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Ruthenium–Lewis Acid Catalyzed Asymmetric Diels–Alder Reactions between Dienes and α,β-Unsaturated Ketones

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Abstract: The complex [Ru(Cp)(*R*,*R*-BIPHOP-F)(acetone)][SbF_6], (*R*,*R*)-**1a**, was used as catalyst for asymmetric Diels–Alder reactions between dienes (cyclopentadiene, methylcyclopentadiene, isoprene, 2,3-dimethylbutadiene) and α,β-unsaturated ketones (methyl vinyl ketone (MVK), ethyl vinyl ketone, divinyl ketone, α-bromovinyl methyl ketone and α-chlorovinyl methyl ketone). The cycloaddition products were obtained in yields of 50–90% and with enantioselectivities up to 96% *ee*. Ethyl vinyl ketone, divinyl ketone and the halogenated vinyl ketones worked best and their reactions with acyclic dienes consistently provided products with >90% *ee*. α-Chlorovinyl methyl ketone performed better than α-bromovinyl methyl ketone. The reaction also provided a [4.3.1]bicyclic ring system in 95% *ee* through an intramolecular cycloaddition reaction. Crystal structure determinations of [Ru(Cp)((*S*,*S*)-BIPHOP-F)(mvk)][SbF_6], (*S*,*S*)-**1b**, and [Ru(Cp)((*R*,*R*)-Me_4BIPHOP-F)(acrolein)][SbF_6], (*R*,*R*)-**2b**, provided the basis for a rationalization of the asymmetric induction.

Keywords: asymmetric catalysis · Diels–Alder reactions · dienophiles · Lewis acids · ruthenium

Introduction

There has been considerable interest over the last decade in developing asymmetric catalysts based on transition metal Lewis acids for reactions such as the Diels–Alder reaction. This field of research has been initiated more than twenty years ago by Koga and co-workers who reported the first asymmetric Diels–Alder reactions catalyzed by a metal-centered Lewis acid.[1] The chiral alkoxy dichloride compounds could catalyze Diels–Alder reactions of cyclopentadiene with dienophiles such as acrolein and methacrolein with 25% *ee* (*endo*) in the case of acrolein and >66% *ee* (*exo*) in the case of methacrolein.

These cycloadditions have since become the benchmark reactions for testing one-point binding Lewis acid catalysts. Many subsequent publications have reported high enantioselectivity and diastereoselectivity in these and similar reactions;[2–5] for reviews see references [6–9]. Generally the catalysts promote cycloadditions by enhancing the electron-withdrawing capacity of the carbonyl group in the α,β-unsaturated enal dienophile, thereby lowering the LUMO energy.

Following our reports on highly enantioselective, recyclable ruthenium–Lewis acid catalysts[3,10,11] we have turned our attention towards extension of the substrate scope to enantioselective Diels–Alder reactions and initiated a study focusing on vinyl ketone dienophiles instead of enals. While it is possible to transform an aldehyde cycloadduct into the corresponding ketone via alkylation and oxidation this adds two steps which can be problematic if the stereogenic center α-to-the-carbonyl is subject to epimerisation under basic conditions. Conversion of an enantiopure aldehyde (prepared by an asymmetric Diels–Alder reaction) to a methyl ketone function was used by Corey in the total synthesis of gibberellic acid.[12]

There have been reports in the literature where organotungsten[13] and organoscandium[14] catalysts have been used in (racemic) cycloadditions of dienophiles such as methyl vinyl ketone and ethyl vinyl ketone with simple acyclic

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dienes such as 2,3-dimethylbutadiene and isoprene. Keto-dienophiles are less active reaction partners in the Diels–Alder reaction than their enal analogues. This is presumably the reason why these systems have been of interest in the field of diene activation by dihapto-coordination of a poorly reactive diene such as 1,3-cyclohexadiene. This concept was originally reported by Welker,[15] and a recent example by Harman[16] utilizes a diene–Mo complex to promote stepwise cycloadditions with dienophiles such as ethyl vinyl ketone with and without BF_3•Et_2O to activate the dienophile partner. In the context of our study, a more relevant example was reported by Hersh[17] who used [Fe(cyclopentadiene)$(CO)_2$(thf)][BF_4] to catalyze Diels–Alder reactions such as the reaction between methyl vinyl ketone and cyclopentadiene. This monocationic iron(II) complex with a cyclopentadiene roof, two monodentate ligands and a labile coordination site had served as a model in our early studies on chiral Fe- and Ru–Lewis acids and thus an asymmetric vinyl ketone Diels–Alder reaction presented an appropriate challenge.

For a successful asymmetric cycloaddition, the catalyst must be able to control the orientation of the ketone in the chiral binding site and to block one enantiotopic face of the alkene, thus directing the approach of the diene to the other face. By minimizing the $A_{1,3}$ strain, enals bind Lewis acids selectively *trans* to the C(O)–C_α bond. This differentiation between the two possible ketone coordination geometries is largely lost with ketones—the two coordination orientations being very similar sterically and electronically. Stereocontrol is thus hard to achieve with a single site Lewis acid catalyst. In addition, ketones coordinate to metals more weakly than aldehydes so the degree of activation for the Diels–Alder reaction is lower.

There are examples of asymmetric Diels–Alder reactions with vinyl ketone dienophiles: MacMillan[18] reported an elegant solution by using chiral amine organocatalysts which form chiral iminium ions with ketone dienophiles such as ethyl vinyl ketone. Steric factors controlled the orientation of the ethyl and vinyl groups and one face of diene attack was blocked by the catalyst. It represents the most extensive study into ketone dienophile cycloadditions with the catalyst working well with vinyl and crotyl ketones with cyclopentadiene, cyclic ketones with cyclopentadiene and also EVK with substituted butadienes—giving cycloadducts in >90% *ee* in most cases. Some computational details of these reactions have recently been published by Gordillo.[19] More recently Corey and Hawkins were able to catalyze asymmetric Diels–Alder reactions with a ketone as the dienophile using boron based Lewis acids.[20–22]

To the best of our knowledge there are no examples of asymmetric Diels–Alder reactions of this type catalyzed by a chiral transition metal Lewis acid. Herein we detail our results obtained with catalyst [Ru(cyclopentadiene)(*R*,*R*-BIPHOP-F)(acetone)][SbF_6] (**1a**) (Figure 1).

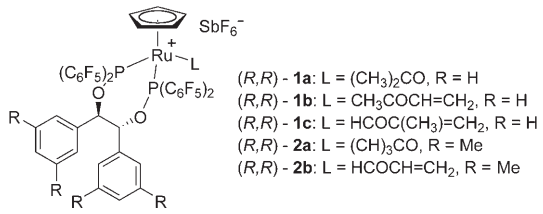


Figure 1. Single-site Ru Lewis acid catalysts.

Results and Discussion

Initial findings: We started by probing the coordination of methyl vinyl ketone (MVK) to catalyst **1a**. This was done by triturating **1a** three times with MVK to afford **1b** as a crystalline material. An X-ray crystal structure determination was carried out and the result is shown in Figure 2.

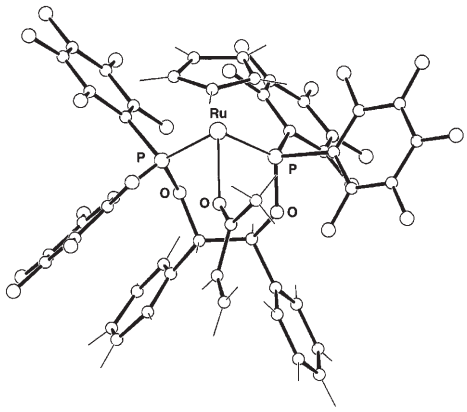
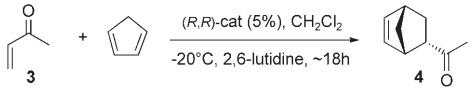


Figure 2. Crystal structure of (*S*,*S*)-**1b**.

MVK is coordinated in an *anti*-s-*trans* conformation as has been found previously for methacrolein in complex (*S*,*S*)-**1c**. The Ru–O bond length (2.176 Å) in **1b** is slightly longer than that found in **1c**[3] (2.160 Å).

All catalysis studies detailed in this article were conducted by using the *R*,*R* enantiomer of catalyst **1a**; however, since our previous crystallographic data for **1c** referred to the *S*,*S* enantiomer, for ease of comparison, the crystal structure solved is that of (*S*,*S*)-**1b**. We began with the Diels–Alder reaction of cyclopentadiene and methyl vinyl ketone (**3**) (Scheme 1) and used the procedure previously described for the analogous enal reactions.[3] With a little optimization using catalyst (*R*,*R*)-**1a**, it was established that 1.5 equivalents of cyclopentadiene gave complete conversion (calculated using GC analysis with an internal standard) within



catalyst **1a** : 91% *endo*, 99% conversion, 32% *ee*
catalyst **2a** : 93% *endo*, 48% conversion, 28% *ee*

Scheme 1. Catalyzed Diels–Alder reaction of MVK with cyclopentadiene.

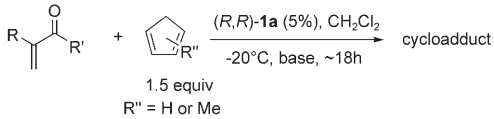
24 h (1 equiv gave incomplete conversion after 25 h, 5 equiv gave complete conversion but slightly lower *ee*). As an increase in the concentration of diene improved the conversion, this would suggest that the cycloaddition is the rate-limiting step. The *ee* obtained was only modest (32% *ee*); however, the use of the more selective catalyst **2a** for the Diels–Alder reaction of cyclopentadiene and methacrolein[10] proved unsuccessful as the catalyst was less active.

Diels–Alder reactions with cyclopentadienes: Cyclopentadiene and methylcyclopentadiene reacted rapidly with vinyl ketone dienophiles in the presence of an acid catalyst at ambient temperature. The cycloadditions of catalyst **1a** performed with cyclopentadiene dienes are summarized in Table 1. These reactions were performed at −20°C in the presence of a catalytic amount of 2,6-lutidine or 2,6-tBu$_2$-pyridine (halogenated dienophiles) to remove traces of Brønsted acid which would catalyze racemic cycloadditions. The bulky pyridines do not coordinate to **1a**. All *ee* values given herein are average values over two catalysis experiments which were in good agreement; the respective yields are given as one GC yield (where the reaction was sampled) and one isolated yield.

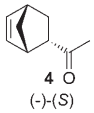
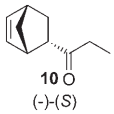
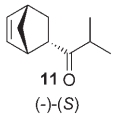
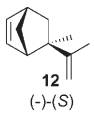
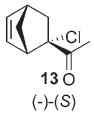
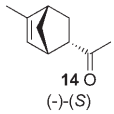
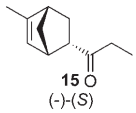
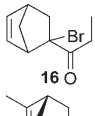
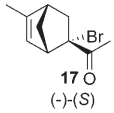
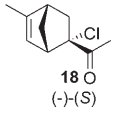
The use of **5** instead of **3** as the dienophile resulted in a promising increase in *ee* and the isolated yield was slightly higher possibly due to the product being slightly less volatile. The *ee* values obtained for **4** and **14** are unremarkable compared with the *ee* value obtained by Hawkins[21] (81% for **4** and 83% for **14**) and Corey[22] (99% for **4**). Increases in *ee* were also observed moving from cyclopentadiene to methylcyclopentadiene. Cycloadduct **15** was obtained in an excellent 93% *ee* with the isomer shown representing 86% of the isomeric mixture. Indeed, the ethyl ketones are more useful compounds than the methyl ketones because of the potential for performing diastereoselective aldol reactions.[23–25] Compound **6** reacted with cyclopentadiene under these reaction conditions but the *ee* value was miserable; this problem was also encountered by Hawkins who obtained **11** in 16% *ee*.

When we investigated α-halogenated dienophiles **7** and **8** we observed much higher enantioselectivities for cycloadditions with both cyclopentadiene and methylcyclopentadiene although the diastereoselectivities and regioselectivities were rather poor. Examples with cyclopentadiene gave only slightly better diastereoselectivities than the selectivity observed for the Brønsted acid catalyzed reaction (*exo*/*endo* 3:2). With methylcyclopentadiene, the major isomer, as shown in Table 1, was present in about 50% which is an improvement of the natural selectivity of the reaction although the *endo* product and the 5-Me isomers were also observed. Only traces of the 2-Me and 3-Me isomers of **17** and **18** were observed which prompted us to examine other monofunctional cyclopentadienes. Indeed **17** resembles an intermediate (99% *ee* from the Diels–Alder reaction of the related aldehyde) in Corey's gibberellic acid synthesis, though with a less functional side chain on the cyclopentadiene. The cycloaddition product was subsequently converted into a fused five- and six-membered ring system via a Cope rearrangement.[12]

Table 1. Diels–Alder reactions of ketone dienophiles with cyclopentadiene and methylcyclopentadiene.



3: R = H, R' = Me
5: R = H, R' = Et
6: R = H, R' = *i*Pr
7: R = Br, R' = Me
8: R = Cl, R' = Me
9: R = Br, R' = Et

Product	Conversion [%]	Yield [%]	*endo* [%]	*exo* [%]	*ee* [%]
 **4** O (-)-(*S*)	99	72	91	–	30
 **10** O (-)-(*S*)	98	80	94	–	47
 **11** O (-)-(*S*)	75	69	91	–	7
 **12** (-)-(*S*)	99	87	–	75	77
 **13** O (-)-(*S*)	100	84	–	71	88
 **14** O (-)-(*S*)	100	83	85	–	60
 **15** O (-)-(*S*)	100	89	86	–	93
 **16** O	75	63	–	58	0
 **17** O (-)-(*S*)	100	99	–	50	70
 **18** O (-)-(*S*)	100	92	–	51	85

Since compound **5** proved to be a better substrate than **3**, compound **9** was also used as a dienophile with cyclopentadiene to give **16**. In this case the cycloadduct formed was racemic and polymerized side product was observed at the end of the reaction. The only explanation for the stark dif-

ference between the formation of **12** and **16** is that when bound to the catalyst **7** easily adopts a planar conformation in the chiral pocket whereas **9** is unable to adopt a completely planar conformation, though a non-planar conformation with the ethyl group twisted ≈90° is possible (Figure 3). In this conformation the ethyl group is pointing in the direction of the diene trajectory. This factor could explain the failure of the cycloaddition with **9** as the dienophile.

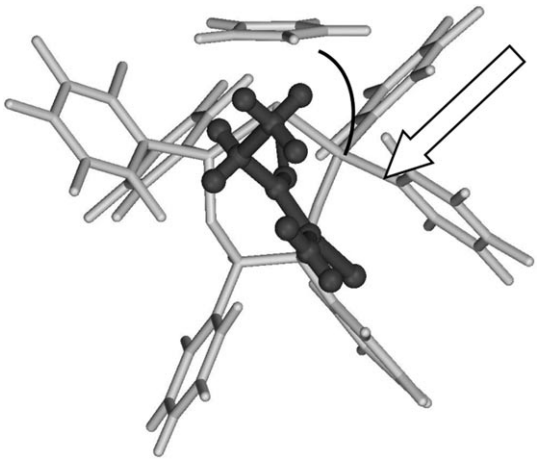
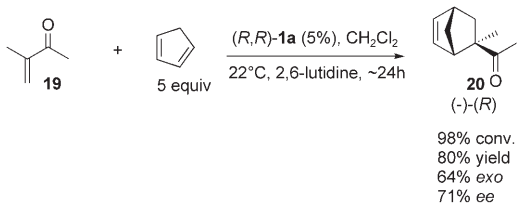


Figure 3. Model of ethyl vinyl ketone coordinated to [CpRu((*R*,*R*)-BIPHOP-F)]$^+$. It shows that the ethyl group hinders the approach of a dieneophile (trajectory indicated by the arrow)

Curiously, though α-bromoacrolein has been widely used as a dienophile in both catalysis and synthesis, α-chloroacrolein appears only three times in Diels–Alder reactions in the literature.[12,26,27] In our hands **8** gave higher *ee* values than **7** presumably because this diene is slightly less reactive and hence the reaction is more enantioselective. When the catalyst was recovered from these reactions a considerable amount of [Ru(cyclopentadiene)(BIPHOP-F)Br] or [Ru(cyclopentadiene)(BIPHOP-F)Cl] was present (usually more than 50% by ^{31}P NMR). As noted in our previous publication[3] the catalyst becomes poisoned by halide abstraction from the product cycloadduct. In these cases complete poisoning of the catalyst was not observed probably because the halide in the product is sterically hindered. Though this is undesirable in the catalysis reaction it is possible to recover the catalyst from the halide complexes by halide abstraction with $AgSbF_6$.

With dienophile **19** (Scheme 2) we observed no conversion under our standard reaction conditions. This is probably a result of the added steric hindrance which reduces the ability of the catalyst to activate the dienophile as the coordination is likely to be poor. However, when this catalysis was performed at ambient temperature with 5 equiv of diene present, complete conversion was observed and good *ee* (71%) of the product (a substantial amount of cyclopentadiene dimerized under these conditions (GC analysis)). The diastereoselectivity of the reaction was similar to the literature precedent by Yamamoto.[28] These products are readily separable by column chromatography. The *endo* product had an *ee* of 60%.

Compound *rac*-**20** has found use in the synthesis of tetrahydrocyclopentathiopyrans by conversion to the thio ketone and retro-Claisen rearrangement.[29]



Scheme 2. Diels–Alder reaction of α-MeMVK with cyclopentadiene.

Stereochemical assignments: Literature absolute configurations quoted by Hawkins[21] for **4** and **11** originate from a paper by Nakazaki[30] who used data reported by Berson[31] for carboxynorbonenes. For these compounds the *S-endo* enantiomer is (−). Corey[22] assigned the absolute configuration of **10** to (−)-*S-endo* by analogy to the corresponding aldehyde which was assigned by Koga.[1] From these data it was possible to assign the absolute configurations of **14** and **15** by using [α] values and CD spectra.

The halogenated products and **20** have not been reported previously. It was therefore necessary to prepare authentic samples of **12** and **20** from the corresponding aldehydes (MeLi addition followed by PCC oxidation), which in turn were prepared by our procedure.[3] Comparison of these authentic samples with samples of **12** and **20** prepared directly by catalysis revealed that the enal catalysis gives the product with the same absolute configuration as the ketone reaction (*R*,*R* catalyst **1a** gives (−)-(*S*)-*exo* cycloadduct **12** and (−)-(*R*)-*exo* cycloadduct **20**). Again, comparison of [α] values and CD spectra demonstrated that this also applies to **13**, **17** and **18**.

When we compared the absolute configuration of products obtained for **3** and **5** as the dienophiles with the corresponding aldehyde reaction (acrolein and cyclopentadiene) we observed a surprising result. Here, the aldehyde reaction gave the (+)-*R endo* product[10] but the ketone reactions afforded the (−)-(*S*)-*endo* products with catalyst (*R*,*R*)-**1a**. This is especially interesting because when we superimposed the crystal structure data for complexes with acrolein ((*R*,*R*)-**2b**-green) and MVK ((*R*,*R*)-**1b**-red) coordinated to Ru, while the orientations of the dienophile are very similar (Figure 4). Note that for **1b** the (*S*,*S*)-enantiomer (X-ray structure) was inverted to show the (*R*,*R*)-enantiomer

The key feature of these crystal structures is that methyl vinyl ketone is bound with the same orientation as that found for aldehydes: an *anti* s-*trans* arrangement for both acrolein and methacrolein.[3] The olefin Cα-*Re* face is blocked by the catalyst. The methyl vinyl ketone is pushed down by the catalyst cyclopentadiene roof and the Cα-*Si* face view the olefin is slightly less accessible compared with

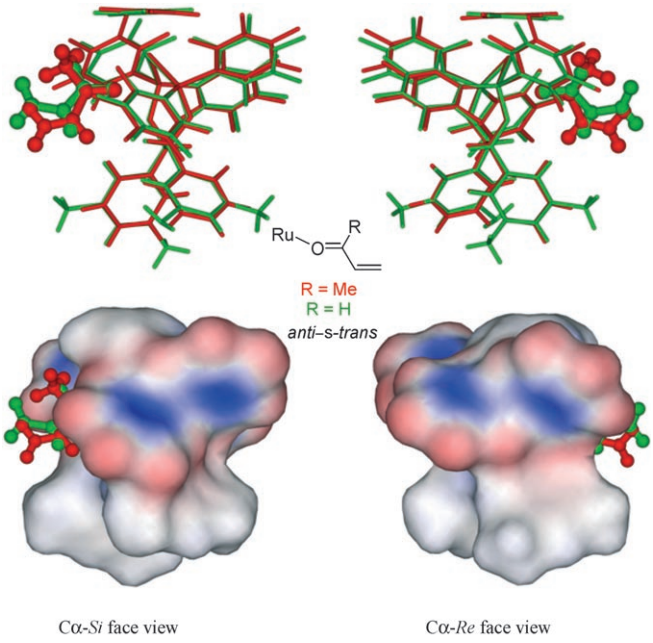


Figure 4. Comparison of surface filled crystal structures of superimposed complexes **1b** and **2b**.

the coordinated enals. The (−)-(*S*)-*endo* product configuration implies a diene addition to the Cα-*Re* face. The methyl vinyl ketone conformation observed in the crystal structure makes this impossible. The shape of the chiral site also makes a diene addition to methyl vinyl ketone in an *anti*–s-*cis* conformation unlikely. A *syn*–s-*trans* coordination mode, as modeled in Figure 5, is feasible; however, it is conceivable that this could be the active species in the catalysis. Here, the Cα-*Re* face is quite accessible.

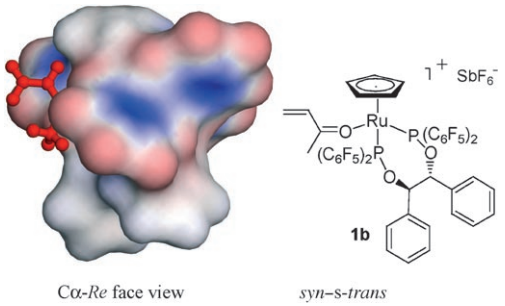


Figure 5. Model of the crystal structure of **1b** with MVK rotated by 180°.

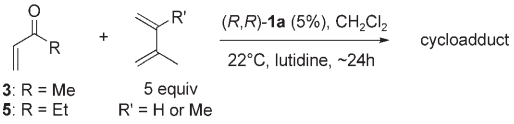
Rotation about the methyl vinyl ketone C=O axis in the catalyst site is not possible and it would thus appear that methyl vinyl ketone coordinates (and dissociates) in either orientation, where with the orientation shown in Figure 5, appears to be the one that reacts preferentially.

If the catalyst is indeed working as well in some cases (e.g. **15** with 93% *ee*) in the "upside-down" dienophile coordination mode, it illustrates the effectiveness of the control that can be gained in the chiral pocket of the catalyst. It may also be the reason that some of these reactions have quite poor stereocontrol (e.g. with MVK as the dienophile). The cycloadditions with halogenated dienophiles and **19** presumably worked consistently better because the catalyst is working in the usual binding mode.

Diels–Alder reactions with acyclic dienes: We also investigated some examples of Diels–Alder reactions with the acyclic dienes 2,3-dimethylbutadiene and isoprene. Using the standard reaction conditions established with cyclopentadiene as the diene we observed no conversion for **3** and **5** as the dienophile and very poor conversions for **7** and **8**. It was therefore necessary to make a few changes to the reaction conditions.

With **3** and **5** as dienophiles, the increase in the amount of diene to 5 equiv and performance of the reaction at ambient temperature improved the conversion though we were unable to get these reactions to go to completion in most cases (Table 2). Again, **5** was a much better dienophile in

Table 2. Diels–Alder reactions of ketone dienophiles and acyclic dienes.



3: R = Me
5: R = Et
5 equiv
R' = H or Me

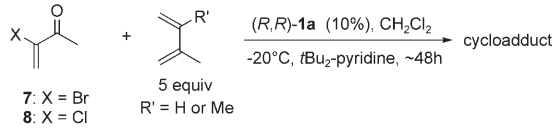
Product	Conversion [%]	Yield [%]	1,4 Isomer [%]	*ee* [%]
21 (-)-(*S*)	67	55		60
22 (-)-(*S*)	99	76		91
23 (-)-(*S*)	54	47	86	46
24 (-)-(*S*)	65	61	91	92

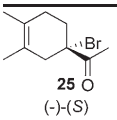
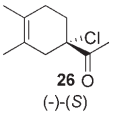
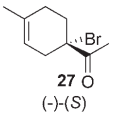
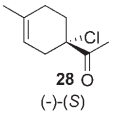
terms of enantioselectivity and in both cases the *ee* was above 90%. Corey[20] had previously reported **22** in 80% *ee* (87% yield) and MacMillan[18] obtained **24** in 85% *ee* (79% yield) so here the Ru catalyst system outperforms the literature catalysts in terms of *ee* though the yields are lower. The absolute stereochemistry of the compounds in Table 2 have been reported previously (except **21**); **23** has been prepared from (−)-limonene,[32] **22** was assigned by Corey[20] by analogy to **10** and MacMillan[18] prepared an authentic sample of **24** from the corresponding chiral aldehyde.

For the halogenated dienophiles the problem was again catalyst poisoning by the product. In these cases it was not possible to raise the temperature of the reaction because

poisoning of the catalyst increased faster than the reaction rate. We therefore resorted to using 5 equiv of diene and 10 mol% catalyst to compensate for the loss of catalyst during the reaction. Even so, during the reaction all of the catalyst was converted into the corresponding halide (confirmed by ^{31}P NMR). The results obtained for these reactions are summarized in Table 3.

Table 3. Diels–Alder reactions of halogenated ketone dienophiles and acyclic dienes.



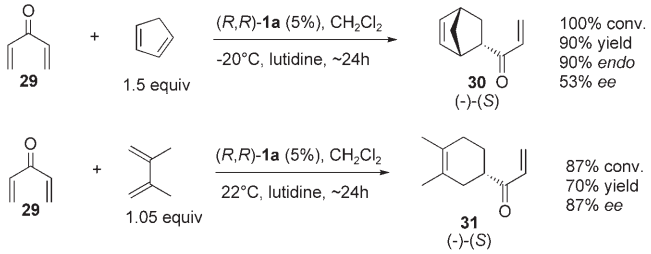
Product	Conversion [%]	Yield [%]	1,4 Isomer [%]	*ee* [%]
 **25** (-)-(*S*)	95	72		90
 **26** (-)-(*S*)	71	69		91
 **27** (-)-(*S*)	71	62	99	94
 **28** (-)-(*S*)	74	62	99	96

In all of the reported examples the *ee* was >90% and the conversion was good when considering that we are loosing 10% of the product through reaction with the catalyst. An increase in *ee* was again observed when moving from **7** to **8** though the yields were lower with **8**.

No literature data of the absolute configuration of the products were available, so that it was necessary to prepare authentic samples of **25** and **27** from the corresponding chiral aldehyde (which was again prepared by using catalyst **1a** as previously published).[3,33] Again, the other cycloadducts **26** and **28** were assigned by using [α] values and CD spectra as also being (−)-(*S*) in configuration. As expected, this implies that the catalyst is operating in its usual mode, that is, with the dienophile methyl group oriented towards the cyclopentadiene roof.

Diels–Alder reactions with divinyl ketone as the dienophile: Another interesting dienophile we examined is divinyl ketone (**29**). Diels–Alder reactions with **29** have been reported by Winker[34] who reacted this dienophile with aliphatic sulphonalene dienes to yield the mono-Diels–Alder cycloadduct. SO_2 extrusion led to a second Diels–Alder reaction affording a tricyclic product.

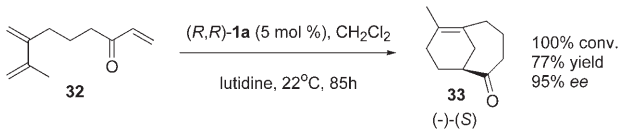
With **29** as the dienophile we used the conditions we had established for cycloadditions with ethyl vinyl ketone **5**. These conditions were effective for preparing **30** but not for **31** because we observed the formation of bis(dimethylcyclohexyl) ketone with 5 equiv of diene; thus, 1.05 equiv of diene was used instead (Scheme 3). Compound **30** is of interest as a chiral Michael acceptor. As pointed out by a reviewer, both **30** and **31** could potentially be kinetically resolved by a second Diels–Alder reaction.



Scheme 3. Diels–Alder reactions of divinyl ketone.

The rates of reaction of **29** exceeded those of **5**. For example, the cyclopentadiene reaction was complete in less than 4 h, while **5** required at least 12 h to achieve the same conversion. Vinyl cycloadduct **30** was formed with a similar modest enantiomeric excess (53% *ee*) as the closely related ethyl cycloadduct **10** (47% *ee*). Lowering the temperature of the reaction in the case of **30** (−30 °C) drastically reduced the conversion. For **31**, the *ee* was only slightly lower (87% *ee*) than that for ethyl cycloadduct **22** (91% *ee*). In this case trace amounts of bis(dimethylcyclohexyl) ketone were still detected in the product mixture which probably accounts for the conversion not being quantitative. The absolute configuration of Michael acceptor product **30** was assigned by comparison of its [α] value and CD spectra to the known compounds **4**, **10** and **11**. Product **31** had a negative [α] value even though its CD spectrum more closely resembles **30** than **22**; thus, we used a similar analogy as Corey[20] (for **22** by comparing it to **10**) for assigning the *S* absolute configuration to **31**.

Intramolecular Diels–Alder reaction: The racemic version of the intramolecular Diels–Alder reaction shown in Scheme 4 was previously reported by Shea and co-workers[35] and substrate **32** can be prepared in three steps. Shea examined several related intramolecular Diels–Alder reactions. We found the synthesis shown in Scheme 4 very interesting because it represents an intramolecular version of the Diels–Alder reaction leading to **22** (see above). In Shea's publication, **32** was cyclized within 15 min at ambient temperature using $AlEt_2Cl$ as the catalyst (70% yield). When this reaction was carried out by using Ru catalyst (*R*,*R*)-**1a**, cyclization was considerably slower but we were able to isolate **33** in very high *ee* (95%) and in a yield comparable with Shea's previous report[35] for the racemic cycloaddition. The conversion given here relates to GC analysis of starting material to product ratio. The absolute configuration of the



Scheme 4. Catalyzed intramolecular asymmetric Diels–Alder reaction gave bridgehead olefin **33**.

product was assigned by comparison of the [α] value and CD spectra to known compound **22**.

The reaction depicted in Scheme 4 demonstrates that the chiral Ru catalyst is capable of forming products containing strained bridgehead olefins. Functionality on the vinyl ketone is tolerated and additional functionality on the diene is also feasible. Indeed, this type of ring system has been widely studied because of its presence in the core of anticancer target phomoidrides; in addition **33** is an intermediate in the synthesis of antifungal agent (±)-ledol,[35,36] a field that has also been reviewed.[37]

Conclusions

To summarise, we report the first examples of a one-point binding transition metal Lewis acid catalyst capable of coordinating and activating an α,β-unsaturated ketone for enantioselective Diels–Alder reactions. Asymmetric induction ranges from modest to excellent. It appears that the catalyst is capable of operating effectively in both *syn* and *anti*–s-*trans* orientations of the dienophile though it seems to work less well with methyl vinyl ketone than ethyl vinyl ketone and divinyl ketone. We have also shown that α-chlorovinyl dienophiles give higher enantioselectivities in these cycloadditions than the bromo analogues. An intramolecular vinyl ketone Diels–Alder reaction product was obtained with almost perfect asymmetric induction. As to the scope and limitations, vinyl, α-methyl and α-halo ketones can work well provided that they are not too sterically hindered. Thus far we have not been successful with cyclic α,β-unsaturated ketones; crotylic ketones also lack reactivity. In terms of dienes, reactions with oxygenated dienes have also not been successful, probably because the electron demand of dienes such as 1-methoxybutadiene, which favors the methoxy group pointing into the catalyst. Furan and cyclohexadiene also failed to give cycloaddition products.

Experimental Section

General: Catalysts **1a** and **2a** were prepared by using our previously published procedures.[3,10] Reactions were carried out under a positive pressure of nitrogen unless otherwise stated. Glassware was oven dried, and further dried by placing under vacuum and heating with a heat gun for ca. 5 min as necessary.

Purification of THF, diethyl ether, *n*-hexane, toluene and dichloromethane was carried out by using a Solvtek© purification system. Dienes and dienophiles were distilled prior to use, while other commercial chemicals were used as supplied unless stated otherwise.

Flash column chromatography was carried out using silica gel (60 Å, 32–63 mesh, Brunschwig SA, Basel). Thin-layer chromatography was performed on pre-coated aluminum plates (Merck silica $60F_{254}$), and visualized using UV light or aqueous $KMnO_4$.

^1H, ^{31}P and ^{13}C NMR spectra were recorded on Bruker AMX 300, 400 and 500 spectrometers. Chemical shifts are quoted relative to tetramethylsilane and referenced to residual solvent peaks as appropriate. Infrared spectra were recorded on a Perkin–Elmer Spectrum One spectrophotometer as neat liquids using a Golden Gate accessory. GC analysis was performed using an HP6890 series GC system equipment with a HP3395 integrator. GC-MS were acquired using a HP6890 series GC system with a S973 Network Mass selective detector. Polarimetry was performed in a Perkin–Elmer 241 Polarimeter with a Na lamp (589 nm, continuous), circular dichroism spectra were recorded with a JASCO J-715 spectropolarimeter and UV-visible spectra on a CARY 100 Bio Varian spectrophotometer. LR-MS were acquired using a Varian CH4 or SM1 spectrometer with the ionizing voltage at 70 eV while HR-MS were measured in + TOF mode in the ESI-MS mode using an Applied Biosystems/Scix (Q-STA) spectrometer.

Crystallographic data: Cell dimensions and intensities were measured at 200 K on a Stoe IPDS diffractometer with graphite-monochromated $Mo_{K\alpha}$ radiation. ($\lambda = 0.71073$ Å). Data were corrected for Lorentz and polarization effects and for absorption. The structures were solved by direct methods (SIR97),[38] all other calculations were performed with XTAL system.[39] (*S*,*S*)-**1b**: $[Ru(C_{47}H_{23}F_{20}O_3P_2)](SbF_6)(CH_2Cl_2)$, $M_r = 1499.4$, orthorhombic, $P2_12_12_1$, $a = 13.4062(6)$, $b = 17.5113(8)$, $c = 23.4079(12)$ Å, $V = 5495.2(5)$ Å^3, $Z = 4$, $\mu = 1.05$ mm^{-1}, $\rho_{calcd} = 1.812$ g cm^{-3}, Flack parameter $x = -0.01(4)$, $S = 1.67(2)$, $R = 0.042$, $\omega R = 0.039$. (*S*,*S*)-**2b**: $[Ru(C_{50}H_{29}F_{20}O_3P_2)](SbF_6)(C_3H_4O)_{1.25}$, $M_r = 1526.7$, triclinic, $P1$, $a = 11.9772(10)$, $b = 15.1762(12)$, $c = 17.8522(14)$ Å, $\alpha = 77.232(9)$, $\beta = 83.459(9)$, $\gamma = 89.530(10)°$, $V = 3143.6(5)$ Å^3, $Z = 2$ ($Z' = 2$), $\mu = 0.84$ mm^{-1}, $\rho_{calcd} = 1.613$ g cm^{-3}, Flack parameter $x = -0.01(6)$, $S = 1.38(1)$, $R = \omega R = 0.044$.

CCDC-604489 and -604490 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif/

4-Methylpent-1-en-3-one (6): Prepared by using a similar procedure to Spangler et al.[40] and NMR data consistent with Nakahira et al.[41] Acrolein (3 mL, 45.7 mmol, 1 equiv) was dissolved in Et_2O (750 mL) and the mixture was cooled to 0 °C. Isopropylmagnesium chloride (2 M solution in Et_2O) (30 mL, 59.4 mmol, 1.3 equiv) was added dropwise over 10 min and the mixture was stirred for 3 h and was then allowed to warm to ambient temperature. The reaction was quenched by dropwise addition of sat. aq. NH_4Cl solution (80 mL). The organic phase was separated and the aqueous phase was extracted with Et_2O (3 × 50 mL). The combined organic phases were dried over $MgSO_4$, filtered, trace hydroquinone stabilizer was added and the solvent was carefully removed in vacuo to yield a pale yellow oil (3.52 g, 76 %). ^1H NMR (300 MHz, CD_2Cl_2): $\delta =$ 0.95 (t, 6H, $J = 6.8$ Hz, $CH(CH_3)_2$), 1.55–1.85 (m, 2H, O*H*, $CH(CH_3)_2$), 3.88 (br t, 1H, $J = 6.0$ Hz, *CH*OH), 5.19 (ddd, 1H, $J = 10.5$, 1.8, 0.6 Hz, *cis*=CH_2), 5.26 (ddd, 1H, $J = 17.2$, 1.4, 0.4 Hz, *trans*=CH_2), 5.92 ppm (ddd, 1H, $J = 17.1$, 10.4, $J = 6.4$ Hz, C*H*=CH_2).

Molecular sieves 4 Å (10 g) were activated and were then slurried in CH_2Cl_2 (40 mL). 4-Methylpent-1-en-3-ol (3.48 g, 34.7 mmol, 1 equiv) was added and the mixture was cooled to 0 °C. *N*-Methylmorpholine-*N*-oxide (NMO) (4.48 g, 38.2 mmol, 1.1 equiv) followed by tetrapropylammonium perruthenate (TPAP) (0.657 g, 1.87 mmol, 0.05 equiv) and the mixture was stirred for 22 h. The reaction mixture was poured directly onto a silica gel column and was eluted with CH_2Cl_2 until before the yellow band (NMO residue) eluted (R_f product = 0.31, pentane/Et_2O 1:1). Upon very careful evaporation of the solvent in vacuo yielded the title compound as a slightly yellow oil (2.1 g, 63 %), which was distilled prior to use. ^1H NMR (300 MHz, $CDCl_3$): $\delta = 1.12$ (d, 6H, $J = 6.9$ Hz, $CH(CH_3)_2$), 2.88 (quin, 1H, $J = 6.9$ Hz, $CH(CH_3)_2$), 5.76 (dd, 1H, $J = 10.3$, 1.5 Hz, *cis*=CH_2), 5.76 (dd, 1H, $J = 17.4$, 1.5 Hz, *trans*=CH_2), 6.44 ppm (dd, 1H, $J =$ 17.5, 10.3 Hz, C*H*=CH_2).

3-Bromo-3-buten-2-one (7): Prepared by the procedure Corey et al.[42] used for preparing α-bromoacrolein; NMR data was consistent with Murphy et al.[43] Methyl vinyl ketone (6 mL, 72.1 mmol, 0.99 equiv) was dissolved in CH_2Cl_2 (40 mL) and the solution was cooled to 0 °C. Bromine (3.67 mL, 71.6 mmol, 1 equiv) in CH_2Cl_2 (60 mL) was added dropwise with vigorous stirring and the mixture was stirred at 0 °C for 5 min before NEt_3 (10 mL, 71.3 mmol, 0.99 equiv) was added dropwise at 0 °C over 15 min. After the addition the mixture was allowed to warm to ambient temperature and was stirred for 1 h. The reaction was quenched by addition of HCl (2 M, 50 mL), the CH_2Cl_2 layer was poured off and was washed with sat. aq. $NaHCO_3$ (50 mL). The organic phases were dried over $MgSO_4$, filtered and the solvent was removed in vacuo. The residue was purified by fractional vacuum distillation (40 °C, 20 mm Hg) and the second fraction of a pale green/yellow oil was collected as the product (6.66 g, 63 %). ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 2.47$ (s, 3H, CH_3), 6.42 (d, 1H, $J = 2.3$ Hz, *trans*=CH_2), 6.80 ppm (d, 1H, $J = 2.3$ Hz, *cis*=CH_2).

3-Chloro-3-buten-2-one[44] **(8)**: Prepared by the procedure described by Ibrahim et al. with minor modifications. Methyl vinyl ketone (17.1 mL, 214.02 mmol, 1 equiv) was dissolved in CCl_4 (150 mL) and the solution was cooled to −20 °C. Chlorine gas, generated by dropwise addition of HCl_{conc} (24.09 g, 211.20 mmol, 1 equiv) onto $Ca(ClO)_2$ (15.09 g, 105.60, 0.5 equiv), was bubbled through a H_2SO_4 drying trap and then through the reaction mixture over 3 h and was finally scrubbed with a KOH_{aq} trap. The volatiles were removed in vacuo to give a 4.5:1 mixture 3,4-dichlorobutan-2-one and 4-chlorobutan-2-one. The mixture was distilled at 66 °C (14 mm Hg) and the residue was further purified by column chromatography eluted with Et_2O/pentane 1:19→1:1 ($R_f = 0.46$, pentane/Et_2O 9:1) and 3,4-dichlorobutan-2-one was isolated as a colorless oil (5.22 g, 17 %). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 2.39$ (s, 3H, CHCH_3), 3.79 (dd, 1H, $J = 11.5$, 5.4 Hz, CH_2Cl), 3.95 (dd, 1H, $J = 11.5$, 7.5 Hz, CH_2Cl), 4.40 ppm (dd, 1H, $J = 7.5$, 5.4 Hz, C*H*ClCClH_2).

3,4-Dichlorobutan-2-one (0.92 g, 6.55 mmol, 1 equiv) was dissolved in chloroform (50 mL) and was stirred with a solution of sat. aq. K_2CO_3 (5 mL) for 1 h. The organic phase was poured off and was dried with $MgSO_4$, filtered and the solvent was removed in vacuo. The residue was purified by fractional vacuum distillation (60 °C, 300 mm Hg) and the first fraction of a pale green/yellow oil was collected as the product (0.43 g, 62 %). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 2.45$ (s, 3H, CHCH_3), 6.17 (d, 1H, $J = 2.1$ Hz, *trans*=CH_2), 6.41 ppm (d, 1H, $J = 2.1$ Hz, *cis*=CH_2).

α-Bromovinyl ethyl ketone (9): Previously reported by Galli et al.,[45] ethyl vinyl ketone (11.9 mL, 120.1 mmol, 0.99 equiv) was dissolved in CH_2Cl_2 (80 mL) and the solution was cooled to 0 °C. Bromine (6.2 mL, 120.8 mmol, 1 equiv) in CH_2Cl_2 (60 mL) was added dropwise with vigorous stirring and the mixture was stirred at 0 °C for 5 min before NEt_3 (16.76 mL, 119.5 mmol, 0.99 equiv) was added dropwise at 0 °C over 15 min. After the addition the mixture was allowed to warm to ambient temperature and was stirred for 1 h. The reaction was quenched by addition of HCl (2 M, 100 mL), the organic layer was poured off and was subsequently washed with sat. aq. $NaHCO_3$ (100 mL). The combined organic phases were dried over $MgSO_4$, filtered and the solvent was removed in vacuo. The residue was purified by fractional vacuum distillation (14 mm Hg) and the second fraction of a pale colorless oil was collected as the product (14.9 g, 76 %). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.14$ (t, 3H, $J = 7.2$ Hz, CH_3), 2.82 (q, 2H, $J = 7.2$ Hz, CH_2), 6.35 (d, 1H, $J =$ 2.4 Hz, *trans*=CH_2), 6.80 ppm (d, 1H, $J = 2.4$ Hz, *cis*=CH_2).

3-Methylbut-3-en-2-one (19): Prepared by a similar procedure to Spangler et al.[40] and spectroscopic data was previously reported by Yamamoto.[28] Freshly distilled methacrolein (from $CaSO_4$) (5 mL, 60.65 mmol, 1 equiv) was dissolved in Et_2O (100 mL) and the mixture was cooled to 0 °C. Methyllithium (1.6 M solution in Et_2O) (49.25 mL, 78.8 mmol, 1.3 equiv) was added dropwise over 5 min and the mixture was stirred for 1 h and was then allowed to warm to ambient temperature. The reaction was quenched by dropwise addition of sat. aq. NH_4Cl solution (100 mL). The organic phase was separated and the aqueous phase was extracted with Et_2O (3×20 mL). The combined organic phases were dried over $MgSO_4$, filtered, trace hydroquinone stabilizer was added and the solvent was carefully removed in vacuo to yield 2-methyl-1-penten-3-ol as a pale yellow oil (5.1 g, 98 %). ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.28$ (d, 3H, $J = 7.8$ Hz, CHCH_3), 1.55 (br s, 1H, O*H*), 1.75 (s, 3H, CCH_3), 4.25 (q, 1H, $J = 6.3$ Hz, C*H*OH), 4.79 (dd, 1H, $J = 1.5$, 1.5 Hz, *cis*=CH_2), 4.96 ppm (dd, 1H, $J = 0.7$, 0.7 Hz, *trans*=CH_2).

Molecular sieves 4 Å (5 g) were activated and were then slurried in CH_2Cl_2 (30 mL). 2-Methyl-1-penten-3-ol (2.1 g, 24.38 mmol, 1 equiv) was added and the mixture was cooled to 0 °C. NMO (3.14 g, 26.82 mmol, 1.1 equiv) followed by TPAP (0.21 g, 0.59 mmol, 0.02 equiv) was added and the mixture was stirred for 16 h. The reaction mixture was poured directly onto a silica gel column and was eluted with CH_2Cl_2 until before the yellow band (NMO residue) eluted. Upon very careful evaporation of the solvent in vacuo 3-methylbut-3-en-2-one was isolated as a slightly yellow oil (1.128 g, 46 %) and distilled by an was isolated prior to use. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 2.39$ (dd, 3H, $J = 1.3$, 1.3 Hz, CHCH_3), 2.87 (s, 3H, CCH_3), 6.33 (dd, 1H, $J = 1.5$, 0.5 Hz, *cis*=CH_2), 6.34 ppm (br s, 1H, *trans*=CH_2).

Penta-1,4-dien-3-one (29):[46] Prepared by the procedure of Kulinkovich et al. with an alternative procedure[47] for the final elimination reaction. Magnesium (1.29 g, 53 mmol, 2.12 equiv) was weighed into a flask fitted with a reflux condenser and was dried in vacuo with strong heating. Iodine (trace) was added and the mixture was slurried in Et_2O (40 mL). The reaction was initiated with gentle heating and once the mixture was colorless, ethylbromide (3.96 mL, 53 mmol, 2.12 equiv) was added dropwise at gentle reflux and the mixture was stirred for 2 h at ambient temperature. The mixture was then added to a solution of titanium tetraisopropoxide (0.74 mL, 2.5 mmol, 0.1 equiv). Ethyl 3-bromopropanoate (3.2 mL, 25 mmol, 1 equiv) in Et_2O (60 mL) was then added dropwise over about 1 h while maintaining the reaction at ambient temperature. After an additional 30 min, 5 % H_2SO_4 solution (250 mL) and the organic phase was poured off. The aqueous phase was extracted with Et_2O (3× 70 mL) then the combined organic layers were washed with water (100 mL), saturated sodium bicarbonate solution (100 mL) and water (100 mL). The organic phase was dried over Na_2SO_4, filtered and the solvent was removed in vacuo. 1-(2-Bromoethyl)-cyclopropanol was used directly without purification. ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.56$–0.58 (m, 2H, CH_2CH_2), 0.84–0.88 (m, 2H, CH_2CH_2), 1.80–2.03 (br m, 1H, O*H*), 2.17 (t, 2H, $J = 7.2$ Hz, CH_2CH_2Br), 3.66 ppm (t, 2H, $J = 7.2$ Hz, CH_2CH_2Br).

1-(2-Bromoethyl)-cyclopropanol (≈4.12 g, 25 mmol, 1 equiv) was dissolved in CCl_4 (60 mL), cooled to 0 °C then NBS (4.89 g, 27.5 mmol, 1.1 equiv) was added and the mixture was stirred at ambient temperature for 2 h. The mixture was filtered and the solvent was removed in vacuo. The residue was then purified by vacuum distillation (b.p. ≈60 °C at ≈10 mm Hg) and 1,5-dibromopentan-3-one (3.572 g, 59 % over two steps) was obtained as a colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): $\delta =$ 3.05 (t, 4H, $J = 6.7$ Hz, CH_2CH_2Br), 3.57 ppm (t, 4H, $J = 6.7$ Hz, CH_2CH_2Br).

1,5-Dibromopentan-3-one (1 g, 4.11 mmol, 1 equiv) was dissolved in CH_2Cl_2 (20 mL) and triethylamine (1.43 mL, 10.2 mmol, 2.5 equiv) was added and the mixture was stirred for 19 h. HCl (0.1 M) (20 mL) was then added and the organic phase was poured off. The aqueous phase was extracted (3×10 mL) with CH_2Cl_2, then the combined organic phases were washed with HCl (0.1 M; 2×20 mL), then water (50 mL). The organic phase was dried over $MgSO_4$, filtered and the solvent was removed in vacuo to afford penta-1,4-dien-3-one as a colorless oil (0.31 g, 93 %), which was distilled under reduced pressure, with gentle heating (maximum 30 °C) prior to use. ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 5.91$ (dd, 2H, $J = 10.6$, 1.3 Hz, *cis*=CH_2), 6.32 (dd, 2H, $J = 17.5$, 1.3 Hz, *trans*=CH_2), 6.67 ppm (dd, 2H, $J = 17.4$, 10.6 Hz, C*H*=CH_2).

General procedure for Diels–Alder reactions: CH_2Cl_2 (0.30 mL) followed by 2,6-lutidine (4 μL, 0.032 mmol, 0.05 equiv), decane (33 μL, 0.16 mmol, 0.26 equiv) and dienophile (0.66 mmol, 1 equiv) were added to a Schlenk charged with catalyst **1a** (46 mg, 0.33 mmol, 0.05 equiv). The mixture was stirred at −20 °C and the diene (0.97 mmol, 1.5 equiv) in CH_2Cl_2 (0.35 mL) was added dropwise down the side of the Schlenk, over 10 min. The catalysis was monitored by removal of ≈10 μL aliquots which were diluted with MeCN (≈0.1 mL) and were injected into the achiral GC. When the reaction had finished, hexane (8 mL) was added, CH_2Cl_2 was removed in vacuo and the mixture was filtered through a

Celite plug. The solvent was removed in vacuo then the residue was dissolved in CH_2Cl_2, passed through a silica gel plug and the solvent was removed in vacuo. Enantiomeric and diastereomeric excesses were determined by chiral GC. For each example the catalysis was performed twice, once with the decane internal standard and the reaction was sampled to monitor conversion, the second time the internal standard was not used and the after the reaction had run its course the product was isolated and a yield was obtained. The *ee* values given in the Results and Discussion section are average values of the two experiments.

Notes concerning stereochemical assignment and conversion: The product absolute configuration was either assigned from a literature reference for an $[\alpha]_D^{20}$ or by preparation of an authentic sample or by comparison of CD spectra of a product with unknown absolute configuration and a related known sample. The catalyst used was always the (+)-(*R*,*R*)-**1a** enantiomer and the chiral GC peaks marked with * are the major enantiomer and diastereomer from the catalysis mixture. *exo* and *endo* nomenclature in all cases gives the ketone the highest priority. The calibration factors quoted were used as follows to determine conversion relative to the decane internal GC standard (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}: 2.50 min).

$$\%\ \text{conversion} = \frac{\Sigma\ \text{product}}{\Sigma\ \text{product} + \Sigma\ \text{decane}} \times 100 \times \text{calibration factor}$$

***endo*-(−)-(1*S*,2*S*,4*S*)-1-Bicyclo[2.2.1]hept-5-en-2-yl-ethanone (4a)**:[21,30] ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.33$ (br d, 1H, $J = 8.0$ Hz, CHCH_2CH), 1.42–1.53 (m, 2H, CHCH_2CH, CHCOCH_2), 1.75 (m, 1H, CHCOCH_2), 2.13 (s, 3H, COCH_3), 2.90 (br s, 1H, =CHC*H*CH$_2$), 3.01 (m, 1H, C*H*COCH$_3$), 3.24 (br s, 1H, CHC*H*CH=CH), 5.86 (dd, 1H, $J = 5.5$, 2.5 Hz, CHCHC*H*=CH), 6.16 ppm (dd, 1H, $J = 5.8$, 3.0 Hz, CHCHCH=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 27.6$ (CH_2), 29.4 (CH_3), 42.9 (CH), 46.0 (CH), 50.1 (CH_2), 52.5 (C), 131.4 (CH), 138.1 (CH), 209.2 ppm (C); IR (film): $\tilde{\nu} = 3061$, 2973, 2870, 1708, 1644, 1519, 1475, 1358, 1337, 1185, 1171, 1091, 983, 717 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 7.42 min, 136 [M^+], 91, 77, 71, 66; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 6.40 min, calibration factor = 1.519; chiral GC (Lipodex-E, H_2, 70 °C isothermal): 56.75/66.48* min. Column chromatography: pentane/Et_2O 9:1, $R_f = 0.20$; isolated yield = 0.065 g, 72 %; $[\alpha]_D^{20} = -29$ (CH_2Cl_2, $c = 0.005$ mg mL^{-1}, 22 % *ee*, with 5 % *exo* product **4b** at 5 % *ee* of unknown configuration); mol CD (0.0073 M, CH_2Cl_2, 20 °C): $\lambda = 343$ ($-6.95\,e^{-5}$), 323 ($-1.72\,e^{-3}$), 289 ($4.47\,e^{-2}$), 234 nm ($-2.26\,e^{-3}$).

***exo*-1-Bicyclo[2.2.1]hept-5-en-2-yl-ethanone (4b; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.27$ (br dd, 1H, $J = 10.0$, 10.0 Hz, CH_2CHCO), 1.33 (br s, 2H, CHCH_2CH), 1.85–1.92 (m, 1H, CH_2CHCO), 2.21 (s, 3H, COCH_3), 2.38 (dd, 1H, $J = 8.8$, 4.8 Hz, C*H*COCH$_3$), 2.90 (br s, 1H, =CHC*H*CH$_2$), 2.99 (br s, 1H, =CHC*H*CCH), 6.14 ppm (m, 2H, C*H*=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 29.2$ (CH_2), 30.0 (CH_3), 41.8 (CH), 45.5 (CH), 46.1 (CH_2), 51.9 (CH), 136.0 (CH), 138.4 (CH), 210.9 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 5.43 min; chiral GC (Lipodex-E, H_2, 70 °C isothermal): 38.40/39.80 min; column chromatography: pentane/Et_2O 9:1, $R_f = 0.29$.

***endo*-(−)-(1*S*,2*S*,4*S*)-1-Bicyclo[2.1.1]hept-5-en-2-yl-propanone (10a)**:[21,22] ^{1}H NMR (400 MHz, CD_2Cl_2): $\delta = 0.96$ (t, 3H, $J = 7.2$ Hz, COCH$_2$CH_3), 1.30–1.38 (br d, 1H, $J = 8.1$ Hz, CHCH_2CH), 1.38–1.50 (m, 2H, CHCH_2CH, CHCOCH_2), 1.68–1.82 (m, 1H, CHCOCH_2), 2.37–2.57 (m, 2H, COCH_2CH$_3$), 2.86 (br s, 1H, =CHC*H*C), 2.96–3.10 (m, 1H, C*H*COCH$_3$), 3.24 (br s, 1H, COCHC*H*CH=CH), 5.80 (dd, 1H, $J = 5.0$, 2.0 Hz, CCHCH=C*H*), 6.12 ppm (dd, 1H, $J = 5.6$, 3.1 Hz, CCHCH=C*H*); ^{13}C NMR (100 MHz, CD_2Cl_2): $\delta = 8.17$ (CH_3), 27.7 (CH_2), 35.2 (CH_2), 43.2 (CH), 46.5 (CH), 50.4 (CH_2), 51.6 (CH), 131.8 (CH), 138.0 (CH), 211.5 ppm (C); IR (film): $\tilde{\nu} = 3060$, 2972, 2939, 2873, 1707, 1570, 1459, 1414, 1352, 1336, 1271, 1178, 1128, 1105, 1027, 923, 835, 716 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 10.9 min, 150 [M^+], 93, 85, 66; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 8.85 min, calibration factor = 1.557. Chiral GC (Lipodex-E, H_2, 80 °C isothermal): 25.91/31.06* min; column chromatography: pentane/Et_2O 9:1, $R_f = 0.41$; isolated yield = 0.078 g (80 %); $[\alpha]_D^{20} = -35°$ (CH_2Cl_2, $c = 0.005$ mg mL^{-1}, 49 % *ee*, with 5 % *exo* product **10b** at 14 % *ee* of unknown configuration); mol CD (0.0066 M, CH_2Cl_2, 20 °C): $\lambda = 324$ ($4.98\,e^{-4}$), 288 ($1.70\,e^{-1}$), 232 nm ($-3.39\,e^{-3}$).

***exo*-1-Bicyclo[2.2.1]hept-5-en-2-yl-propanone (10b; minor product)**: ^{1}H NMR (400 MHz, CD_2Cl_2): $\delta = 1.02$ (t, 3H, $J = 7.3$ Hz, CH$_2$CH_3), 1.20–1.27 (m, 1H, CH_2CHCO), 1.27 (br d, 1H, $J = 7.5$ Hz, CHCH_2CH), 1.35 (br d, 1H, $J = 8.3$ Hz, CHCH_2CH), 1.80r–1.88 (m, 1H, CH_2CHCO), 2.33–2.40 (m, 1H, C*H*COCH$_3$), 2.40–2.64 (s, 2H, COCH_2CH$_3$), 2.87 (br s, 1H, =CHC*H*CH$_2$), 2.91 (br s, 1H, =CHC*H*CCH), 6.14 ppm (m, 2H, C*H*=C*H*); ^{13}C NMR (100 MHz, CD_2Cl_2): $\delta = 8.3$ (CH_3), 29.7 (CH_2), 36.1 (CH_2), 42.3 (CH), 46.2 (CH), 46.4 (CH_2), 50.8 (CH), 136.4 (CH), 138.6 (CH), 213.5 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 7.74 min; chiral GC (Lipodex-E, H_2, 80 °C isothermal): 17.99/19.43 min; column chromatography: pentane/Et_2O 9:1, $R_f = 0.56$.

***endo*-(−)-(1*S*,2*S*,4*S*)-1-Bicyclo[2.2.1]hept-5-en-2-yl-2-methylpropan-1-one (11a)**:[21,30] ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.06$ (dd, 6H, $J = 13.2$, 6.9 Hz, COCH(CH_3)$_2$), 1.32 (br d, 1H, $J = 8.3$ Hz, CHCH_2CH), 1.41–1.49 (m, 2H, CH_2CHCO, CHCH_2CH), 1.73 (ddd, 1H, $J = 11.6$, 7.9, 4.9 Hz, CH_2CHCO), 2.75 (sept, 1H, $J = 6.8$ Hz, CHCOC*H*(CH$_3$)$_2$), 2.89 (br s, 1H, =CHC*H*C), 3.13–3.19 (m, 1H, C*H*COCH(CH$_3$)$_2$), 3.20 (br s, 1H, COCHC*H*CH=CH), 5.80 (dd, 1H, $J = 5.6$, 2.7 Hz, CCHCH=C*H*), 6.14 ppm (dd, 1H, $J = 5.6$, 3.1 Hz, CCHCH=C*H*); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 18.1$ (CH_3), 19.2 (CH_3), 27.6 (CH_2), 39.4 (CH), 42.7 (CH), 46.0 (CH), 49.6 (CH), 49.9 (CH_2), 131.4 (CH), 137.4 (CH), 215.0 ppm (C); IR (film): $\tilde{\nu} = 3061$, 2969, 2938, 2872, 1706, 1571, 1466, 1446, 1381, 1361, 1336, 1127, 1093, 940, 916, 699 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 12.22 min, 164 [M^+], 121, 99, 93, 66; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 9.84 min, calibration factor = 1.492; chiral GC (Lipodex-E, H_2, 70 °C isothermal): 35.48*/44.44 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f = 0.53$; isolated yield = 0.074 g, 69 %; $[\alpha]_D^{20} = -5°$ (CH_2Cl_2, $c = 0.007$ mg mL^{-1}, 7 % *ee*, with 9 % *exo* product **11b** at 18 % *ee* of unknown configuration); mol CD (0.0042 mol L^{-1}, CH_2Cl_2, 20 °C): $\lambda = 326$ ($-5.71\,e^{-4}$), 292 ($1.04\,e^{-1}$), 244 ($7.63\,e^{-4}$), 228 nm ($5.10\,e^{-2}$).

***exo*-1-Bicyclo[2.2.1]hept-5-en-2-yl-2-methylpropan-1-one (11b; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.10$ (dd, 6H, $J = 6.8$, 4.8 Hz, COCH(CH_3)$_2$), 1.21–1.32 (m, 2H, CH_2CHCO, CHCH_2CH), 1.46 (br d, 1H, $J = 8.6$ Hz, CHCH_2CH), 1.81 (ddd, 1H, $J = 11.3$, 3.5, 3.5 Hz, CH_2CHCO), 2.47–2.51 (m, 1H, C*H*COCH(CH$_3$)$_2$), 2.75 (sept, 1H, $J = 6.8$ Hz, COC*H*(CH$_3$)$_2$), 2.90 (br s, 2H, CH$_2$C*H*CH=CHC*H*CCH), 6.14 ppm (br t, 2H, $J = 3.2$ Hz, C*H*=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 18.5$ (CH_3), 18.7 (CH_3), 29.5 (CH_2), 40.7 (CH), 41.7 (CH), 45.7 (CH), 45.8 (CH_2), 46.6 (CH), 136.0 (CH), 138.1 (CH), 216.9 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 8.93 min; chiral GC (Lipodex-E, H_2, 70 °C isothermal): 24.44/26.37 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f = 0.68$.

***exo*-(−)-(1*S*,2*S*,4*S*)-1-(2-Bromobicyclo[2.2.1]hept-5-en-2-yl)-ethanone (12a)**:[42] ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.22$ (br d, 1H, $J = 9.2$ Hz, CHCH_2CH), 1.61 (br s, 1H, CHCH_2CH), 1.65 (m, 1H, CCH_2), 2.47 (s, 3H, COCH_3), 2.67 (dd, 1H, $J = 13.1$, 3.6 Hz, CCH_2), 2.97 (br s, 1H, =CHC*H*CH$_2$), 3.47 (dd, 1H, $J = 2.3$, 0.9 Hz, =CHC*H*C), 6.22 (dd, 1H, $J = 5.5$, 3.0 Hz, CCHC*H*=CH), 6.45 ppm (dd, 1H, $J = 5.6$, 3.0 Hz, CCHCH=C*H*); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 25.8$ (CH_3), 39.2 (CH_2), 42.1 (CH), 47.3 (CH_2), 50.7 (CH), 71.9 (C), 135.1 (CH), 139.1 (CH), 201.9 ppm (C); IR (film): $\tilde{\nu} = 3405$, 3065, 2979, 2875, 1707, 1575, 1459, 1444, 1354, 1221, 1224, 1162, 1114, 1022, 938, 856, 709 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 13.29 min, 214 [M^+], 135, 91, 66; 13.45 min, 216 [M^+], 135, 91, 66; HRMS-ESI (positive): *m*/*z*: calcd for $C_9H_{11}O$: 135.0809; found: 135.0810, accuracy: 0.0734 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 10.89 min, calibration factor = 1.409. Chiral GC (Lipodex-E, H_2, 90 °C isothermal): 36.01*/45.84 min; column chromatography:pentane/Et_2O 9:1, $R_f = 0.56$; isolated yield = 0.124 g, 87 %; $[\alpha]_D^{20} = -29°$ (CH_2Cl_2, $c = 0.01$ mg mL^{-1}, 79 % *ee*, with 25 % *endo* product **12b** at 58 % *ee* of unknown configuration); mol CD (0.00046 M, CH_2Cl_2, 20 °C): $\lambda = 327$ ($4.26\ e^{-3}$), 360 ($2.67\,e^{-1}$), 233 nm ($3.64\,e^{-1}$).

***endo*-1-(2-Bromobicyclo[2.2.1]hept-5-en-2-yl)-ethanone (12b; minor product)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.83$ (m, 1H, CHCH_2CH),

2.19 (brd, 1H, $J=6.6$ Hz, $CHCH_2CH$), 2.29 (dd, 1H, $J=10.2$, 2.8 Hz, CCH_2), 2.35 (s, 3H, $COCH_3$), 2.41 (dd, 1H, $J=10.2$, 2.0 Hz, CCH_2), 2.95 (brs, 1H, $=CHCHCH_2$), 3.34 (dd, 1H, $J=1.9$, 1.1 Hz, $=CHCHC$), 5.93 (dd, 1H, $J=4.4$, 2.3 Hz, $CCHCH=CH$), 6.25 ppm (dd, 1H, $J=4.2$, 2.8 Hz, $CCHCH=CH$); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=25.7$ (CH_3), 39.9 (CH_2), 43.0 (CH), 49.1 (CH_2), 53.9 (CH), 72.1 (C), 131.5 (CH), 141.3 (CH), 200.6 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 11.17 min; chiral GC (Lipodex-E, H_2, 90 °C isothermal): 41.40/51.14 min; column chromatography: pentane/Et_2O 9:1, $R_f=0.56$.

***exo*-(1*S*,2*S*,4*S*)-1-(2-Chlorobicyclo[2.2.1]hept-5-en-2-yl)-ethanone (13a)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=1.32$ (brd, 1H, $J=9.1$ Hz, $CHCH_2CH$), 1.45 (dd, 1H, $J=17.1$, 3.8 Hz, CCH_2), 1.57 (m, 1H, $CHCH_2CH$), 2.43 (s, 3H, $COCH_3$), 2.69 (dd, 1H, $J=13.1$, 3.5 Hz, CCH_2), 2.93 (brs, 1H, $=CHCHCH_2$), 3.29 (brd, 1H, $J=1.5$ Hz, $=CHCHC$), 6.21 (dd, 1H, $J=5.6$, 3.0 Hz, $CCHCH=CH$), 6.43 ppm (dd, 1H, $J=5.6$, 3.0 Hz, $CCHCH=CH$); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=25.8$ (CH_3), 40.0 (CH_2), 42.6 (CH), 48.1 (CH_2), 51.1 (CH), 78.3 (C), 134.0 (CH), 139.8 (CH), 203.2 ppm (C); IR (film): $\tilde{\nu}=2982$, 2876, 1716, 1444, 1356, 1333, 1274, 1228, 1166, 1115, 1025, 939, 858, 755, 715 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 10.60 min, 170 [M^+], 135, 91, 66; 10.68 min, 170 [M^+], 135, 91, 66; HRMS-ESI (positive): m/z: calcd for $C_9H_{11}ClO$ 170.0498; found: 170.0499, accuracy: −0.2 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 8.08 min, calibration factor = 1.474; chiral GC (Lipodex-E, H_2, 80 °C isothermal): 30.43*/38.20 min; column chromatography: pentane/Et_2O 19:1, $R_f=0.31$; isolated yield = 0.094 g, 84 %; $[\alpha]_D^{20}$ = −31° (CH_2Cl_2, $c=0.012$ mg mL^{-1}, 86 % *ee*, with 30 % *endo* product **13b** at 73 % *ee* of unknown configuration); mol CD (0.0067 M, CH_2Cl_2, 20 °C): λ = 284 (4.06 e^{-3}), 332 (1.05 e^{-3}), 296 (−1.40 e^{-1}), 264 (−2.50 e^{-2}), 247 (−6.73 e^{-2}), 236 nm (3.74 e^{-2}).

***endo*-1-(2-Chlorobicyclo[2.2.1]hept-5-en-2-yl)-ethanone (13b; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=1.77$ (m, 1H, $CHCH_2CH$), 2.04 (dd, 1H, $J=13.1$, 3.5 Hz,), 2.10 (brd, 1H, $J=8.8$ Hz, $CHCH_2CH$), 2.30 (s, 3H, $COCH_3$), 2.36 (dd, 1H, $J=13.1$, 2.8 Hz, CCH_2), 2.96 (brs, 1H, $=CHCHCH_2$), 3.19 (brd, 1H, $J=1.5$ Hz, $=CHCHC$), 5.90 (dd, 1H, $J=5.5$, 2.8 Hz, $CCHCH=CH$), 6.26 ppm (dd, 1H, $J=5.5$, 3.0 Hz, $CCHCH=CH$); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=25.6$ (CH_3), 39.5 (CH_2), 42.6 (CH), 48.8 (CH_2), 53.8 (CH), 77.8 (C), 131.5 (CH), 141.6 (CH), 200.9 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 8.32 min; chiral GC (Lipodex-E, H_2, 80 °C isothermal): 36.50/47.95 min; column chromatography: pentane/Et_2O 19:1, $R_f=0.31$.

***endo*-(−)-(1*S*,2*S*,4*S*)-1-(5-Methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (14a)**:[48] ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=1.29$–1.34 (m, 1H, $CHCH_2CH$), 1.44–1.57 (m, 2H, $CHCH_2CH$, $CHCOCH_2$), 1.66–1.74 (m, 1H, $CHCOCH_2$), 1.74 (d, 3H, $J=1.5$ Hz, CCH_3), 2.12 (s, 3H, $COCH_3$), 2.64 (brs, 1H, $=CCHCH_2$), 3.02 (ddd, 1H, $J=8.5$, 8.5, 4.0 Hz, $CHCOCH_3$), 3.15 (brs, 1H, $=CHCHCH$), 5.38 ppm (brs, 1H, $C=CH$); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=15.0$ (CH_3), 26.7 (CH_2), 29.1 (CH_3), 46.6 (CH), 47.4 (CH), 49.6 (CH_2), 54.5 (CH), 123.8 (CH), 148.3 (C), 209.1 ppm (C); IR (film): $\tilde{\nu}=3055$, 2960, 2869, 1705, 1626, 1443, 1356, 1168, 721 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 8.42 min, 150 [M^+], 107, 91, 80, 71; HRMS-ESI (positive): m/z: calcd for $C_{10}H_{14}O$: 151.1122; found: 151.1119, accuracy: −2.5824 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 7.47 min, calibration factor = 1.769. Chiral GC (Hydrodex-β, H_2, 90 °C isothermal): 19.30/20.22* min. Column chromatography: pentane/Et_2O 9.5:0.5, $R_f=0.17$. Isolated yield = 0.082 g (83 %). $[\alpha]_D^{20}$ = −72° (CH_2Cl_2, $c=0.01$ mg mL^{-1}, 60 % *ee*, with 11 % regioisomer **14b** at 1 % *ee* of unknown configuration and 4 % regioisomer **14c** at 35 % *ee* of unknown configuration); mol CD (0.0066 M, CH_2Cl_2, 20 °C): λ = 324 (−3.10 e^{-3}), 289 (4.73 e^{-1}), 242 (1.19 e^{-2}), 233 (5.88 e^{-2}).

***endo*-1-(4-Methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (14b; minor product)**:[48] ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=1.22$–1.32 (m, 2H, CCH_2CH), 1.39 (ddd, 1H, $J=11.6$, 4.8, 2.8 Hz, CCH_2CHCO), 1.44 (s, 3H, CCH_3), 2.06–2.10 (m, 1H, CCH_2CHCO), 2.07 (s, 3H, $COCH_3$), 2.79 (dd, 1H, $J=9.6$, 4.8 Hz, $CHCOCH_3$), 2.81 (brs, 1H, $=CHCH$), 5.79 (d, 1H, $J=5.6$ Hz, $=CHCHCCH$), 6.12 ppm (dd, 1H, $J=5.6$, 3.2 Hz, $CH=CH$); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 6.29 min; chiral GC (Hydrodex-β, H_2, 90 °C isothermal): 15.73/16.07 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f=0.17$.

***endo*-1-(6-Methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (14c; minor product)**:[48] ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=1.20$–1.32 (m, 2H, $CHCH_2CH$), 1.53–1.59 (m, 1H, CH_2CHCO), 1.63 (d, 3H, $J=1.83$ Hz, CCH_3), 1.70–1.78 (m, 1H, CH_2CHCO), 2.18 (s, 3H, $COCH_3$), 2.78 (brs, 1H, $CHCHCOCH_3$), 3.03 (brs, 1H, $=CHCHCH_2$), 3.08 (m, 1H, $CHCOCH_3$), 5.72 ppm (brs, 1H, $CH=C$); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 6.19 min; chiral GC (Hydrodex-β, H_2, 90 °C isothermal): 21.94/23.39 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f=0.17$.

***endo*-(−)-(1*S*,2*S*,4*S*)-1-(5-Methylbicyclo[2.2.1]hept-5-en-2-yl)-propanone (15a)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=1.02$ (t, 3H, $J=7.3$ Hz, $COCH_2CH_3$), 1.29–1.34 (m, 1H, $CHCH_2CH$), 1.46–1.58 (m, 2H, $CHCH_2CH$, $CHCOCH_2$), 1.68–1.74 (m, 1H, $CHCOCH_2$), 1.74 (d, 3H, $J=1.5$ Hz, CCH_3), 2.44 (m, 2H, $COCH_2CH_3$), 2.64 (brs, 1H, $=CCHCH_2$), 3.03 (ddd, 1H, $J=8.3$, 8.3, 4.0 Hz, $CHCOCH_3$), 3.13 (brs, 1H, $=CHCHCH$), 5.33 ppm (brs, 1H, $C=CH$); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=8.10$ (CH_3), 15.26 (CH_3), 27.0 (CH_2), 35.0 (CH_2), 46.9 (CH), 47.6 (CH), 49.7 (CH_2), 53.6 (CH), 124.1 (CH), 148.4 (C), 211.9 ppm (C); IR (film): $\tilde{\nu}=2964$, 2938, 2908, 2871, 1707, 1626, 1459, 1444, 1414, 1376, 1353, 1132, 1115, 1103, 730 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 12.35 min, 164 [M^+], 107, 91, 85, 80; HRMS-ESI (positive): m/z: calcd for $C_{11}H_{16}O$: 164.1201; found: 164.020, accuracy: −0.3 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 9.68 min, calibration factor = 1.637; chiral GC (Hydrodex-β, H_2, 90 °C isothermal): 31.75/34.18* min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f=0.22$; isolated yield: 0.096 g, 89 %; $[\alpha]_D^{20}$ = −123° (CH_2Cl_2, $c=0.01$ mg mL^{-1}, 94 % *ee*, with 9 % regioisomer **15b** at 33 % *ee* of unknown configuration and 5 % regioisomer **15c** at 85 % *ee* of unknown configuration); mol CD (0.0064 M, CH_2Cl_2, 20 °C): λ = 325 (−3.44 e^{-5}), 288 (6.88 e^{-2}), 238 (−2.14 e^{-3}).

***endo*-1-(4-Methylbicyclo[2.2.1]hept-5-en-2-yl)-propanone (15b; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=1.04$ (t, 3H, $J=7.0$ Hz, $COCH_2CH_3$), 1.22–1.32 (m, 2H, CCH_2CH), 1.24 (s, 3H, CCH_3), 1.34–1.40 (m, 1H, CCH_2CHCO), 1.80 (dd, 1H, $J=27.9$, 19.6 Hz, CCH_2CHCO), 2.46–2.62 (m, 3H, $CHCOCH_2CH_3$, $CHCOCH_2CH_3$), 2.81 (brs, 1H, $=CHCH$), 5.84 (d, 1H, $J=5.4$ Hz, $=CHC$), 6.13 ppm (dd, 1H, $J=5.3$, 3.1 Hz, $CHCH=CH$); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 8.39 min; chiral GC (Hydrodex-β, H_2, 90 °C isothermal): 24.42/24.77 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f=0.22$.

***endo*-1-(6-Methylbicyclo[2.2.1]hept-5-en-2-yl)-propanone (15c; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=1.00$–1.30 (m, 1H, $CHCH_2CH$), 1.06 (t, 3H, $J=7.3$ Hz, $COCH_2CH_3$), 1.17–1.30 (m, 1H, $CHCH_2CH$), 1.32–1.41 (m, 1H, CH_2CHCO), 1.34 (s, 3H, CCH_3), 1.88 (ddd, 1H, $J=7.9$, 4.1, 4.1 Hz, CH_2CHCO), 2.40–2.61 (m, 3H, $CHCOCH_2CH_3$, $COCH_2CH_3$), 2.61 (brs, 1H, $CHCH_2CHCO$), 2.85 (brs, 1H, $=CCHCH$), 5.61 ppm (brs, 1H, $CH=C$); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 9.68 min; chiral GC (Hydrodex-β, H_2, 90 °C isothermal): 37.75/40.43 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f=0.23$.

***exo*-1-(2-Bromobicyclo[2.2.1]hept-5-en-2-yl)-propanone (16a)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=1.17$ (t, 3H, $J=7.3$ Hz, $COCH_2CH_3$), 1.17–1.22 (m, 1H, $CHCH_2CH$), 1.53–1.62 (m, 2H, $CHCH_2CH$, CCH_2), 2.65 (dd, 1H, $J=13.4$, 3.6 Hz, CCH_2), 2.76–2.94 (m, 2H, $COCH_2CH_3$), 2.96 (brs, 1H, $=CHCHCH_2$), 3.44 (dd, 1H, $J=2.5$, 1.5 Hz, $=CHCHC$), 6.16 (dd, 1H, $J=5.6$, 2.8 Hz, $CCHCH=CH$), 6.40 ppm (dd, 1H, $J=5.6$, 3.2 Hz, $CCHCH=CH$); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=9.4$ (CH_3), 31.3 (CH_2), 39.3 (CH_2), 42.2 (CH), 47.3 (CH_2), 50.6 (CH), 71.9 (C), 135.0 (CH), 139.1 (CH), 203.6 ppm (C); IR (film): $\tilde{\nu}=3066$, 2978, 2877, 1708, 1574, 1459, 1445, 1416, 1331, 1202, 1138, 983, 934, 913, 717 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 15.90 min, 230 [M^+], 228 [M^+], 201, 199, 173, 171, 165, 163, 91, 66; HRMS-ESI (positive): m/z: calcd for $C_{10}H_{13}BrO$: 228.0149; found: 228.0148, accuracy: 0.5 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 12.90 min, calibration factor = 1.361; chiral GC (Lipodex-E,

H_2, 90 °C isothermal): 20.40/21.47 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f = 0.70$; isolated yield: 0.095 g, 63 %.

***endo*-1-(2-Bromobicyclo[2.2.1]hept-5-en-2-yl)-propanone (16b; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.10$ (t, 3H, $J = 2.8$ Hz, $COCH_2CH_3$), 1.79–1.85 (m, 1H, $CHCH_2CH$), 2.18 (brd, 1H, $J = 8.8$ Hz, $CHCH_2CH$), 2.29 (dd, 1H, $J = 13.6$, 3.5 Hz, CCH_2), 2.42 (dd, 1H, $J = 13.6$, 2.7 Hz, CCH_2), 2.53 (dq, 1H, $J = 17.4$, 7.3 Hz, $COCH_2CH_3$), 2.87–2.94 (m, 1H, $COCH_2CH_3$), 2.95 (brs, 1H, =$CHCHCH_2$), 3.36 (dd, 1H, $J = 2.5$, 1.5 Hz, =$CHCHC$), 5.90 (dd, 1H, $J = 5.6$, 2.8 Hz, $CCHCH$=CH), 6.24 ppm (dd, 1H, $J = 5.6$, 2.8 Hz, CCHCH=CH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 8.7$ (CH_3), 31.0 (CH_2), 39.8 (CH_2), 42.6 (CH), 48.8 (CH_2), 53.5 (CH), 71.6 (C), 131.5 (CH), 140.9 (CH), 205.1 ppm (C); GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 16.03 min, 230 [M^+], 228 [M^+], 201, 199, 173, 171, 165, 163, 91, 66; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 13.150 min; chiral GC (Lipodex-E, H_2, 90 °C isothermal): 22.38/24.22 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f = 0.70$.

***exo*-(−)-(1*S*,2*S*,4*S*)-1-(2-Bromo-5-methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (17a)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.16$ (brd, 1H, $J = 7.0$ Hz, $CHCH_2CH$), 1.53 (dd, 1H, $J = 9.9$, 2.8 Hz, CCH_2), 1.56–1.61 (m, 1H, $CHCH_2CH$), 1.85 (s, 3H, CCH_3), 2.46 (s, 3H, $COCH_3$), 2.63 (brs, 1H, =$CCHCH_2$), 2.67 (dd, 1H, $J = 9.6$, 2.8 Hz, CCH_2), 3.34 (dd, 1H, $J = 2.3$, 1.1 Hz, =$CHCHC$), 5.68 ppm (brs, 1H, C=CH); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 15.4$ (CH_3), 25.7 (CH_3), 38.4 (CH_2), 46.4 (CH_2), 46.7 (CH), 51.4 (CH), 74.5 (C), 127.4 (CH), 149.4 (C), 202.1 ppm (C); IR (film): $\tilde{\nu} = 2970$, 2873, 1707, 1631, 1442, 1354, 1227, 1154, 1015, 939, 740 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 14.32 min, 230 [M^+], 228 [M^+], 149, 105, 91, 80; 14.93 min, 230 [M^+], 228 [M^+], 149, 105, 91, 80; 14.98 min, 230 [M^+], 228 [M^+], 149, 105, 91, 80; HRMS-ESI (positive): m/z: calcd for $C_{10}H_{13}O$: 149.0966; found: 149.0966, accuracy: 0.1 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 12.10 min, calibration factor = 1.631; chiral GC (Lipodex-E, H_2, 75 °C isothermal): 87.36*/94.5 min and (Hydrodex-β, H_2, 90 °C isothermal): 61.52 min (unresolved); column chromatography: pentane/Et_2O 9.5:0.5, $R_f = 0.40$; isolated yield: 0.15 g, 99 %; $[\alpha]_D^{20} = -45°$ (CH_2Cl_2, $c = 0.005$ mg mL^{-1}, 70 % *ee*); $[\alpha]_D^{20} = -22°$ (CH_2Cl_2, $c = 0.012$ mg mL^{-1}, 71 % *ee*, with 13 % **17b** at 67 % *ee* with unknown configuration, 8 % **17d** 14 % *ee* with unknown configuration); mol CD (0.0046 M, CH_2Cl_2, 20 °C): $\lambda = 351$ ($-9.16\,e^{-4}$), 306 ($-3.84\,e^{-1}$), 250 nm ($3.67\,e^{-1}$).

***endo*-1-(2-Bromo-5-methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (17b; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.69$ (d, 3H, $J = 1.8$ Hz, CCH_3), 1.81–1.86 (m, 1H, $CHCH_2CH$), 2.14 (brd, 1H, $J = 8.8$ Hz, $CHCH_2CH$), 2.23 (dd, 1H, $J = 13.4$, 3.5 Hz, CCH_2), 2.33 (s, 3H, $COCH_3$), 2.43 (dd, 1H, $J = 13.9$, 2.8 Hz, CCH_2), 2.66 (brs, 1H, =$CCHCH_2$), 3.24 (dd, 1H, $J = 3.0$, 1.5 Hz, =$CHCHC$), 5.41 ppm (brs, 1H, C=CH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 15.7$ (CH_3), 25.6 (CH_3), 38.9 (CH_2), 47.5 (CH), 48.3 (CH_2), 53.6 (CH), 77.4 (C), 123.35 (CH), 152.4 (C), 202.4 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 12.26 min; chiral GC (Hydrodex-β, H_2, 90 °C isothermal): 59.12/69.70 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f = 0.41$.

***exo*-1-(2-Bromo-4-methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (17c; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.37$–1.42 (m, 1H, CCH_2CH), 1.40 (s, 3H, CCH_3), 1.71–1.77 (m, 2H, CCH_2C, CCH_2CH), 2.54 (s, 3H, $COCH_3$), 2.78 (dd, 1H, $J = 13.1$, 3.8 Hz, CCH_2C), 2.84 (brs, 1H, =$CHCHC$), 5.88 (brd, 1H, $J = 5.5$ Hz, CCH=$CHCH$), 6.34 ppm (dd, 1H, $J = 5.2$, 3.0 Hz, CCH=CHCH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 15.2$ (CH_3), 30.7 (CH_3), 41.8 (CH), 44.7 (CH_2), 50.0 (CH_2), 59.4 (C), 77.9 (C), 139.0 (CH), 141.4 (CH), 206.0 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 10.51 min; chiral GC (Lipodex-E, H_2, 75 °C isothermal): 54.00/59.37 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f = 0.85$.

***endo*-1-(2-Bromo-4-methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (17d; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.55$–1.61 (m, 1H, CCH_2CH), 1.58 (s, 3H, CCH_3), 2.10 (brd, 1H, $J = 8.8$ Hz CCH_2CH), 2.32 (s, 3H, $COCH_3$), 2.38 (dd, 1H, $J = 13.6$, 3.6 Hz, CCH_2C), 2.58 (dd, 1H, $J = 13.1$, 3.3 Hz, CCH_2C), 2.82 (brs, 1H, =$CHCHC$), 5.85 (brd, 1H, $J = 5.5$ Hz, CCH=$CHCH$), 6.16 ppm (dd, 1H, $J = 5.5$, 3.0 Hz, CCH=CHCH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 17.2$ (CH_3), 27.1 (CH_3), 41.5 (CH), 44.9 (CH_2), 54.6 (CH_2), 56.8 (C), 77.9 (C), 136.7 (CH), 139.7 (CH), 200.9 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 11.34 min; chiral GC (Hydrodex-β, H_2, 90 °C isothermal): 53.32/57.03 min; column chromatography: pentane/Et_2O 9.5:0.5, $R_f = 0.41$.

***exo*-(−)-(1*S*,2*S*,4*S*)-1-(2-Chloro-5-methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (18a)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.27$ (brd, 1H, $J = 9.1$ Hz, $CHCH_2CH$), 1.38 (dd, 1H, $J = 13.1$, 3.6 Hz, CCH_2), 1.54–1.59 (m, 1H, $CHCH_2CH$), 1.84 (s, 3H, CCH_3), 2.41 (s, 3H, $COCH_3$), 2.65 (brs, 1H, =$CCHCH_2$), 2.72 (dd, 1H, $J = 13.0$, 3.7 Hz, CCH_2), 3.16 (brs, 1H, =$CHCHC$), 5.72 ppm (brs, 1H, C=CH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 15.4$ (CH_3), 25.6 (CH_3), 38.9 (CH_2), 46.8 (CH), 47.0 (CH_2), 51.6 (CH), 80.3 (C), 125.9 (CH), 149.8 (C), 203.3 ppm (C); IR (film): $\tilde{\nu} = 2972$, 2875, 1715, 1630, 1443, 1344, 1230, 1199, 1160, 1114, 940, 789 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 12.46 min, 186 [M^+], 184 [M^+], 149, 148, 105, 91, 80; HRMS-ESI (positive): m/z: calcd for $C_{10}H_{13}ClO$: 184.0655; found: 184.0654, accuracy: 0.6 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 9.514 min, calibration factor = 1.371; chiral GC (Hydrodex-β, H_2, 70 °C isothermal): 95.41*/97.4 min; column chromatography: pentane/Et_2O 95:5, $R_f = 0.57$; isolated yield = 0.111 g, 92 %; $[\alpha]_D^{20} = -19°$ (CH_2Cl_2, c 0.012 mg mL^{-1}, 87 % *ee*, with 28 % **18b** at 75 % *ee* with unknown configuration, 12 % **18c** at 79 % *ee* with unknown configuration and 7 % **18d** at 35 % *ee* with unknown configuration); mol CD (0.0067 M, CH_2Cl_2, 20 °C): $\lambda = 348$ ($-1.48\,e^{-3}$), 315 ($-5.84\,e^{-2}$), 312 ($-5.45\,e^{-2}$), 305 ($-8.10\,e^{-2}$), 296 ($-5.79\,e^{-2}$), 280 ($-8.04\,e^{-3}$), 256 ($-1.954\,e^{-1}$), 244 ($7.52\,e^{-3}$).

***endo*-1-(2-Chloro-5-methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (18b; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.65$ (d, 3H, $J = 1.6$ Hz, CCH_3), 1.54–1.59 (m, 1H, $CHCH_2CH$), 1.98 (dd, 1H, $J = 13.3$, 3.6 Hz, CCH_2), 2.00–2.07 (m, 1H, $CHCH_2CH$), 2.28 (s, 3H, $COCH_3$), 2.38 (dd, 1H, $J = 13.6$, 3.2 Hz, CCH_2), 2.65 (brs, 1H, =$CCHCH_2$), 3.09 (brs, 1H, =$CHCHC$), 5.37 ppm (brs, 1H, C=CH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 15.3$ (CH_3), 25.2 (CH_3), 38.2 (CH_2), 46.9 (CH), 54.2 (CH_2), 54.3 (CH), 78.3 (C), 123.0 (CH), 152.5 (C), 200.8 ppm (C); GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 12.25 min, 186 [M^+], 184 [M^+], 149, 148, 105, 91, 80; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 9.60 min; chiral GC (Hydrodex-β, H_2, 70 °C isothermal): 87.82/113.04 min; column chromatography: pentane/Et_2O 95:5, $R_f = 0.58$.

***exo*-1-(2-Chloro-4-methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (18c; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.34$ (s, 3H, CCH_3), 1.37 (ddd, 1H, $J = 9.1$, 3.7, 1.7 Hz, CCH_2CH), 1.58 (dd, 1H, $J = 12.6$, 3.5 Hz, CCH_2C), 1.86 (brd, 1H, $J = 9.1$ Hz, CCH_2CH), 2.46 (s, 3H, $COCH_3$), 2.81 (dd, 1H, $J = 12.6$, 3.8 Hz, CCH_2C), 2.84 (brs, 1H, =$CHCHC$), 5.93 (d, 1H, $J = 5.5$ Hz, CCH=$CHCH$), 6.36 ppm (dd, 1H, $J = 5.3$, 3.0 Hz, CCH=CHCH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 14.4$ (CH_3), 29.8 (CH_3), 41.7 (CH), 45.4 (CH_2), 50.9 (CH_2), 59.8 (C), 82.6 (C), 139.3 (CH), 139.6 (CH), 207.8 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 7.90 min; chiral GC (Lipodex-E, H_2, 80 °C isothermal): 20.02/21.57 min; column chromatography: pentane/Et_2O 95:5, $R_f = 0.62$.

***endo*-1-(2-Chloro-4-methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (18d; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.51$ (s, 3H, CCH_3), 1.74–1.79 (m, 1H, CCH_2CH), 2.00–2.08 (m, 1H, CCH_2CH), 2.23–2.34 (m, 2H, CCH_2C), 2.27 (s, 3H, $COCH_3$), 2.82 (brs, 1H, =$CHCHC$), 5.81 (brd, 1H, $J = 5.8$ Hz, CCH=$CHCH$), 6.17 ppm (dd, 1H, $J = 5.8$, 3.3 Hz, CCH=CHCH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 15.3$ (CH_3), 25.2 (CH_3), 41.9 (CH), 44.5 (CH_2), 47.8 (CH_2), 57.2 (C), 80.3 (C), 137.6 (CH), 139.6 (CH), 201.6 ppm (C); GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 11.65 min, 186 [M^+], 184 [M^+], 149, 148, 105, 91, 80; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 8.64 min; chiral GC (Hydrodex-β, H_2, 70 °C isothermal): 78.62/85.4 min; column chromatography: pentane/Et_2O 95:5, $R_f = 0.59$.

***exo*-(−)-(1*S*,2*R*,4*S*)-1-(2-Methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (20a)**:[28,49] ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 0.77$ (dd, 1H, $J = 11.8$, 2.7 Hz, CH_2C), 1.07 (s, 3H, CCH_3), 1.20 (brd, 1H, $J = 8.5$ Hz, $CHCH_2CH$), 1.38–1.41 (m, 1H, $CHCH_2CH$), 2.21 (s, 3H, $COCH_3$), 2.39 (dd, 1H, $J = 11.9$, 4.0 Hz, CH_2C), 2.79 (brs, 1H, =$CHCHCH_2$), 2.97 (brs, 1H, =$CHCHC$), 6.10 (dd, 1H, $J = 5.5$, 3.0 Hz, CH=$CHCHC$), 6.25 ppm (dd, 1H, $J = 5.5$,

2.8 Hz, CCHCH=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 23.4 (CH_3), 26.1 (CH_3), 36.0 (CH_2), 42.8 (CH), 48.6 (CH_2), 49.0 (CH), 56.1 (C), 133.5 (CH), 139.0 (CH), 213.1 ppm (C); IR (film): $\tilde{\nu}$ = 3060, 2966, 2874, 1702, 1571, 1449, 1352, 1333, 1258, 1154, 1115, 860, 839, 714 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 9.42 min, 150 [M^+], 107, 85, 66; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 6.88, calibration factor = 1.504; chiral GC (Lipodex-E, H_2, 70 °C isothermal): 17.4*/19.6; column chromatography: pentane/Et_2O 9.5:0.5, R_f = 0.32; isolated yield: 0.079 g, 80 %; $[\alpha]_D^{20}$ = −60° (CH_2Cl_2, c = 0.004 mg mL^{-1}, 69 % *ee*); $[\alpha]_D^{20}$ = −7° (CH_2Cl_2, c = 0.011 mg mL^{-1}, 74 % *ee*, with 33 % *exo* product **20b** at 63 % *ee* of unknown configuration); mol CD (0.0063 M, CH_2Cl_2, 20 °C): λ = 328 (−7.60 e^{-3}), 294 (−9.62 e^{-1}), 232 nm (3.81 e^{-2}).

***endo*-1-(2-Methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (20b; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.35 (dd, 1H, J = 11.8, 3.6 Hz, CH_2C), 1.36 (s, 3H, CCH_3), 1.46–1.49 (m, 1H, CHCH_2CH), 1.63 (br d, 1H, J = 8.6 Hz, CHCH_2CH), 1.98 (dd, 1H, J = 12.1, 2.7 Hz, CH_2C), 2.09 (s, 3H, COCH_3), 2.77 (br s, 1H, =CHC*H*CH$_2$), 2.82 (br s, 1H, =CHC*H*C), 6.00 (dd, 1H, J = 5.8, 2.8 Hz, CCHC*H*=CH), 6.11 ppm (dd, 1H, J = 8.6, 3.0 Hz, CCHCH=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 25.4 (CH_3), 26.4 (CH_3), 36.4 (CH_2), 42.7 (CH), 47.1 (CH_2), 50.8 (CH), 56.7 (C), 134.2 (CH), 138.1 (CH), 211.8 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 7.32 (*endo*); ciral GC (Lipodex-E, H_2, 70 °C isothermal): 22.8/28.6 (*endo*) min; column chromatography: pentane/Et_2O 9.5:0.5, R_f = 0.21.

1-(−)-(1*S*)-(3,4-Dimethylcyclohex-3-enyl)-ethanone (21):[14] ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.42–1.53 (m, 1H, CCH_2CH), 1.56 (br s, 3H, CCH_3), 1.58 (br s, 3H, CCH_3), 1.87–2.12 (m, 5H, CCH_2CH, CH_2CH_2), 2.12 (s, 3H, COCH_3), 2.49–2.53 ppm (m, 1H, C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 19.0 (CH_3), 19.2 (CH_3), 25.5 (CH_2), 28.1 (CH_3), 31.4 (CH_2), 33.3 (CH_2), 48.5 (CH), 124.1 (C), 125.6 (CH), 212.1 ppm (C); IR (film): $\tilde{\nu}$ = 2910, 2833, 1707, 1437, 1378, 1351, 1231, 1166, 1123, 957 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 1 min then heating 20 °C min^{-1}): 5.81 min, 152 [M^+], 137, 119, 109, 91, 79; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 10.28 min, calibration factor = 1.386; chiral GC (Lipodex-E, H_2, 80 °C isothermal): 74.4/77.0* min, column chromatography: pentane/Et_2O 95:5, R_f = 0.29; isolated yield: 0.055 g, 55 %; $[\alpha]_D^{20}$ = −77° (CH_2Cl_2, c = 0.01 mg mL^{-1}, 67 % *ee*); mol CD (0.0039 M, CH_2Cl_2, 20 °C): λ = 322.0 (−4.71 e^{-3}), 286 (8.05 e^{-2}), 235 nm (−1.03 e^{-1}).

1-(−)-(1*S*)-(3,4-Dimethylcyclohex-3-enyl)-propanone (22):[20] ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.05 (t, 3H, J = 7.2 Hz, CH_2CH_3), 1.44–1.52 (m, 1H, CCH_2CH), 1.60 (s, 3H, CCH_3), 1.62 (s, 3H, CCH_3), 1.75–2.21 (m, 5H, CCH_2CH, CH_2CH_2), 2.35–2.62 ppm (m, 3H, C*H*, CH_2CH$_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 7.8 (CH_3), 18.8 (CH_3), 19.0 (CH_3), 25.5 (CH_2), 31.3 (CH_2), 33.3 (CH_2), 33.8 (CH_2), 47.3 (CH), 124.1 (C), 125.3 (C), 214.4 ppm (C); IR (film): $\tilde{\nu}$ = 2877, 2907, 2833, 1707, 1452, 1412, 1377, 1343, 1217, 1114, 992, 855 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 1 min then heating 20 °C min^{-1}): 6.46 min, 166 [M^+], 151, 167, 119, 109, 91, 79; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 12.01 min, calibration factor = 1.372. Chiral GC (Hydrodex-β, H_2, 85 °C isothermal): 89.63/92.72 min; column chromatography: pentane/Et_2O 95:5, R_f = 0.43; isolated yield: 0.083 g, 76 %; $[\alpha]_D^{20}$ = −104° (CH_2Cl_2, c = 0.01 mg mL^{-1}, 93 % *ee*); mol CD (0.0063 M, CH_2Cl_2, 20 °C): λ = 287.0 (1.96 e^{-1}), 237.0 (−9.80 e^{-2}).

1-(−)-(1*S*)-(4-Methylcyclohex-3-enyl)-ethanone (23a):[32] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.40–1.50 (m, 1H, CCH$_2$CH_2CH), 1.66 (br s, 3H, CCH_3), 1.88–2.15 (m, 5H, CH_2CH_2CHCH_2), 2.16 (s, 3H, COCH_3), 2.56–2.64 (m, 1H, CH$_2$C*H*CH$_2$), 5.36–5.38 ppm (m, 1H, C=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 23.6 (CH_3), 25.1 (CH_2), 27.2 (CH_2), 28.2 (CH_3), 29.7 (CH_2), 47.4 (CH), 119.4 (CH), 134.0 (C), 212.1 ppm (C); IR (film): $\tilde{\nu}$ = 2914, 2836, 1706, 1438, 1376, 1352, 1282, 1223, 1166, 911, 799 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 1 min then heating 20 °C min^{-1}): 5.05 min, 138 [M^+], 123, 109, 105, 95, 91, 79; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 7.23 min, calibration factor = 1.425; chiral GC (Lipodex-E, H_2, 55 °C isothermal): 43.5/46.3* min, column chromatography: pentane/Et_2O 95:5, R_f = 0.26; isolated yield: 0.043 g, 47 %; $[\alpha]_D^{20}$ = −12° (CH_2Cl_2, c = 0.01 mg mL^{-1}, 50 % *ee*, with 9 % 1,3-regioisomer **23b** at 40 % *ee* of unknown configuration); mol CD (0.0072 M, CH_2Cl_2, 20 °C): λ = 313 (−3.70 e^{-3}), 265 (5.78 e^{-3}), 230 nm (−1.76 e^{-2}).

1-(3-Methylcyclohex-3-enyl)-ethanone (23b; minor product): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.50–1.66 (m, 1H, CCH$_2$CH_2CH), 1.63 (br s, 3H, CCH_3), 1.88–2.15 (m, 5H, CH_2CH_2CHCH_2), 2.15 (s, 3H, COCH_3), 2.47–2.56 (m, 1H, CH$_2$C*H*CH$_2$), 5.36–5.38 ppm (m, 1H, C=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 23.8 (CH_3), 24.7 (CH_2), 25.0 (CH_2), 28.2 (CH_3), 31.6 (CH_2), 48.6 (CH), 120.8 (CH), 132.6 (C), 211.9 ppm (C); GC-MS EI (positive) (HP-5MS, He, 80 °C for 1 min then heating 20 °C min^{-1}): 5.00 min, 138 [M^+], 123, 109, 105, 95, 91, 79; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 7.07 min. Chiral GC (Lipodex-E, H_2, 55 °C isothermal): 54.0/72.2 min; column chromatography: pentane/Et_2O 95:5, R_f = 0.26.

1-(−)-(1*S*)-(4-Methylcyclohex-3-enyl)-propanone (24a):[18] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.05 (t, 3H, J = 7.3 Hz, CH_2CH_3), 1.55–1.63 (m, 1H, CCH$_2$CH_2CH), 1.65 (br s, 3H, CCH_3), 1.85–2.10 (m, 5H, CH_2CH_2CHCH_2), 2.41–2.65 (m, 3H, CH$_2$C*H*CH$_2$, COCH_2CH$_3$), 5.37–5.41 ppm (m, 1H, C=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 7.8 (CH_3), 23.4 (CH_3), 25.1 (CH_2), 27.3 (CH_2), 29.6 (CH_2), 33.8 (CH_2), 46.3 (CH), 119.4 (CH), 133.8 (C), 214.5 ppm (C); IR (film): $\tilde{\nu}$ = 2966, 2912, 2836, 1708, 1439, 1412, 1376, 1342, 1148, 1126, 915, 799 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 1 min then heating 20 °C min^{-1}): 5.75 min, 152 [M^+], 137, 123, 109, 105, 95, 79; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 9.43 min, calibration factor = 1.420; chiral GC (Hydrodex-β, H_2, 65 °C isothermal): 151.72/161.01 min; column chromatography: pentane/Et_2O 95:5, R_f = 0.48; isolated yield: 0.062 g, 61 %; $[\alpha]_D^{20}$ = −104° (CH_2Cl_2, c = 0.0065 mg mL^{-1}, 93 % *ee*, with 13 % 1,3-regioisomer **24b** at 76 % *ee* of unknown configuration); mol CD (0.0042 M, CH_2Cl_2, 20 °C): λ = 286 (1.23 e^{-1}), 250 (1.58 e^{-2}), 231 nm (−8.79 e^{-2}).

1-(3-Methylcyclohex-3-enyl)-propanone (24b; minor product): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.06 (t, 3H, J = 7.1 Hz, CH_2CH_3), 1.55–1.63 (m, 1H, CCH$_2$CH_2CH), 1.67 (br s, 3H, CCH_3), 1.85–2.10 (m, 5H, CH_2CH_2CHCH_2), 2.41–2.65 (m, 3H, CH$_2$C*H*CH$_2$, COCH_2CH$_3$), 5.37–5.41 ppm (m, 1H, C=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 7.8 (CH_3), 23.6 (CH_3), 24.6 (CH_2), 24.9 (CH_2), 25.3 (CH_2), 31.6 (CH_2), 46.9 (CH), 120.5 (CH), 133.6 (C), 214.3 ppm (C); GC-MS EI (positive) (HP-5MS, He, 80 °C for 1 min then heating 20 °C min^{-1}): 5.69 min, 152 [M^+], 137, 123, 109, 105, 95, 79; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 9.24 min. Chiral GC (Hydrodex-β, H_2, 65 °C isothermal): 143.51/168.31 min; column chromatography: pentane/Et_2O 95:5, R_f = 0.48.

1-(−)-(1*S*)-(1-Bromo-3,4-dimethylcyclohex-3-enyl)-ethanone (25): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.77 (dd, 3H, J = 0.8, 0.8 Hz, CCH_3), 1.80 (dd, 3H, J = 0.8, 0.8 Hz, CCH_3), 2.18–2.48 (m, 4H, CH_2CH_2), 2.56 (s, 3H, COCH_3), 2.49 ppm (dd, 2H, J = 62.1, 23.1 Hz, CCH_2C); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 18.6 (CH_3), 19.2 (CH_3), 24.0 (CH_3), 30.4 (CH_2), 33.2 (CH_2), 42.4 (CH_2), 67.8 (C), 122.4 (C), 125.3 (C), 202.3 ppm (C); IR (film): $\tilde{\nu}$ = 2910, 2859, 1711, 1431, 1353, 128e4, 1227, 1200, 1171, 1124, 1059, 992 cm^{-1}; MS ESI (positive): m/z: 255 [M^++Na], 253 [M^++Na], 179, 133, 101; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 16.69 min, 151 [M^+−Br], 135, 107, 91, 77; HRMS-ESI (positive): m/z: calcd for $C_{10}H_{15}BrNaO$: 253.0203; ound: 253.0208, accuracy: 1.5965 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 14.0 min, calibration factor = 1.224; chiral GC (Lipodex-E, H_2, 90 °C isothermal): 52.3*/58.1 min; column chromatography: pentane/Et_2O 20:1, R_f = 0.39; isolated yield: 0.109 g, 72 %; $[\alpha]_D^{20}$ = −30° (CH_2Cl_2, c = 0.01 mg mL^{-1}, 91 % *ee*); mol CD (0.0049 M, CH_2Cl_2, 20 °C): λ = 339 (−1.49 e^{-3}), 301 (4.32 e^{-2}), 247 nm (−3.18 e^{-1}).

1-(−)-(1*S*)-(1-Chloro-3,4-dimethylcyclohex-3-enyl)-ethanone (26): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.62–1.67 (m, 6H, CCH_3), 2.00–2.48 (m, 3H, CH_2CH_2), 2.25–2.37 (m, 1H, CH_2CH$_2$), 2.37 (s, 3H, COCH_3), 2.49 ppm (br d, 2H, J = 17.7 Hz, CCH_2C); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 18.7 (CH_3), 19.2 (CH_3), 24.3 (CH_3), 29.3 (CH_2), 32.3 (CH_2), 41.6 (CH_2), 72.8 (C), 121.7 (C), 125.2 (C), 203.9 ppm (C); IR (film): $\tilde{\nu}$ = 2914, 2860, 1717, 1432, 1353, 1229, 1201, 1159, 1125, 1063, 995, 887, 849, 798 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 14.3 min, 186 [M^+], 151, 135, 107, 91, 77; HRMS-ESI

(positive): m/z: calcd for: $C_{10}H_{15}O$: 151.1123; found: 151.1123, accuracy: 0.0 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 11.6 min, calibration factor = 1.282; chiral GC (Lipodex-E, H_2, 80 °C isothermal): 47.2*/53.8 min; column chromatography: pentane/Et_2O 20:1, R_f = 0.46; isolated yield: 0.085 g, 69 %; $[\alpha]_D^{20}$ = −15° (CH_2Cl_2, c = 0.012 mg mL^{-1}, 91 % *ee*); mol CD (0.0062 M, CH_2Cl_2, 20 °C): λ = 384 (−4.06 e^{-3}), 332 (1.05 e^{-3}), 296 (−1.39 e^{-1}), 264 (−2.50 e^{-2}), 247 (−6.73 e^{-2}), 236 (3.74 e^{-2}).

1-(−)-(1*S*)-(1-Bromo-4-methylcyclohex-3-enyl)-ethanone (27a):[50] ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.72 (dd, 3H, J = 0.6, 0.6 Hz, CCH_3), 2.02–2.38 (m, 4H, CH_2CH_2), 2.47 (s, 3H, COCH_3), 2.79 (dd, 2H, J = 39.0, 18.6 Hz, CCH_2C), 5.36 ppm (m, 1H, C=CH); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 23.1 (CH_3), 23.9 (CH_3), 28.8 (CH_2), 32.6 (CH_2), 36.6 (CH_2), 67.0 (C), 117.1 (CH), 133.8 (C), 202.4 ppm (C); IR (film): $\tilde{\nu}$ = 2967, 2910, 1710, 1429, 1356, 1223, 1203, 1157, 1072, 1055, 999, 867, 779 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 14.3 min, 137 [M^+−Br], 121, 91, 77; HRMS-ESI (positive): m/z: calcd for $C_9H_{13}O$: 137.0966; found: 137.0966, accuracy: −0.1 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 11.68 min, calibration factor = 1.324; chiral GC (Lipodex-E, H_2, 75 °C isothermal for 120 min then heating at 0.1 °C min^{-1}): 103.2*/108.1 min or Chirasil Dex-CB, He, 85 °C isothermal for 80 min then heating at 0.1 °C min^{-1}): 94.98*/96.25 min; column chromatography: pentane/Et_2O 20:1, R_f = 0.26; isolated yield: 0.089 g, 62 ; $[\alpha]_D^{20}$ = −27° (CH_2Cl_2, c = 0.01 mg mL^{-1}, 93 % *ee*, with 1 % 1,3-regioisomer **27b** at 84 % *ee* with unknown configuration); mol CD (0.0053 M, CH_2Cl_2, 20 °C): λ = 300 (1.56 e^{-1}), 237 nm (−9.05 e^{-1}).

1-(1-Bromo-3-methylcyclohex-3-enyl)-ethanone (27b): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.74 (dd, 3H, J = 0.6, 0.6 Hz, CCH_3), 2.02–2.38 (m, 4H, CH_2CH_2), 2.47 (s, 3H, COCH_3), 2.66 (dd, 2H, J = 30.5, 17.3 Hz, CCH_2C), 5.48 ppm (m, 1H, C=CH); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 23.1 (CH_3), 23.3 (CH_3), 32.1 (CH_2), 36.6 (CH_2), 40.8 (CH_2), 67.3 (C), 120.0 (CH), 130.4 (C), 202.2 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 11.9 min; chiral GC (Lipodex-E, H_2, 75 °C isothermal for 120 min then heating at 0.1 °C min^{-1}): 123.7/126.6 min or Chirasil Dex-CB, He, 85 °C isothermal for 80 min then heating at 0.1 °C min^{-1}): 85.71*/89.55 min; column chromatography: pentane/Et_2O 20:1, R_f = 0.26.

1-(−)-(1*S*)-(1-Chloro-4-methylcyclohex-3-enyl)-ethanone (28a): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.70 (brs, 3H, CCH_3), 1.96–2.40 (m, 4H, CH_2CH_2), 2.38 (s, 3H, COCH_3), 2.41 (brd, 1H, J = 16.9 Hz, CCH_2C), 2.72 (brd, 1H, J = 16.9 Hz, CCH_2C), 5.32 ppm (m, 1H, C=CH); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 23.3 (CH_3), 24.4 (CH_3), 27.8 (CH_2), 31.9 (CH_2), 36.0 (CH_2), 72.0 (C), 116.7 (CH), 133.8 (C), 204.14 ppm (C); IR (film): $\tilde{\nu}$ = 2968, 2914, 1717, 1431, 1357, 1223, 1206, 1158, 1059, 1024, 877, 792 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 11.7 min, 137 [M^+−Cl], 121, 93, 91, 77; HRMS-ESI (positive): m/z: calcd for $C_9H_{13}O$: 137.0966; found: 137.0966, accuracy: 0.1 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 9.3 min, calibration factor = 1.430; chiral GC (Lipodex-E, H_2, 70 °C isothermal): 62.8*/67.3 min; column chromatography: pentane/Et_2O 20:1, R_f = 0.26; isolated yield: 0.073 g, 62 %; $[\alpha]_D^{20}$ = −11° (CH_2Cl_2, c = 0.006 mg mL^{-1}, 96 % *ee*, with 2 % 1,3-regioisomer **28b** at 40 % *ee* with unknown configuration); mol CD (0.0037 M, CH_2Cl_2, 20 °C): λ = 312 (1.81 e^{-2}), 292 (3.39 e^{-2}), 235 nm (−3.52 e^{-1}).

1-(1-Chloro-3-methylcyclohex-3-enyl)-ethanone (28b; minor product): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.70 (brs, 3H, CHCH_3), 1.96–2.40 (m, 4H, CH_2CH_2), 2.39 (s, 3H, COCH_3), 2.41 (brd, 1H, J = 13.6 Hz, CCH_2C), 2.68 (brd, 1H, J = 13.6 Hz, CCH_2C), 5.44 ppm (m, 1H, C=CH); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 23.5 (CH_3), 24.2 (CH_3), 28.1 (CH_2), 31.5 (CH_2), 40.2 (CH_2), 72.6 (C), 120.1 (CH), 133.1 (C), 204.5 ppm (C); GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 11.5 min, 137 [M^+−Cl], 121, 93, 91, 77; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 8.9 min; chiral GC (Lipodex-E, H_2, 70 °C isothermal): 76.6/78.8 min; column chromatography: pentane/Et_2O 20:1, R_f = 0.26.

***endo*-(−)-(1*S*,2*S*,4*S*)-1-Bicyclo[2.2.1]hept-5-en-2-yl-propenone (30a)**:[51] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.36 (brd, 1H, J = 8.1 Hz, CHCH_2CH), 1.46 (brd, 1H, J = 8.1 Hz, CHCH_2CH), 1.54 (ddd, 1H, J = 6.3, 3.3, 2.5 Hz, CHCH_2CHCO), 1.78–1.84 (m, 1H, CHCH_2CCO), 2.92 (brs, 1H, = CHCHCH$_2$), 3.23 (brs, 1H, CHCHCH=CH), 3.23–3.27 (m, 1H, CH$_2$CHCO), 5.72 (dd, 1H, J = 10.6, 1.5 Hz, *cis*-COCH=CH_2), 5.82 (dd, 1H, J = 5.3, 2.3 Hz, CHCHCH=CH), 6.15 (dd, 1H, J = 5.3, 2.8 Hz, CHCHCH=CH), 6.23 (dd, 1H, J = 17.4, 0.3 Hz, *trans*-COCH=CH_2), 6.46 ppm (dd, 1H, J = 17.4, 10.6 Hz, COCH=CH$_2$); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 27.8 (CH_2), 42.8 (CH), 46.1 (CH), 49.7 (CH), 49.8 (CH_2), 127.3 (CH_2), 131.5 (CH), 135.7 (CH), 137.4 (CH), 200.5 ppm (C); IR (film): $\tilde{\nu}$ = 3060, 2972, 2941, 2870, 1695, 1675, 1610, 1446, 1401, 1336, 1202, 1123, 1100, 1006, 984, 961, 839, 708 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 10.76 min, 148 [M^+], 130, 91, 83, 77, 66; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 8.43 min, calibration factor = 1.506. Chiral GC (Hydrodex-β, H_2, 100 °C isothermal): 20.96/22.22* min, column chromatography: pentane/Et_2O 9.5:0.5, R_f = 0.29; isolated yield: 0.088 g, 90 %; $[\alpha]_D^{20}$ = −66° (CH_2Cl_2, c = 0.005 mg mL^{-1}, 51 % *ee*, with 5 % *exo* product **30b** at 50 % *ee* of unknown configuration); mol CD (0.0064 M, CH_2Cl_2, 20 °C): λ = 342 (4.87 e^{-2}), 301 (1.04 e^{-1}), 245 (−1.54 e^{-1}), 233 nm (1.12 e^{-2}).

***exo*-1-Bicyclo[2.2.1]hept-5-en-2-yl-propenone (30b; minor product)**: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.27–1.32 (m, 1H, CHCH_2CHCO), 1.37 (s, 2H, CHCH_2CH), 1.92 (ddd, 1H, J = 8.3, 4.5, 4.5 Hz, CHCH_2CCO), 2.62 (dd, 1H, J = 8.8, 3.5 Hz, CH$_2$CHCO), 2.92 (brs, 1H, =CHCHCH$_2$), 2.99 (brs, 1H, CHCHCH=CH), 5.79 (dd, 1H, J = 10.6, 1.5 Hz, *cis*-COCH=CH_2), 6.15–6.17 (m, 2H, CH=CH), 6.23 (dd, 1H, J = 17.4, 1.3 Hz, *trans*-COCH=CH_2), 6.43 ppm (dd, 1H, J = 17.7, 10.6 Hz, COCH=CH$_2$); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 29.5 (CH_2), 41.8 (CH), 45.6 (CH_2), 46.0 (CH), 48.3 (CH), 127.7 (CH_2), 135.8 (CH), 136.5 (CH), 138.4 (CH), 202.5 ppm (C); achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 7.53 min; chiral GC (Hydrodex-β, H_2, 100 °C isothermal): 16.53/17.37 min; column chromatography: pentane/Et_2O 9.5:0.5, R_f = 0.34.

1-(−)-(1*S*)-(3,4-Dimethylcyclohex-3-enyl)-propenone (31): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.48–1.61 (m, 1H, CCH_2CH), 1.62 (brs, 6H, CH_3), 1.82–2.26 (m, 5H, CH_2CH$_2$CHCH$_2$), 2.79–2.91 (m, 1H, CH$_2$CHCO), 5.76 (dd, 1H, J = 10.5, 1.5 Hz, *cis*-COCH=CH_2), 6.26 (dd, 1H, J = 17.5, 1.5 Hz, *trans*-COCH=CH_2), 6.46 ppm (dd, 1H, J = 17.5, 10.5 Hz, COCH=CH$_2$); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 18.8 (CH_3), 19.0 (CH_3), 25.5 (CH), 31.2 (CH), 33.2 (CH), 44.9 (CH_2), 124.1 (C), 125.3 (C), 127.9 (CH), 134.9 (CH), 203.3 ppm (C); IR (film): $\tilde{\nu}$ = 2909, 2833, 1696, 1673, 1612, 1438, 1402, 1312, 1285, 1252, 1221, 1182, 1118, 1076, 983, 962, 923, 732 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 14.81 min, 164 [M^+], 149, 131, 121, 109, 91, 79, 67; HRMS-ESI (positive): m/z: calcd for $C_{11}H_{16}O$: 164.1201; found: 164.1200, accuracy: 0.5 ppm; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 11.85 min, calibration factor = 1.406; chiral GC (Hydrodex-β, H_2, 100 °C isothermal): 39.42/40.83* min; column chromatography: pentane/Et_2O 9.5:0.5, R_f = 0.35; isolated yield: 0.074 g, 70 %; $[\alpha]_D^{20}$ = −90° (CH_2Cl_2, c = 0.009 mg mL^{-1}, 88 % *ee*); mol CD (0.0024 M, CH_2Cl_2, 20 °C): λ = 338 (5.79 e^{-2}), 280 (−4.81 e^{-2}), 263 (−3.32 e^{-2}), 250 (−5.34 e^{-2}), 238 nm (5.42 e^{-2}).

8-Methyl-7-methylenenona-1,8-dien-3-one (32) and (±)-7-methylbicyclo-[4.3.1]dec-6-en-2-one (32):[35] The procedures used to prepare **32** and **33** (racemically) were used directly as described in Shea's paper and the products (and yields) obtained were consistent with the reported data.

Procedure for intramolecular Diels–Alder reaction: CH_2Cl_2 (0.5 mL) followed by 2,6-lutidine (4 μL, 0.032 mmol, 0.05 equiv) were added to a Schlenk charged with catalyst **1a** (46 mg, 0.33 mmol, 0.05 equiv), finally the substrate **32** (107.7 mg, 0.66 mmol, 1 equiv) in CH_2Cl_2 (0.5 mL). The mixture was stirred at 22 °C and the catalysis was monitored by removal of ≈10 μL aliquots which were diluted with MeCN (≈0.1 mL) and were injected into the achiral GC. At the end of the reaction, hexane (8 mL) was added, the CH_2Cl_2 was removed in vacuo and the mixture was filtered through a Celite plug. The solvent was removed in vacuo then the residue was purified by chromatography using a silica gel column.

1-(−)-(1*S*)-7-Methylbicyclo[4.3.1]dec-6-en-2-one (33):[35] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.45–1.58 (m, 1H, COCH$_2$CH_2), 1.62 (s, 3H, CH_3), 1.71–1.79 (m, 1H, CH$_3$C=CCH_2CH), 1.84–2.13 (m, 6H, CH$_3$C=CCH_2CH, CH_2CH$_2$C(CH$_3$)=C, COCH$_2$CH_2), 2.26 (ddd, 1H, J = 11.3, 5.5,

2.8 Hz, $COCH_2CH_2$), 2.48 (ddd, 1H, $J=14.9$, 3.5, 1.7 Hz, $CH_3C=CCH_2CH_2$), 2.54–2.59 (m, 1H, COCH), 2.67 (dd, 1H, $J=12.6$, 6.0 Hz, $CH_3C=CCH_2CH_2$), 2.89 ppm (ddd, 1H, $J=14.1$, 11.4, 3.0 Hz, $COCH_2CH_2$); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=17.9$ (CH_3), 24.1 (CH_2), 27.4 (CH_2), 30.0 (CH_2), 32.6 (CH_2), 32.8 (CH_2), 42.0 (CH_2), 47.1 (CH), 130.6 (C), 135.7 (C), 216.7 ppm; IR (film): $\tilde{\nu}=2932$, 2866, 1697, 1475, 1439, 1376, 1318, 1301, 1203, 1144, 1073, 1031, 993, 900 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 17.03 min, 164 [M^+], 149, 135, 121, 108, 93, 93, 79; achiral GC (OV-17, He, 80 °C for 5 min then heating 5 °C min^{-1}): 10.853 (**32**), 14.198 min (**33**); chiral GC (Hydrodex-β, H_2, 100 °C (30 min) then heating at 0.5 °C min^{-1} to 120 °C: 53.393/54.342* min; column chromatography: pentane/Et_2O 95:5, $R_f=0.30$ (**32**), $R_f=0.16$ (**33**); isolated yield: 0.082 g, 77 %; $[\alpha]_D^{20}=-10°$ (CH_2Cl_2, $c=0.009$ mg mL^{-1}, 95 % *ee*); mol CD (0.00054 M, CH_2Cl_2, 20 °C): λ = 322 ($-6.55\,e^{-2}$), 316 ($-4.22\,e^{-2}$), 311 ($-6.19\,e^{-2}$), 239 (3.77), 226 nm ($-4.38\,e^{-2}$).

General procedure for preparing cycloadduct samples of known absolute configuration:[42] Chiral aldehydes were prepared with catalyst **1a** using our published procedures.[3,52]

The aldehyde (1 equiv) was dissolved in Et_2O (5 mL) and the solution was cooled to −78 °C. MeLi (1.6 M in Et_2O) (1.6 equiv) was added dropwise and the mixture was stirred at −78 °C for 3 h before being poured into ice water (20 mL). The organic layer was poured off and the water was extracted with Et_2O (2×30 mL), the combined organic layers were dried over $MgSO_4$, filtered and the solvent was removed in vacuo. The residue was purified by column chromatography Et_2O/pentane 9:1→1:1 and the products were isolated as mixtures of diastereomers.

Pyridinium chlorochromate (4.9 equiv) was dissolved in CH_2Cl_2 (20 mL) and neutral alumina (24.5 equiv) was added. The solvent was removed in vacuo then CH_2Cl_2 (10 mL) was added as described by Cheng et al.[53] The diastereomeric alcohol mixture of (1 equiv) dissolved in CH_2Cl_2 (5 mL) was added and the solution was stirred for 2 h. The mixture was filtered through a Fluorosil plug and was then purified by chromatography through silica gel eluted with pentane/Et_2O 9:1.

***exo*-(−)-(1*S*,2*S*,4*S*)-1-(2-Bromobicyclo[2.2.1]hept-5-en-2-yl)-ethanone (12a)**: *exo*-(−)-(1*S*,2*S*,4*S*)-2-Bromo-*exo*-2-formylbicyclo[2.2.1]hept-5-ene (85 % *ee*) (105 mg, 0.522 mmol, 1 equiv) was used to prepare 1-(1*S*,2*S*,4*S*)-(2-bromobicyclo[2.2.1]hept-5-en-2-yl)-(*R*,*S*)-ethanol ($R_f=0.21$, pentane/Et_2O 9:1), which was a waxy white solid (73 mg, 64 %) and a mixture of inseparable diastereomers ratio 7:3. IR (solid state): $\tilde{\nu}=3439$, 2972, 2923, 1706, 1665, 1449, 1376, 1278, 1249, 1116, 1086, 911, 854 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 15.0 min, 137 [M^+−Br], 91, 77, 71, 66; 15.1 min, 137 [M^+−Br], 119, 91, 66; HRMS-ESI (positive): *m*/*z*: calcd for $C_9H_{13}O$: 137.0966; found: 137.0964, accuracy: −1.7517 ppm.

Diastereomer 1 (major): ^1H NMR (300 MHz, CD_2Cl_2): $\delta=1.28$ (d, 3H, $J=6.0$ Hz, CH_3), 1.30–1.40 (m, 1H, $CHCH_2CH$), 1.48–1.61 (m, 3H, $CHCH_2CH$, $CHCH_2C$, OH), 1.85 (brs, 1H, $CHCH_2C$), 2.88 (brs, 1H, =$CHCH_2C$), 3.32–3.43 (m, 2H, =CHCH, CHOH), 6.13 (m, 1H, =CHCHC), 6.31 ppm (m, 1H, =$CHCHCH_2C$); ^{13}C NMR (100 MHz, CD_2Cl_2): $\delta=22.2$ (CH_3), 41.2 (CH_2), 43.2 (CH), 47.2 (CH_2), 52.2 (CH), 74.5 (CH), 86.7 (C), 137.3 (CH), 138.3 ppm (CH).

Diastereomer 2 (minor): ^1H NMR (300 MHz, CD_2Cl_2): $\delta=1.32$ (d, 3H, $J=6.0$ Hz, CH_3), 1.48–1.61 (m, 2H, $CHCH_2CH$, OH), 1.64 (dd, 1H, $J=11.8$, 1.3 Hz, $CHCH_2CH$), 1.78 (dd, 1H, $J=13.5$, 3.4 Hz, $CHCH_2C$), 2.23 (dd, 1H, $J=13.6$, 3.5 Hz, $CHCH_2C$), 2.99 (brs, 1H, =$CHCH_2C$), 3.32–3.43 (m, 1H, =CHCH, CHOH), 6.13 (m, 1H, =CHCHC), 6.31 ppm (m, 1H, =$CHCHCH_2C$); ^{13}C NMR (100 MHz, CD_2Cl_2): $\delta=21.6$ (CH_3), 43.1 (CH_2), 47.0 (CH), 50.7 (CH_2), 52.0 (CH), 75.4 (CH), 85.9 (C), 137.3 (CH), 138.2 ppm (CH).

1-(1*S*,2*S*,4*S*)-(2-Bromobicyclo[2.2.1]hept-5-en-2-yl)-(*R*,*S*)-ethanol (73 mg, 0.336 mmol) was oxidized and the product was isolated ($R_f=0.56$, pentane/Et_2O 20:1) as a colorless oil (62 mg, 86 %); ^1H NMR spectra and chiral GC analysis were consistent with an authentic sample of **12a**. Chiral GC (Lipodex-E, H_2, 85 °C isothermal): 97 % *de* (*exo*), 85 % *ee*. $[\alpha]_D^{20}=-88°$ (CH_2Cl_2, $c=0.01$ mg mL^{-1}, 84 % *ee*, with 1 % **12b** at 63 % *ee* with unknown configuration); mol CD (0.0046 M, CH_2Cl_2, 20 °C): λ = 349 ($-7.05\,e^{-4}$), 302 ($-6.58\,e^{-2}$), 238 nm ($4.89\,e^{-2}$).

***exo*-(−)-(1*S*,2*R*,4*S*)-1-(2-Methylbicyclo[2.2.1]hept-5-en-2-yl)-ethanone (20a)**: *exo*-(−)-(1*S*,2*R*,4*S*)-2-Methylbicyclo[2.2.1]hept-5-ene-2-carbaldehyde (91 % *ee*) (114 mg, 0.837 mmol) was used to prepare 1-(1*S*,2*R*,4*S*)-(2-methylbicyclo[2.2.1]hept-5-en-2-yl)-(*R*,*S*)-ethanol ($R_f=0.46$, 0.39, pentane/Et_2O 8:2), which was a waxy white solid (67 mg, 52 %) and a mixture of inseparable diastereomers ratio 7:3. IR (solid state): $\tilde{\nu}=3269$, 3059, 2967, 2879, 1573, 1455, 1373, 1331, 1124, 1087, 1361, 906, 727, 702 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 10.99 min, 152 [M^+], 134, 119, 107, 91, 79, 66; HRMS-ESI (positive): *m*/*z*: calcd for $C_{10}H_{14}$: 134.1095; found: 134.1094, accuracy: 1.0 ppm.

Diastereomer 1 (major): ^1H NMR (400 MHz, $CDCl_3$): $\delta=1.17$ (dd, 1H, $J=11.6$, 2.7 Hz, $CHCH_2CH$), 0.80 (s, 3H, CH_3), 1.17 (d, 3H, $J=6.6$ Hz, $CHCH_3$), 1.35–1.39 (m, 2H, $CHCH_2CH$, $CHCH_2C$), 1.46 (brs, 1H, OH), 1.59 (brd, 1H, $J=8.6$, $CHCH_2C$), 2.73–2.76 (brs, 1H, =$CHCHCH_2C$), 2.76–2.79 (m, 1H, =CHCHC), 3.78 (brq, 1H, $J=6.3$ Hz, CHOH), 6.10–6.13 ppm (m, 2H, CH=CH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=17.2$ (CH_3), 19.5 (CH_3), 38.1 (CH_2), 43.5 (CH), 46.5 (C), 47.0 (CH_2), 48.0 (CH), 74.0 (CH), 136.3 (CH), 136.5 ppm (CH).

Diastereomer 2 (minor): ^1H NMR (400 MHz, $CDCl_3$): $\delta=0.68$ (s, 3H, CH_3), 0.84 (dd, 1H, $J=9.8$, 2.8 Hz, $CHCH_2CH$), 1.19 (d, 3H, $J=6.6$ Hz, $CHCH_3$), 1.32–1.37 (m, 1H, $CHCH_2C$), 1.46 (brs, 1H, OH), 1.57–1.59 (m, 1H, $CHCH_2C$), 1.76 (dd, 1H, $J=11.9$, 3.8 Hz, $CHCH_2CH$), 2.41–2.43 (brs, 1H, =$CHCHCH_2C$), 2.79–2.83 (m, 1H, =CHCHC), 3.78 (brq, 1H, $J=6.3$ Hz, CHOH), 6.10–6.13 ppm (m, 2H, CH=CH); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=17.5$ (CH_3), 18.8 (CH_3), 39.1 (CH_2), 43.6 (CH), 46.4 (C), 47.3 (CH_2), 49.1 (CH), 75.0 (CH), 135.6 (CH), 137.0 ppm (CH).

1-(1*S*,2*R*,4*S*)-(2-Methylbicyclo[2.2.1]hept-5-en-2-yl)-(*R*,*S*)-ethanol (51 mg, 0.33 mmol) was oxidized and the product was isolated ($R_f=0.32$, pentane/Et_2O 9.5:0.5) as a colorless oil (40 mg, 81 %). ^1H NMR spectra and chiral GC analysis were consistent with an authentic sample of **20a**. Chiral GC (Lipodex-E, H_2, 70 °C isothermal): 88 % *de* (*exo*), 91 % *ee*. $[\alpha]_D^{20}=-91°$ (CH_2Cl_2, $c=0.008$ mg mL^{-1}, 91 % *ee*, with 6 % **20b** at >95 % *ee* with unknown configuration); mol CD (0.0063 M, CH_2Cl_2, 20 °C): λ = 328 ($-7.60\,e^{-3}$), 294 ($-9.62\,e^{-1}$), 232 nm ($3.81\,e^{-2}$).

1-(−)-(1*S*)-(1-Bromo-3,4-dimethylcyclohex-3-enyl)-ethanone (25): (−)-(1*S*)-1-Bromo-3,4-dimethylcyclohex-3-enecarbaldehyde (74 % *ee*) (212 mg, 0.97 mmol) was used to prepare 1-(1*S*)-(1-bromo-3,4-dimethylcyclohex-3-enyl)-(*R*,*S*)-ethanol ($R_f=0.17$, pentane/Et_2O 9:1), which was a waxy white solid (150 mg, 66 %) and a mixture of inseparable diastereomers 6:4. IR (solid state): $\tilde{\nu}=3270$, 3071, 2975, 2902, 1575, 1441, 1401, 1372, 1330, 1291, 1270, 1252, 1213, 1192, 1106, 1088, 1073, 1042, 1014, 990, 904 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 13.3 min, 153 [M^+−Br], 109, 95; 18.1 min, 152 [M^+−Br], 135, 119, 109, 91; 18.2 min, 152 [M^+−Br], 135, 119, 109, 91, 79; HRMS-ESI (positive): *m*/*z*: calcd for $C_{10}H_{17}O$: 153.1279; found: 153.1281, accuracy: 1.0427 ppm.

Diastereomer 1 (major): ^1H NMR (300 MHz, CD_2Cl_2): $\delta=1.26$ (d, 3H, $J=6.3$ Hz, $CHCH_3$), 1.59 (m, 3H, CCH_3), 1.63 (m, 3H, CCH_3), 1.87 (brs, 1H, OH), 1.95–2.10 (m, 2H, =CCH_2CH_2), 2.20–2.30 (m, 2H, =CCH_2CH_2), 2.36 (brs, 2H, =CCH_2C), 3.44 ppm (q, 1H, $J=6.2$ Hz, $CHCH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=18.3$ (CH_3), 18.6 (CH_3), 18.8 (CH_3), 30.2 (CH_2), 34.2 (CH_2), 42.4 (CH_2), 74.3 (CH), 81.4 (C), 121.6 (C), 124.8 ppm (C).

Diastereomer 2 (minor): ^1H NMR (300 MHz, CD_2Cl_2): $\delta=1.27$ (d, 3H, $J=6.2$ Hz, CH_3), 1.59 (m, 4H, =CCH_2CH_2, CCH_3), 1.63 (m, 3H, CCH_3), 1.87 (brs, 1H, OH), 1.95–2.10 (m, 1H, =CCH_2CH_2), 1.95–2.10 (m, 1H, =CCH_2CH_2), 2.20–2.30 (m, 2H, =CCH_2CH_2), 2.56 (brs, 1H, =CCH_2C), 3.52 ppm (q, 1H, $J=6.2$ Hz, $CHCH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=18.2$ (CH_3), 18.8 (CH_3), 18.9 (CH_3), 30.1 (CH_2), 33.1 (CH_2), 43.8 (CH_2), 73.7 (CH), 80.6 (C), 122.2 (C), 124.3 ppm (C).

1-(1*S*)-(1-Bromo-3,4-dimethylcyclohex-3-enyl)-(*R*,*S*)-ethanol (150 mg, 0.64 mmol, 1 equiv) was oxidized and the product was isolated ($R_f=0.39$, pentane/Et_2O 20:1) as a colorless oil (103 mg, 67 %). ^1H NMR spectra and chiral GC analysis were consistent with an authentic sample of **25**. Chiral GC (Lipodex-E, H_2, 90 °C isothermal): 68 % *ee*; $[\alpha]_D^{20}=-23°$ (CH_2Cl_2, $c=0.011$ mg mL^{-1}, 68 % *ee*); mol CD (0.0049 M, CH_2Cl_2, 20 °C): λ = 339 ($-1.49\,e^{-3}$), 301 ($4.32\,e^{-2}$), 247 nm ($-3.18\,e^{-1}$).

1-(−)-(1*S*)-(1-Bromo-4-methylcyclohex-3-enyl)-ethanone (27a): (−)-(1*S*)-1-Bromo-4-methylcyclohex-3-enecarbaldehyde (98% *ee*) (202 mg, 0.99 mmol) was used to prepare 1-(1*S*)-(1-bromo-4-methylcyclohex-3-enyl)-(*R*,*S*)-ethanol (R_f = 0.26, pentane/Et_2O 5:1), which was a waxy white solid (120 mg, 54%) and a mixture of inseparable diastereomers (6:4). IR (solid state): $\tilde{\nu}$ = 3409, 2969, 2908, 1430, 1378, 1248, 1123, 1095, 1059, 1009, 981, 953, 910, 887, 786 cm^{-1}; GC-MS EI (positive) (HP-5MS, He, 80 °C for 5 min then heating 5 °C min^{-1}): 15.8 min, 138 [M^+−Br], 121, 105, 95, 79; 16.0 min, 138 [M^+−Br], 121, 105, 95, 79; HRMS-ESI (positive): *m*/*z*: calcd for $C_9H_{15}O$: 139.1122; found: 139.1122, accuracy: −0.648 ppm.

Diastereomer 1 (major): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.30 (d, 3H, *J* = 6.3 Hz, $CHCH_3$), 1.60–1.80 (m, 1H, $=CCH_2CH_2$), 1.70 (m, 3H, CCH_3), 1.92 (brs, 1H, O*H*), 2.00–2.17 (m, 1H, $=CCH_2CH_2$), 2.22–2.38 (m, 2H, $=CCH_2CH_2$), 2.46 (dd, 2H, *J* = 64.7, 20.7 Hz, $=CHCH_2C$), 3.48 (q, 1H, *J* = 6.3 Hz, $CHCH_3$), 5.30 ppm (brs, 1H, C=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 19.1 (CH_3), 23.4 (CH_3), 28.9 (CH_2), 34.3 (CH_2), 36.8 (CH_2), 74.7 (CH), 80.2 (C), 117.8 (C), 133.7 ppm (C).

Diastereomer 2 (minor): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.33 (d, 3H, *J* = 6.0 Hz, CH_3), 1.60–1.80 (m, 1H, $=CCH_2CH_2$), 1.70 (m, 3H, CCH_3), 1.92 (brs, 1H, O*H*), 2.00–2.17 (m, 1H, $=CCH_2CH_2$), 2.22–2.38 (m, 2H, $=CCH_2CH_2$), 2.66 (dd, 2H, *J* = 43.9, 18.4 Hz, $=CHCH_2C$), 3.58 (q, 1H, *J* = 6.3 Hz, $CHCH_3$), 5.30 ppm (brs, 1H, C=C*H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 19.3 (CH_3), 23.3 (CH_3), 28.9 (CH_2), 32.9 (CH_2), 38.3 (CH_2), 74.2 (CH), 79.7 (C), 117.8 (C), 133.1 ppm (C).

1-(1*S*)-(1-Bromo-4-methylcyclohex-3-enyl)-(*R*,*S*)-ethanol (145 mg, 0.62 mmol) was oxidized and the product was isolated (R_f = 0.26, pentane/Et_2O 20:1) as a colorless oil (87 mg, 77%), ^{1}H NMR spectra and chiral GC analysis were consistent with an authentic sample of **27a**. Chiral GC (Lipodex-E, H_2, 70 °C isothermal): >85% *ee*; $[\alpha]_D^{20}$ = −28° (CH_2Cl_2, *c* = 0.011 mg mL^{-1}, 85% *ee*, with 1% 1,3-regioisomer **27b** at 99% *ee* with unknown configuration); mol CD (0.0053 M, CH_2Cl_2, 20 °C): λ = 300 (1.56 e^{-1}), 237 nm (−9.05 e^{-1}).

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