated at 120 °C for 3 h. Most part of the acetic acid was removed under reduced pressure and the residue was taken up with H_2O (500 ml) and extracted with ethyl ether (3×50 ml). The organic phase was separated and extracted with 10% HCl (3×20 ml). The acid phase was basified with 10% NaOH solution and then extracted with ethyl ether (3×50 ml). The organic phase was dried on anhydrous Na_2SO_4, the solvent was evaporated and the residue was purified by flash chromatography (petroleum ether/ethyl acetate=9/1) to give **22**: 0.80 g (31%); mp 197–198 °C; $[\alpha]_D^{25}$ −52.7 (*c* 0.11, $CHCl_3$); ^{1}H NMR: *δ* 7.16 (s, 1H), 2.93–2.84 (m, 6H), 2.72–2.61 (m, 2H), 2.33–2.25 (m, 2H), 1.39 (s, 6H), 1.29 (d, 2H, *J*=9.6 Hz), 0.68 (s, 6H). ^{13}C NMR: *δ* 161.5, 134.8, 126.9, 49.9, 40.2, 39.2, 31.0, 31.0, 26.1, 21.2. Anal. Calcd for $C_{19}H_{25}N$: C, 85.34; H, 9.42; N, 5.24. Found: C, 85.30; H, 9.44; N, 5.26.

4.2.6. (1R,3S,4R,5R,6S,8R)-Bis(1,3,6,8-methano)-2,2,4,5,7,7-hexamethyl-1,2,3,4,5,6,7,8-octahydroacridine **25**

Following the above procedure and using (1*R*,2*S*,5*S*)-2,6,6-trimethylbicyclo[3.1.1]heptan-3-one and (1*R*,2*S*,5*R*)-2,6,6-trimethyl-4-methylenebicyclo[3.1.1]heptan-3-one, the tetrahydroquinoline **25** was obtained: 140 mg (8%); mp 85–86 °C; $[\alpha]_D^{25}$ +13.5 (*c* 0.72, $CHCl_3$); ^{1}H NMR: *δ* 6.66 (s, 1H), 3.13–3.03 (m, 2H), 2.64–2.58 (t, 2H, *J*=5.4 Hz), 2.52–2.40 (m, 2H), 2.13–2.06 (m, 2H), 1.38 (s, 6H), 1.35 (s, 6H), 1.29 (d, 2H, *J*=9.6 Hz), 0.62 (s, 6H). ^{13}C NMR: *δ* 157.0, 137.6, 130.0, 47.1, 46.9, 41.3, 38.3, 28.8, 26.4, 21.1, 18.5. Anal. Calcd for $C_{21}H_{29}N$: C, 85.37; H, 9.89; N, 4.74. Found: C, 85.33; H, 9.90; N, 4.77.

4.2.7. (5S,7R,8R)-2-Phenyl-8-hydroxy-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinoline **27**

Mp 122–123 °C; $[\alpha]_D^{20}$ +5.15 (*c* 0.93, $CHCl_3$); ^{1}H NMR: *δ* 8.00 (d, 2H, *J*=7.2 Hz), 7.54–7.34 (m, 5H), 5.03 (d, 1H, *J*=3.3 Hz), 3.19 (broad, 1H), 2.83 (t, 1H), 2.68–2.61 (m, 1H), 2.56–2.51 (m, 1H), 1.58 (d, 1H, *J*=9.9 Hz), 1.44 (s, 3H), 0.76 (s, 3H). ^{13}C NMR: *δ* 157.2, 154.9, 139.6, 139.2, 133.6, 128.4, 128.3, 126.6, 118.8, 71.3, 46.5, 45.5, 44.7, 29.5, 26.4, 20.8. Anal. Calcd for $C_{18}H_{19}NO$: C, 81.47; H, 7.22; N, 5.28. Found: C, 81.55; H, 7.24; N, 5.27.

4.2.8. (5S,7R,8S)-2-Phenyl-8-hydroxy-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinoline **28**

Mp 109–110 °C; $[\alpha]_D^{20}$ +135.9 (*c* 0.72, $CHCl_3$); ^{1}H NMR: *δ* 8.00 (d, 2H, *J*=7.2 Hz), 7.54–7.34 (m, 5H), 4.96 (d, 1H, *J*=3.3 Hz), 3.19 (broad, 1H), 2.83 (t, 1H), 2.68–2.61 (m, 1H), 2.56–2.51 (m, 1H), 1.58 (d, 1H, *J*=9.9 Hz), 1.44 (s, 3H), 0.70 (s,3H). ^{13}C NMR:*δ* 158.1, 154.9, 139.3, 154.9, 139.3, 139.1, 133.5, 126.4, 128.3, 126.6, 118.6, 74.0, 46.8, 46.2, 40.3, 33.9, 26.6, 23.0. Anal. Calcd for $C_{18}H_{19}NO$: C, 81.47; H, 7.22; N, 5.28. Found: C, 81.53; H, 7.21; N, 5.24.

4.2.9. (5S,7R,8R)-2-Phenyl-8-methoxy-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinoline **29**

Sodium hydride (0.022 g, 0.91 mmol) was cautiously added to a cooled (0 °C) solution of (5*S*,7*R*,8*R*)-2-phenyl-8-hydroxy-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinoline (0.133 g, 0.5 mmol) in THF (12 ml). After 1 h was added CH_3I (0.063 ml, 0.143 g, 1.0 mmol) at 0 °C and the resulting mixture was stirred at 0 °C for 2 h. Water was added and the organic phase was separated and the aqueous was extracted with Et_2O (3×10 ml). The combined organic phase was dried on anhydrous Na_2SO_4, the solvent was evaporated and the residue was purified by flash chromatography (petroleum ether/ethyl acetate=8/2) to give **29**: 113 mg (93%); $[\alpha]_D^{25}$ +96.2 (*c* 0.11, $CHCl_3$); ^{1}H NMR: *δ* 8.03 (d, 2H, *J*=6.9 Hz), 7.51 (d, 1H, *J*=7.8 Hz) 7.48–7.33 (m, 3H), 7.30 (d, 1H, *J*=7.8 Hz), 4.62 (d, 1H, *J*=3.0 Hz) 2.79–2.60 (m, 4H), 1.46 (s, 3H), 0.82 (s, 3H). ^{13}C NMR: *δ* 156.70, 155.0, 139.7, 139.6, 133.5, 128.5, 128.3, 126.7, 118.4, 83.4, 59.3, 47.0, 44.8, 40.3, 34.4, 26.7, 23.2. Anal. Calcd for $C_{19}H_{21}NO$: C, 81.68; H, 7.58; N, 5.01. Found: C, 81.70; H, 9.38; N, 4.55.

4.2.10. (5S,7R,8S)-2-Phenyl-8-methoxy-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinoline **30**

Starting from (5*S*,7*R*,8*S*)-2-phenyl-8-hydroxy-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinoline and following the above procedure, the tetrahydroquinoline **30** was obtained: 132 mg (95%); $[\alpha]_D^{25}$ +26.8 (*c* 0.13, $CHCl_3$); ^{1}H NMR: *δ* 8.02 (d, 2H, *J*=7.2 Hz), 7.51 (d, 1H, *J*=7.8 Hz), 7.48–7.32 (m, 3H), 7.29 (d, 1H, *J*=8.1 Hz), 4.52 (d, 1H, *J*=2.7 Hz), 3.84 (s, 3H), 2.77 (t, 1H, 6 Hz), 2.63–2.54 (m, 2H), 1.70–1.65 (m, 1H), 1.45 (s, 3H), 0.64 (s, 3H). ^{13}C NMR: *δ* 156.0, 155.0, 139.7, 139.5, 128.5, 128.3, 126.7, 118.6, 80.6, 58.8, 46.5, 45.2, 44.3, 29.5, 26.5, 20.9. Anal. Calcd for $C_{19}H_{21}NO$: C, 81.68; H, 7.58; N, 5.01. Found: C, 81.70; H, 9.38; N, 4.55.

4.3. General procedure for the preparation of *N*-oxides

3-Chloroperbenzoic acid (0.61 mmol) was added portion-wise to a solution of the proper pyridine derivative (0.47 mmol) in CH_2Cl_2 (10 ml). After 24 h stirring at room temperature, the reaction mixture was washed successively with saturated $NaHCO_3$ (3×8 ml) and brine (10 ml). The aqueous phase was extracted with CH_2Cl_2 (3×10 ml) and the combined organic phase was dried on anhydrous Na_2SO_4, the solvent was evaporated and the residue was purified by flash chromatography (ethyl acetate) to give *N*-oxides.

4.3.1. (1S,4R,5R,8S)-Bis(1,4,5,8-methano)-4,5,11,11,12,12-hexamethyl-1,2,3,4,5,6,7,8-octahydroacridine N-oxide **14**

Compound **14** was obtained from octahydroacridine **19** and purified by flash chromatography using ethyl acetate: 126 mg (86%); mp 190–191 °C; $[\alpha]_D^{25}$ −2.9 (*c* 0.69, MeOH); ^{1}H NMR: *δ* 0.67 (s, 6H), 0.91 (s, 6H), 1.09 (ddd, 2H, *J*=12.7, 9.0, 3.9 Hz), 1.55 (ddd, 2H, *J*=12.9, 9.0, 3.9 Hz), 1.66 (s, 6H), 1.83 (ddd, 2H, *J*=12.9, 9.8, 3.9 Hz), 2.08 (ddt, 2H, *J*=12.7, 9.8, 3.9 Hz), 2.76 (d, 2H, *J*=3.9 Hz), 6.89 (s, 1H). Anal. Calcd for $C_{21}H_{29}NO$: C, 80.98; H, 9.38; N, 4.50. Found: C, 80.96; H, 9.40; N, 4.54.

4.3.2. (2R,4R,5R,7R)-Bis(2,4,5,7-methano)-3,3,6,6-tetramethyl-1,2,3,4,5,6,7,8-octahydroacridine N-oxide **15**

Compound **15** was obtained from octahydroacridine **22** and purified by flash chromatography using ethyl acetate: 65 mg (89%); mp 234–235 °C; $[\alpha]_D^{25}$ −14.4 (*c* 0.62, $CHCl_3$); ^{1}H NMR: *δ* 6.84 (s, 1H), 4.02 (t, 2H, *J*=5.4 Hz), 2.91 (s, 4H), 2.76–2.65 (m, 2H), 2.31–2.24 (m,

2H), 1.44 (s, 6H), 1.25 (d, 2H, J=9.9 Hz), 0.72 (s, 6H). ^{13}C NMR: δ 152.4, 129.4, 125.4, 40.1, 39.8, 39.1, 31.3, 30.4, 25.8, 21.3. Anal. Calcd for $C_{19}H_{25}NO$: C, 80.52; H, 8.89; N, 4.94. Found: C, 80.55; H, 8.84; N, 4.95.

4.3.3. (1R,3S,4R,5R,6S,8R)-Bis(1,3,6,8-methano)-2,2,4,5,7,7-hexamethyl-1,2,3,4,5,6,7,8-octahydroacridine N-oxide **16**

Compound **16** was obtained from octahydroacridine **25** and purified by flash chromatography using ethyl acetate: 142 mg (97%); foam solid; $[\alpha]_D^{25}$ +25.9 (c 0.14, $CHCl_3$); ^{1}H NMR: δ 6.51 (s, 1H), 3.35–3.38 (dd, 2H, J=6.6, 3.0 Hz), 2.65–2.70 (t, 2H, J=5.7 Hz), 2.47–2.54 (m, 2H), 2.11–2.18 (m, 2H), 1.53 (d, 6H, J=6.6 Hz), 1.44 (s, 2H), 1.39 (s, 6H), 0.61 (s, 6H). ^{13}C NMR: δ 147.0, 141.7, 121.6, 47.6, 46.5, 41.5, 34.5, 28.2, 25.8, 20.5, 15.7. Anal. Calcd for $C_{21}H_{29}NO$: C, 80.98; H, 9.38; N, 4.50. Found: C, 80.92; H, 9.39; N, 4.56.

4.3.4. (5S,7R,8S)-2-Phenyl-8-methoxy-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinoline N-oxide **31**

Compound **31** was obtained from octahydroacridine **29** and purified by flash chromatography using petroleum ether/ethyl acetate=4/6: 77 mg (55%); foam solid; $[\alpha]_D^{25}$ +161.3 (c 0.23, $CHCl_3$); ^{1}H NMR: δ 7.78 (dd, 2H, J=8.1, 1.8 Hz), 7.24 (d, 1H, J=7.8 Hz), 6.91 (d, 1H, J=7.8 Hz), 4.68 (d, 1H, J=2.4 Hz), 3.71 (s, 3H), 2.81 (t, 1H, J=5.7), 2.64–2.54 (m, 2H), 1.47 (s, 3H), 1.80–1.72 (m, 1H), 0.67 (s, 3H). ^{13}C NMR: δ 148.1, 145.2, 144.3, 133.2, 129.5, 128.9, 120.0, 125.5, 122.5, 76.6, 59.0, 46.3, 45.8, 43.5, 29.4, 26.2, 20.7. Anal. Calcd for $C_{19}H_{21}NO_2$: C, 77.26; H, 7.17; N, 4.74. Found: C, 77.25; H, 7.18; N, 4.74.

4.3.5. (5S,7R,8R)-2-Phenyl-8-methoxy-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinoline N-oxide **32**

Compound **32** was obtained from octahydroacridine **30** and purified by flash chromatography using petroleum/ethyl acetate=4/6: 83 mg (60%); mp 167–169 °C; $[\alpha]_D^{25}$ +98.5 (c 0.61, $CHCl_3$); ^{1}H NMR: δ 7.78 (dd, 2H, J=8.1,1.8 Hz), 7.50–7.38 (m, 3H), 7.23 (d, 1H, J=7.8 Hz), 6.92 (d, 1H, J=7.8 Hz), 4.75 (d, 1H, J=3 Hz), 3.69 (s, 3H), 2.80–2.65 (m, 3H), 1.47 (s, 3H), 1.33 (d, 1H, J=8.7 Hz), 1.80–1.72 (m, 1H), 0.95 (s, 3H). ^{13}C NMR: δ 144.2, 145.7, 144.7, 133.3, 129.6, 128.9, 128.0, 125.3, 122.3, 79.4, 59.1, 47.1, 44.0, 40.6, 34.5, 26.7, 23.4. Anal. Calcd for $C_{19}H_{21}NO_2$: C, 77.26; H, 7.17; N, 4.74. Found: C, 77.25; H, 7.18; N, 4.74.

4.3.6. 2-Bis[(5S,7S)-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinolin-2-yl]propane N-oxide **33**

The above procedure was followed starting from **1**, but using a large excess of **1** (5 equiv) with respect to MCPBA was used. The unconverted starting material **1** and **33** were recovered by flash chromatography: 130 mg (69%); foam solid; $[\alpha]_D^{25}$ −37.5 (c 0.52, $CHCl_3$); ^{1}H NMR: δ 7.28 (d, 1H, J=7.5 Hz), 7.09 (d, 1H, J=7.8 Hz), 6.88 (d, 1H, J=7.5 Hz), 6.86 (d, 1H, J=7.8 Hz), 3.16–2.56 (m, 6H), 2.39–2.30 (m, 2H), 2.30–2.22 (m, 2H), 1.86 (s, 3H), 1.77 (s, 3H), 1.38 (s, 3H), 1.35 (s, 3H), 1.34–1.18 (m, 2H), 0.63 (s, 3H), 0.59 (s, 3H). ^{13}C NMR: δ 163.2, 154.9, 154.8, 146.5, 142.6, 137.6, 132.9, 121.8, 120.7, 115.2, 65.7, 45.9, 45.7, 45.2, 39.4, 39.2, 39.1, 36.4, 31.7, 31.2, 30.8, 27.6, 25.9, 25.7, 25.5, 21.1, 20.8. Anal. Calcd for $C_{27}H_{34}N_2O$: C, 80.55; H, 8.51; N, 6.96. Found: C, 80.50; H, 8.53; N, 6.97.

4.3.7. 2-Bis[(6R,8R)-6,8-methano-7,7-dimethyl-5,6,7,8-tetrahydroquinolin-2-yl]propane N-oxide **34**

The above procedure was followed starting from **9**, but using a large excess of **4** (5 equiv) with respect to MCPBA was used. The unconverted starting material **4** and **34** were recovered by flash chromatography: 149 mg (79%); mp 85–90 °C; $[\alpha]_D^{25}$ +35.7 (c 0.83, $CHCl_3$); ^{1}H NMR: δ 7.31 (d, 1H, J=3.9 Hz), 7.28 (d, 1H, J=3.3 Hz), 7.05 (d, 1H, J=8.1 Hz), 6.98 (d, 1H, J=7.8 Hz), 3.90 (t, 1H, J=5.4 Hz), 2.94 (s, 2H), 2.85 (s, 2H), 2.73 (t, 1H, J=11.1 Hz), 2.61–2.52 (m, 2H), 2.28–2.21 (m, 2H), 1.84 (s, 3H), 1.72 (s, 3H), 1.37 (s, 3H), 1.33 (s, 3H), 1.18–1.31 (m, 2H), 0.63 (s, 3H), 0.58 (s, 3H). ^{13}C NMR: δ 164.4, 161.8, 156.1, 154.4, 135.1, 131.0, 125.9, 124.5, 120.7, 116.1, 50.0, 45.3, 40.2, 40.0, 39.7, 39.0, 38.9, 31.2, 30.9, 30.6, 30.2, 28.1, 26.0, 25.7, 25.3, 21.0, 21.0. Anal. Calcd for $C_{27}H_{34}N_2O$: C, 80.55; H, 8.51; N, 6.96. Found: C, 80.50; H, 8.52; N, 6.98.

4.4. General procedure for the preparation of *N,N′*-dioxides

3-Chloroperbenzoic acid (0.13 mmol) was added portion-wise to a solution of the proper dipyridylmethane (0.5 mmol) in CH_2Cl_2 (10 ml). After 24 h stirring at room temperature, the reaction mixture was washed successively with saturated $NaHCO_3$ (3×8 ml) and brine (10 ml). The aqueous phase was extracted with CH_2Cl_2 (3×10 ml) and the combined organic phase was dried on anhydrous Na_2SO_4, the solvent was evaporated and the residue was purified by flash chromatography (ethyl acetate) to give *N,N′*-dioxides.

4.4.1. 2-Bis[(5S,7S)-5,7-methano-6,6-dimethyl-5,6,7,8-tetrahydroquinolin-2-yl]propane N,N′-dioxide **10**

Compound **10** was obtained starting from **1**: 0.165 g (79%); mp 202–205 °C; $[\alpha]_D^{25}$ −7.28 (c 0.11, $CHCl_3$); ^{1}H NMR: δ 7.31 (d, 2H, J=8.1 Hz), 6.89 (d, 2H, J=8.1 Hz), 2.89 (dq, 4H, J=18.9, 2.7 Hz), 2.73 (t, 2H, J=5.4 Hz), 2.63–2.53 (m, 2H), 2.36–2.28 (m, 2H), 1.89 (s, 6H), 1.37 (s, 6H), 1.36–1.18 (m, 2H), 0.62 (s, 6H). ^{13}C NMR: δ 153.9, 145.2, 141.6, 123.2, 119.5, 45.6, 41.9, 39.3, 39.2, 31.1, 30.7, 25.7, 24.4, 20.8. Anal. Calcd for $C_{27}H_{34}N_2O_2$: C, 77.48; H, 8.19; N, 6.69. Found: C, 77.51; H, 8.16; N, 6.66.

4.4.2. 2-Bis[(5R,7R,8S)-7,8-methano-5,9,9-trimethyl-5,6,7,8-tetrahydroquinolin-2-yl]propane N,N′-dioxide **11**

Compound **11** was obtained starting from **2**: 53.5 mg (24%); mp 94–97 °C; $[\alpha]_D^{25}$ +151.2 (c 0.36, $CHCl_3$); ^{1}H NMR: δ 7.34 (d, 2H, J=8.4 Hz), 7.11 (d, 2H, J=8.4 Hz), 2.89–2.74 (m, 2H), 2.28–2.08 (m, 4H), 1.80 (s, 6H), 1.39–1.26 (m, 4H), 1.25 (d, 6H, J=6.6 Hz), 1.22 (s, 6H), 0.62 (s, 6H). ^{13}C NMR: δ 153.8, 147.5, 138.4, 121.7, 118.9, 89.0, 41.8, 32.2, 29.8, 27.5, 24.7, 24.0, 23.2, 22.4, 18.0, 15.1. Anal. Calcd for $C_{29}H_{38}N_2O_2$: C, 77.99; H, 8.58; N, 6.27. Found: C, 77.82; H, 8.57; N, 6.25.

4.4.3. 2-Bis[(5R,7R,8S)-5,7-methano-6,6,8-trimethyl-tetrahydroquinolin-2-yl]propane N,N′-dioxide **12**

Compound **12** was obtained starting from **3**: 0.134 g (60%); mp 185–188 °C; $[\alpha]_D^{25}$ +91.9 (c 0.43, $CHCl_3$); ^{1}H NMR: δ 7.23 (d, 2H, J=8.1 Hz), 6.86 (d, 2H, J=8.1 Hz), 3.23–3.09 (m, 2H), 2.71 (t, 2H, J=5.7), 2.52–2.40 (m, 2H), 2.10–2.01 (m, 2H), 1.84 (s, 6H), 1.41 (m, 2H), 1.37 (s, 6H), 1.22 (d, 6H, J=6.6 Hz), 0.58 (s, 6H). ^{13}C NMR: δ 155.1, 148.2, 141.1, 123.1, 118.5, 47.1, 46.4, 41.8, 41.4, 34.3, 28.1, 25.8, 25.0, 20.4, 14.1. Anal. Calcd for $C_{29}H_{38}N_2O_2$: C, 77.99; H, 8.58; N, 6.27. Found: C, 77.98; H, 8.58; N, 6.28.

4.4.4. 2-Bis[(6R,8R)-6,8-methano-7,7-dimethyl-5,6,7,8-tetrahydroquinolin-2-yl]propane N,N′-dioxide **13**

Compound **13** was obtained starting from **4**: 159 mg (76%); mp 82–84 °C; $[\alpha]_D^{25}$ −35.9 (c 0.22, $CHCl_3$); ^{1}H NMR: δ 7.33 (d, 2H, J=8.1 Hz), 7.06 (d, 2H, J=8.1 Hz), 3.83 (t, 2H, J=2.7 Hz), 2.90 (dq, 4H, J=17.1, 2.7 Hz), 2.66–2.54 (m, 2H), 2.27–2.18 (m, 2H), 1.88 (s, 6H), 1.36 (s, 6H), 1.80 (s, 2H), 0.63 (s, 6H). ^{13}C NMR: δ 158.1, 154.9, 153.5, 130.0, 125.7, 120.0, 42.5, 40.1, 39.9, 39.0, 31.2, 29.9, 25.7, 24.3, 21.0. Anal. Calcd for $C_{27}H_{34}N_2O_2$: C, 77.48; H, 8.19; N, 6.69. Found: C, 77.50; H, 8.15; N, 6.68.

4.5. General procedure for the allylation reaction

To a stirred solution of catalyst (0.03 mmol) in acetonitrile (2 ml) kept under nitrogen, an aldehyde (0.3 mmol) and diisopropylethylamine (0.154 ml, 0.9 mmol) were added in this order. The mixture was then cooled to 0 °C and allyl(trichloro)silane

(0.054 ml, 0.36 mmol) was added dropwise by means of a syringe. After 48 h stirring at 0 °C the reaction was quenched by the addition of a saturated aqueous solution of $NaHCO_3$ (1 ml). The mixture was allowed to warm-up to room temperature and water (2 ml) and AcOEt (5 ml) were added. The organic phase was separated and dried over Na_2SO_4, filtered, and concentrated under vacuum at room temperature to afford the crude products. These were purified by flash chromatography with different hexanes/AcOEt mixtures as eluants. Yield and ee are indicated in the tables.

4.5.1. 1-Phenyl-3-buten-1-ol

This product was purified with a hexanes/AcOEt 90:10 mixture as eluant. The enantiomeric excess was determined by HPLC on a Chiracel OD column (hexane/isopropanol 95:5; flow rate 0.8 ml/min; λ 220 nm): t_R=10.4 min, t_S=11.3 min.

4.5.2. 1-(4-Methylphenyl)-3-buten-1-ol

This product was purified with a hexanes/AcOEt 90:10 mixture as eluant. The enantiomeric excess was determined by HPLC on a Chiracel OD column (hexane/isopropanol 99:1; flow rate 0.8 ml/min; λ 220 nm): t_R=26.3 min, t_S=25.0 min.

4.5.3. 1-(4-Nitrophenyl)-3-buten-1-ol

This product was purified with a hexanes/AcOEt 80:20 mixture as eluant. The enantiomeric excess was determined by HPLC on a Chiralpak AD column (hexane/isopropanol 97:3; flow rate 0.8 ml/min; λ 220 nm): t_R=31.9 min, t_S=34.7 min.

4.5.4. 1-(2-Thienyl)-3-buten-1-ol

This product was purified with DCM as eluant. The enantiomeric excess was determined by HPLC on a Chiracel OD column (hexane/isopropanol 90:10; flow rate 0.8 ml/min; λ 230 nm): t_R=7.1 min, t_S=7.7 min.

4.5.5. 1-(3-Thienyl)-3-buten-1-ol

This product was purified with a hexanes/AcOEt 60:40 mixture as eluant. The enantiomeric excess was determined by HPLC on a Chiracel OD column (hexane/isopropanol 95:5; flow rate 0.8 ml/min; λ 220 nm): t_R=11.1 min, t_S=14.1 min.

4.5.6. (E)-1-Phenyl-1,5-hexadien-3-ol

This product was purified with a hexanes/AcOEt 90:10 mixture as eluant. The ee was determined by HPLC on a Chiracel OD column (hexane/isopropanol 99:1; flow rate 0.8 ml/min; λ 220 nm): t_R=10.3 min, t_S=16.1 min.

4.5.7. 1-Phenyl-5-hexen-3-ol

This product was purified with a hexanes/AcOEt 80:20 mixture as eluant. The enantiomeric excess was determined by HPLC on a Chiracel OD column (hexane/isopropanol 95:5; flow rate 0.8 ml/min; λ 210 nm): t_R=10.7 min, t_S=15.8 min.

4.6. General procedure for the epoxide opening reaction

To a stirred solution of catalyst (0.03 mmol) in CH_2Cl_2 (2 ml) kept under nitrogen, stilbene epoxide or cyclooctene epoxide (0.3 mmol) and diisopropylethylamine (0.154 ml, 0.9 mmol) were added in this order. The mixture was then cooled to −78 °C and tetrachlorosilane (0.3 mmol) was added dropwise by means of a syringe. After 12 h stirring at −78 °C the reaction was quenched by the addition of a saturated aqueous solution of $NaHCO_3$ (1 ml). The mixture was allowed to warm-up to room temperature and water (2 ml) and AcOEt (5 ml) were added. The organic phase was separated and dried over Na_2SO_4, filtered, and concentrated under vacuum at room temperature to afford the crude chlorohydrin that was finally purified by flash chromatography with different hexanes/AcOEt mixtures as eluants. Yield and ee are indicated in the tables.

*4.6.1. Chlorohydrin **44***

This product was purified with a hexanes/AcOEt 90:10 mixture as eluant. The enantiomeric excess was determined by HPLC on a Chiralpak AD column (hexane/isopropanol 97:3; flow rate 0.8 ml/min; λ 220 nm): t_{minor}=24.8 min, t_{major}=26.1 min.

*4.6.2. Chlorohydrin **46***

This product was purified with a hexanes/AcOEt 90:10 mixture as eluant. The enantiomeric excess was determined on the trifluoroacetate derivative by GC on chiral stationary phase (Agilent HP-chiral) t_{minor}=31.0 min, t_{major}=32.2 min.

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