An Efficient Synthesis of Highly Functionalised 4-Substituted 2-Azetidinones by a Stereoselective Intermolecular Diels−Alder Reaction of Different Types of 2-Azetidinone-Tethered Dienes

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The diastereoselectivity of the intermolecular Diels–Alder reaction of 2-azetidinone-tethered dienes was investigated. Diene precursors were prepared from 4-azetidinone-2-carbaldehydes through an allylation–dehydration process or by the sequence Wittig reaction/enolate trapping. Dienes with a β-lactam ring at the allyl carbon of the diene moiety reacted with some acyclic symmetric dienophiles, such as dimethyl acetylenedicarboxylate and dimethyl fumarate, to yield Diels–Alder adducts efficiently in a highly diastereoselective manner. In addition, reaction with an unsymmetrical monoactivated dienophile, methyl propiolate, produced a single regioisomer. Intermolecular Diels–Alder reaction of 2-azetidinone-tethered dienes with cyclic dienophiles such as *N*-methyl and *N*-phenylmaleimide proceeded with modest *endo*/*exo* diastereoselectivity. Reaction of 2-azetidinone-tethered furans with dimethyl acetylenedicarboxylate gave 7-oxabicyclo[2.2.1]heptanes with modest diastereoselectivity. Retro-Diels–Alder reaction of these adducts, with cleavage of bonds other than those formed in the initial Diels–Alder cycloaddition, gave 4-ethynyl-β-lactams.

Introduction

The development of efficient approaches to the stereocontrolled synthesis of β-lactams continues to be of crucial importance as they constitute the most widely employed class of antimicrobial agents (β-lactam antibiotics account for 50% of the world's total antibiotic market).[1] In recent years several natural monocyclic β-lactams have been shown to exhibit high antibacterial activity, which suggests that a suitably substituted monocyclic 2-azetidinone ring might perhaps be the minimum requirement for biological activity.[2] Antielastase activity of 1,3,4-trisubstituted and 3,4-disubstituted 2-azetidinones has been determined against enzymes, for example, human leucocyte elastase.[3] In addition, the recent discoveries of some 1,3,4-trisubstituted-β-lactams as new potent cholesterol absorption inhibitors,[4] human cytomegalovirus protease inhibitors,[5] and thrombin inhibitors[6] justify a renewed interest in these compounds. Furthermore, monocyclic β-lactams frequently serve as precursors for the synthesis of polycyclic β-lactam antibiotics. In particular, the synthesis of trinems is generally based on the use of 4-cyclohexenyl-2-azetidinones.[7] On the other hand, the Diels−Alder reaction has become one of the most frequently employed carbon−carbon bond-forming reactions in organic synthesis, since it provides easy access to a wide variety of cyclic systems, usually with predictable stereochemistry.[8,9] Generally, facial selectivity of cycloaddition can be influenced by a chiral building block in which one face of the diene or dienophile is blocked preferentially. Incorporation of a stereogenic centre in an allylic position of either a dienophile or a diene, particularly when a heteroatom is present, is known to influence the direction of reaction.[10] Although many investigations have been made in this field into various types of systems, there is little information available on the regio- and stereochemistry of reactions with 2-azetidinone-tethered dienes as chiral buildings blocks in the Diels−Alder reaction. Only one report is available which involves racemic *trans*-3-butadienyl-2-azetidinones and some symmetrical dienophiles.[11] In the course of developing efficient routes to functionalised 2-azetidinones and their synthetic applications,[12] we have developed a tandem one-pot elimination/intramolecular Diels−Alder cycloaddition of 2-azetidinone tethered-trienes.[12a][12b] We wish to report here a highly regio- and diastereoselective intermolecular Diels−Alder reaction of various symmetric and unsymmetric dienophiles with different types of 2-azetidinone-tethered dienes **1**−**3** (Figure 1).

Results and Discussion

The starting materials, 4-oxoazetidine-2-carbaldehydes **4a**−**c**, were prepared both in the racemic and optically pure form by standard methodology. The racemic compound **4a**

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Supporting information for this article is available on the WWW under http://www.wiley-vch.de/home/eurjoc or from the author. It contains spectroscopic and analytical data for compounds (+)-**1b**−**c**, **3a**−**c**, **4c**, (+)-**5b**, ***E*-6a**, (+)-***E*-6b**, (+)-***Z*-6b**, **8a**, **9a**, **10b**, **10c**.

  1434−193X/01/0510−2001 $ 17.50+.50/0

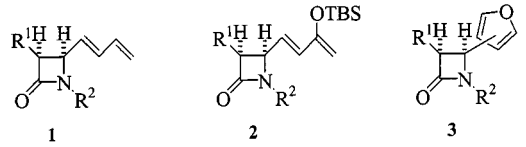


Figure 1. Types of 2-azetidinone-tethered dienes **1**−**3** used for intermolecular Diels−Alder reactions

was obtained as a single *cis* diastereoisomer from *N*,*N*-bis(*p*-methoxyphenyl)glyoxal diimine, following our one-pot method.[13] The enantiopure 2-azetidinones **5a**−**b** were obtained as single *cis* enantiomers from the corresponding imine of (*R*)-2,3-*O*-isopropylideneglyceraldehyde, through a Staudinger reaction with methoxyacetyl chloride in the presence of Et_3N.[14] Standard acetonide hydrolysis followed by oxidative cleavage smoothly formed the 4-oxoazetidine-2-carbaldehydes **4b**−**c** (Figure 2).[12a][12b]

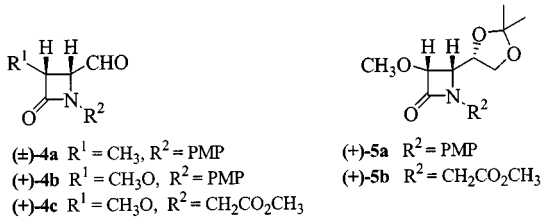
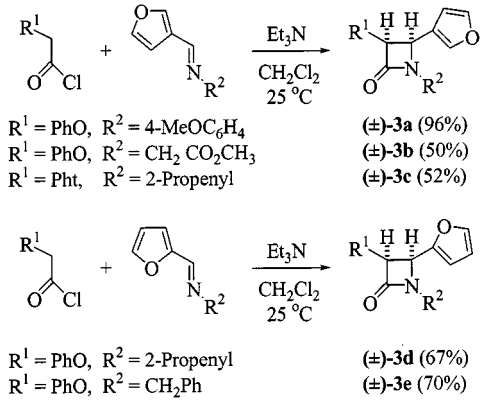


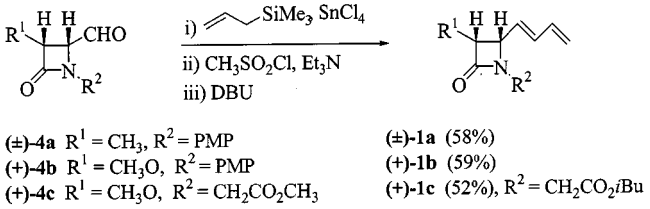
Figure 2. Starting β-lactam aldehydes **4** and their precursors **5**

The furyl-β-lactams **3a**−**e** were prepared as single *cis* diastereomers by a standard ketene-imine cycloaddition (Scheme 1).

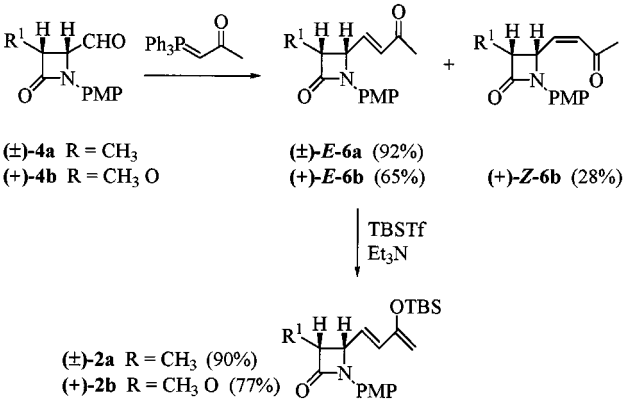


Scheme 1

The *E*-dienes **1** were easily prepared by allylation of the 4-oxoazetidine-2-carbaldehydes **4** and further formal dehydration following our previously reported procedure (Scheme 2).[12a][12b] The diene (+)-**1c** was obtained from the mesylate derived from aldehyde (+)-**4c** by a standard method, but with the addition of excess isobutyl alcohol. In this way, a more stable product for further synthetic transformations was achieved. Reaction between the stabilized 1-triphenylphosphoranylidene-2-propanone and 4-oxoazetidine-2-carbaldehyde **4a** gave the α,β-unsaturated ketone *E*-**6a** as the sole product with an excellent 92% yield. However, 4-oxoazetidine-2-carbaldehyde **4b**, with a methoxy group at C3, gave two products which were separated and identified as the isomeric products *E*-**6b** and *Z*-**6b**. The ^1H NMR spectra of alkenes **6** showed the signals of olefinic protons with coupling constants of ca. 16.0 Hz and 9.0 Hz, which correspond to *E* and *Z* configurations, respectively. The α,β-unsaturated ketones *E*-**6a** and *E*-**6b** were transformed, in very good yields (77−90%), into the activated dienes **2a**−**b** by treatment with *tert*-butyldimethylsilyl trifluoromethanesulfonate in the presence of Et_3N (Scheme 3).

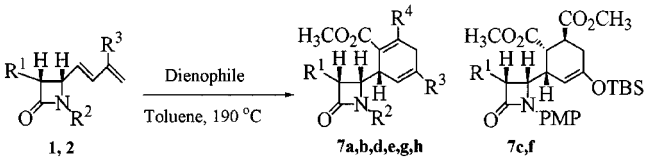


Scheme 2



Scheme 3

The 2-azetidinone-tethered dienes **1** and **2** yielded the Diels−Alder adducts **7a**−**g** (57−97%) in a highly diastereoselective manner (Scheme 4, Table 1) on heating in a sealed tube in toluene at 190 °C with various dienophiles such as dimethyl acetylenedicarboxylate, dimethyl fumarate, or methyl propiolate. In addition, the reaction with an unsymmetric monoactivated dienophile, methyl propiolate, gave a single regioisomer (Table 1, entries 4, 7). The regio- and stereochemistries of adducts **7** were established by NOE experiments.[15]



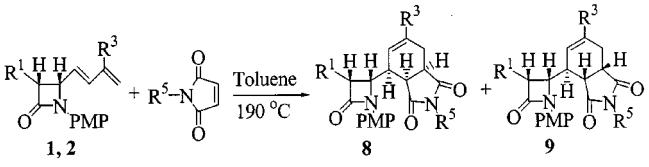
Scheme 4

Next, we studied the reactivity of 2-azetidinone-tethered dienes with cyclic dienophiles. An intermolecular Diels−Alder cycloaddition of dienes **1** and **2** with *N*-methyl or *N*-phenylmaleimide gave products **8a**−**c** and **9a**−**c** (Scheme 5, Table 2). The diastereomeric mixtures of adducts **8** and **9** were separated by column chromatography and the relative stereochemistry was established unambigu-

Table 1. Intermolecular Diels–Alder reaction of 2-azetidinone-tethered dienes **1** and **2** with acyclic dienophiles: synthesis of cycloadducts **7**

entry	R^1	R^2	R^3	Dienophile[a]	Adduct	d. r.[b]	Yield(%)[c]
1	CH_3	PMP[d]	H	E≡E	(±)-**7a**	100 : 0	66
2	CH_3	PMP	TBSO	E≡E	(±)-**7b**	95 : 5	97
3	CH_3	PMP	TBSO		(±)-**7c**	92 : 8	80
4	CH_3	PMP	TBSO	≡E	(±)-**7d**	100 : 0	82
5	CH_3O	PMP	H	E≡E	(–)-**7e**	100 : 0	77
6	CH_3O	PMP	TBSO		(+)-**7f**	83 : 17	57
7	CH_3O	PMP	TBSO	≡E	(+)-**7g**	100 : 0	89
8	CH_3O	CH_2CO_2iBu	H	E≡E	(–)-**7h**	100 : 0	50

[a] E = CO_2CH_3. – [b] Determined by integration of well-resolved signals in the ^1H NMR spectra of crude reaction mixtures prior to purification. – [c] Yield of pure, isolated product with correct analytical and spectral data. For reactions forming diastereomeric mixtures, the listed yields are for the pure combined mixture of isomers. – [d] PMP = 4-$MeOC_6H_4$.



Scheme 5

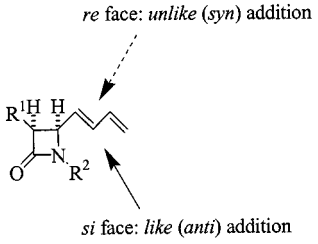


Figure 3. Facial selectivity in Diels–Alder reactions

Table 2. Intermolecular Diels–Alder reaction of 2-azetidinone-tethered dienes **1** and **2** with cyclic dienophiles: synthesis of cycloadducts **8/9**

Entry	R^1	R^3	R^5	Adducts	**8/9** ratio[a]	Yield (%)[b]
1	CH_3	H	CH_3	(±)-**8a**/(±)-**9a**	65:35	83
2	CH_3	TBSO	CH_3	(±)-**8b**/(±)-**9b**	60:40	73
3	CH_3O	H	Ph	(+)-**8c**/(+)-**9c**	70:30	86

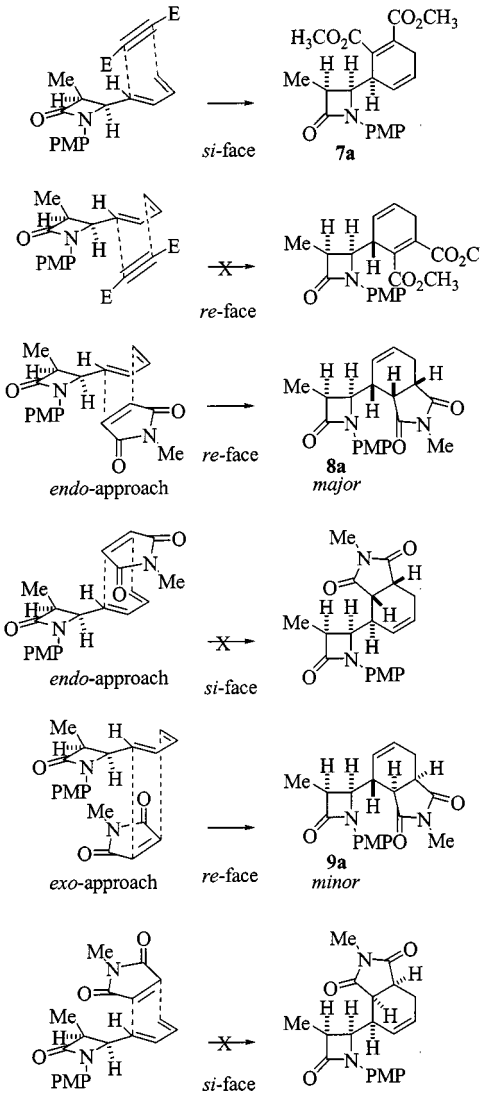
[a] Yield of pure, isolated product with correct analytical and spectral data. For reactions forming diastereomeric mixtures, the listed yields are for the pure combined mixture of diastereoisomers.[b] Determined by integration of well-resolved signals in the ^1H NMR spectra of the crude reaction mixtures prior to purification.

ously by NMR experiments and by the X-ray crystal structure analysis of compound **8b**.

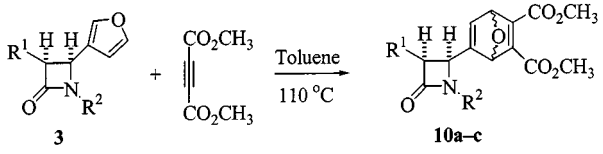
These results suggest that the reaction with acyclic dienophiles proceeds by selective attack on the *si* face of the chiral diene (the addition of the dienophile occurs *anti* to the directing allylic functionality), whereas the reaction with cyclic dienophiles proceeds at a *re* face in an *endo* cycloaddition manner (Figure 3).[16] The stereochemical outcome of the intermolecular Diels–Alder reaction in 2-azetidinone-tethered dienes could be rationalized through the transition states depicted in Scheme 6 for cycloadducts **7a**–**9a**.

We therefore explored the reactivity of 2-azetidinone-tethered furans with various dienophiles, taking into account that 7-oxabicyclo[2.2.1]heptanes are valuable synthetic intermediates which have been further elaborated to substituted arenes, carbohydrate derivatives, and various natural products.[17] The 2-azetidinones **3d**–**e**, with a 2-furyl substituent at C3, were unreactive under our standard Diels–Alder conditions. By contrast, when compounds **3a**–**c** with a 3-furyl substituent at C3 were used as 2-azetidinone-tethered dienes, the intermolecular Diels–Alder reaction with dimethyl acetylenedicarboxylate in boiling toluene gave the 7-oxabicyclo[2.2.1]heptanes **10a**–**c** with modest diastereoselectivity (Scheme 7, Table 3). Fortunately, the adducts **10a**(*major*) and **10a**(*minor*) could be separated by flash chromatography; however, compounds **10b**,**c**(*major*) and **10b**,**c**(*minor*) could not be separated and were characterised as mixtures. Some other dienophiles tested, such as dimethyl fumarate and dimethyl maleate, were unreactive with the 2-azetidinone-tethered furans **3a**–**c**.

Interestingly, heating adducts **10b**,**c** in a sealed tube in toluene at 190 °C with dimethyl acetylenedicarboxylate pro-



Scheme 6



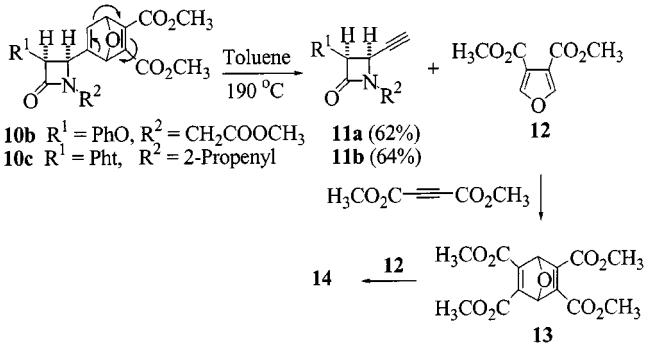
Scheme 7

Table 3. Intermolecular Diels–Alder reaction of the 2-azetidinone-tethered furans **3** with dimethyl acetylenedicarboxylate; synthesis of the cycloadducts **10**

Entry	R^1	R^2	Adducts	*dr*[a]	Yield (%)[b]
1	PhO	PMP	**(±)-10a**	77:23	74
2	PhO	CH_2COOCH_3	**(±)-10b**	70:30	98
3	Pht[c]	2-Propenyl	**(±)-10c**	65:35	81

[a] Determined by integration of well-resolved signals in the ^1H NMR spectra of the crude reactio mixtures prior to purification. – [b] Yield of pure, isolated product with correct analytical and spectral data. For reactions forming diastereomeric mixtures, the listed yields are for the pure combined mixture of diastereoisomers. – [c] Pht = phthalimido.

duced the 4-ethynyl-β-lactams **11a**,**b** and compound **14**. Adducts **10b**,**c** evolve through a retro-Diels–Alder reaction, with the cleavage of bonds other than those formed in the initial Diels–Alder reaction, to give the 4-ethynyl-β-lactams **11a**,**b** and 3,4-dicarboxymethyl furan (**12**).[18] The initially formed 3,4-disubstituted furan **12** undergoes a Diels–Alder reaction with dimethyl acetylenedicarboxylate to give product **13**. Oxanorbornadiene **13**, after a new Diels–Alder cycloaddition, presumably gives compound **14** as a mixture of isomers,[19] similar to closely related processes in the literature (Scheme 8).[20]



Scheme 8. Retro-Diels–Alder reaction of adducts **10**

Configurational Assignment for Diels–Alder Adducts

The structure and stereochemistry of compounds **7**–**10** have been assigned by NMR techniques and by X-ray diffraction. The *cis* stereochemistry of the four-membered ring is set during the cyclization step that forms the 2-azetidinone ring, and the *cis* stereochemistry is transferred unaltered during the further synthetic steps. We have recently noted in pyrrolidinyl-β-lactams that the vicinal coupling constants of the two protons located at the single bond connecting the two rings are diagnostic of the relative stereochemistry.[12h] The vicinal coupling constants of the two protons (4-H in the β-lactamic ring, and the hydrogen α to the new double bond in the six-membered ring) for the **7** isomers are approximately 5.5 Hz, which suggests a relative *syn* stereochemistry, whereas these vicinal coupling constants for the **8**/**9** isomers are approximately 10.5 Hz and indicate a relative *anti* stereochemistry for this connection.[21]

NOE irradiation of H4 in compound **7e** resulted in an 8% enhancement of the signal corresponding to H1′, while irradiation of H1′ resulted in a 9% enhancement of the signal corresponding to H4. Thus, a *syn* relative disposition between H4 and H1′ was established for this moiety (Figure 4). The NOE enhancements of H1′ were in the same range for adducts **7a** (7%), **7b** (4%), **7c** (6%) and **7g** (6%) when H4 was irradiated, and are consistent with the proposed stereochemistries. The regiochemistry of compounds **7d** and **7g** was established on the basis of NOE experiments: no NOE enhancements were observed for H3′ when H1′ was irradiated (Figure 4). For compound **7c**, irradiation of H1′ or H4 resulted in an NOE enhancement of H2′ (7 and 4% respectively). Furthermore, an NOE enhancement of 6% was observed for H1′ when H4 was irradiated, and this

is consistent with a *cis* H1′-H2′/*syn* H4-H1′ relative stereochemistry (Figure 4).

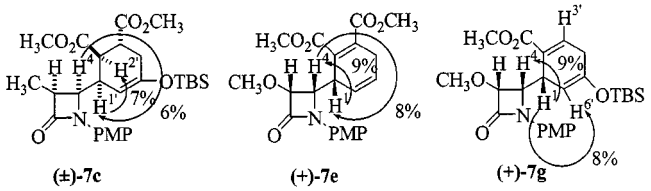


Figure 4. Selected NOE experiments for some compounds **7**

For adducts **8** and **9**, formed from cyclic dienophiles, no NOE enhancement for H4 was observed when H1′ was irradiated, and therefore an *anti* relationship between H4 and H1′ is assigned. A *trans* relative disposition between H1′ and H6′ was established for compounds **9** because of the absence of an NOE enhancement of H6′ on irradiation of H1′. The X-ray analysis of the major adduct **8b** confirmed the *anti* H4-H1′/*cis* H1′-H6′ relative stereochemistry in major isomers **8** (Figure 5).[22]

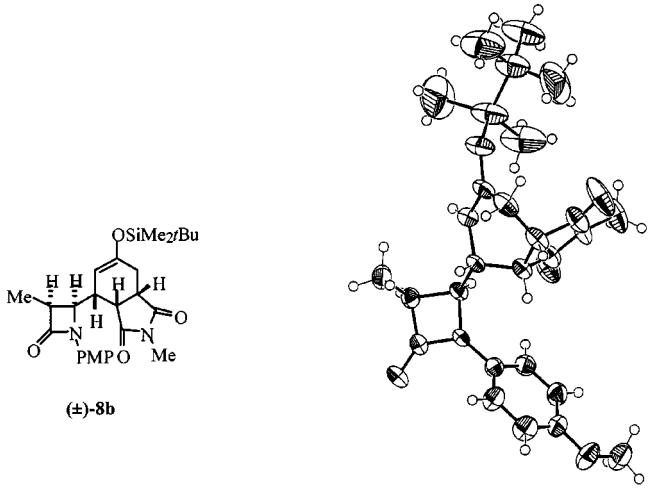


Figure 5. Projection of a molecule of compound **8b** as determined by X-ray crystallography

The stereochemistry of cycloadducts **10** could not be assigned without uncertainties on the basis of NMR experiments. Unfortunately, efforts to obtain a single crystal were unsuccessful.

Conclusion

In conclusion, the present study provides the first insight into the manner in which different types of racemic and optically pure *cis*-2-azetidinone-tethered dienes undergo intermolecular Diels−Alder reaction with a variety of symmetric and unsymmetric dienophiles. In addition, the reaction has been shown, in most cases, to be highly regio- and stereoselective, and provides a synthetically feasible entry into various types of racemic and homochiral 1,3,4-trisubstituted 2-azetidinones in a controlled manner. The extension of this methodology to the preparation of differently substituted derivatives of the trinem class is currently under investigation in our laboratories.

Experimental Section

General: General experimental data and procedures have been previously reported.[12a] − NMR spectra were recorded in $CDCl_3$ solutions, except where stated otherwise. Chemical shifts are given in ppm relative to TMS (^{1}H: δ = 0.0), or $CDCl_3$ (^{13}C: δ = 77.0). − Specific rotation $[\alpha]_D$ values are given in deg per dm at 20 °C, and the concentration (*c*) is expressed in g per 100 mL. All commercially available compounds were used without further purification. The following chemicals were prepared according to our previously reported procedures: **1a**,[12a,12b] **3d**,[12c] **3e**,[12c] **4a**,[12a,12b] **(+)-4b**,[12a,12b] and **(+)-5a**.[12a,12b]

General Procedure for the Preparation of Dienes 2: *tert*-Butyldimethylsilyl trifluoromethanesulfonate (317 mg, 1.2 mmol) was slowly added to a stirred solution of the corresponding ketone (1.0 mmol) in dichloromethane (5 mL) and triethylamine (1.2 mL) at 0 °C, and then the reaction mixture was stirred for 1 h at 0 °C. Water (1 mL) was added at 0 °C, and the mixture allowed to warm to room temperature before it was partitioned between dichloromethane and water. The organic extract was washed with brine, dried ($MgSO_4$), and concentrated under reduced pressure. Chromatography of the residue with hexanes/ethyl acetate (8:2 containing 10% of triethylamine) as eluent gave analytically pure compounds **2**.[23]

(3*SR*,4*RS*)-4-[(1*E*)-3-*tert*-Butyldimethylsilyloxy-1,3-butadienyl]-1-(*p*-methoxyphenyl)-3-methyl-2-azetidinone (2a): From ketone ***E*-6a** (259 mg, 1.0 mmol), compound **2a** (335 mg, 90%) was obtained as a colourless solid; m.p. 61−64 °C (hexanes/ethyl acetate). − ^{1}H NMR: δ = −0.01 and 0.03 (s, each 3 H), 0.79 (s, 9 H), 1.07 (d, *J* = 7.6 Hz, 3 H), 3.33 (dq, *J* = 7.6, 5.9 Hz, 2 H), 3.64 (s, 3 H), 4.22 and 4.25 (s, each 1 H), 4.48 (dq, *J* = 7.8, 5.9 Hz, 1 H), 5.85 (dd, *J* = 15.1, 7.8 Hz, 1 H), 6.07 (d, *J* = 15.1 Hz, 1 H), 6.70 and 7.21 (d, *J* = 9.0 Hz, each 2 H). − ^{13}C NMR: δ = 167.8, 155.8, 153.8, 133.1, 131.7, 125.2, 118.2, 114.2, 97.2, 56.4, 55.4, 48.8, 25.7, 18.2, 9.8, −4.5. − IR (KBr): ṽ = 1747 cm^{-1}. − MS (CI): *m*/*z* (%) = 374 (100) [M$^+$ + 1], 373 (34) [M$^+$]. − $C_{21}H_{31}NO_3Si$ (373.6): calcd. C 67.52, H 8.36, N 3.75, Si 7.52; found C 67.64, H 8.50, N 3.70, Si 7.42.

(3*R*,4*S*)-4-[(1*E*)-3-*tert*-Butyldimethylsilyloxy-1,3-butadienyl]-3-methoxy-1-(*p*-methoxyphenyl)-2-azetidinone [(+)-2b]: From ketone **(+)-*E*-6b** (630 mg, 2.29 mmol), compound **(+)-2b** (687 mg, 77%) was obtained as a colourless solid; m.p. 58−60 °C (hexanes/ethyl acetate). − $[\alpha]_D$ = +95.6 (*c* = 1.2, $CHCl_3$). − ^{1}H NMR: δ = −0.01 and 0.03 (s, each 3 H), 0.79 (s, 9 H), 3.33 (s, 3 H), 3.64 (s, 3 H), 4.21 and 4.25 (s, each 1 H), 4.52 (m, 2 H), 5.94 (m, 1 H), 6.18 (d, *J* = 15.4 Hz, 1 H), 6.70 and 7.20 (d, *J* = 9.0 Hz, each 2 H). − ^{13}C NMR: δ = 163.6, 156.5, 154.2, 134.3, 131.2, 124.3, 118.8, 11.4, 97.6, 84.9, 60.2, 58.8, 55.5, 25.8, 18.4, −4.7. − IR (KBr): ṽ = 1754 cm^{-1}. − MS (CI): *m*/*z* (%) = 338 (100) [M$^+$ + 1], 337 (46) [M$^+$]. − $C_{18}H_{31}NO_3Si$ (337.5): calcd. C 64.75, H 8.02, N 3.60, Si 7.21; found C 64.57, H 7.98, N 3.50, Si 7.10.

General Procedure for the Preparation of Diels−Alder Adducts 7−9: To a solution of the corresponding diene **1**−**2** (0.40 mmol), and hydroquinone (cat.) in toluene (6 mL) was added the appropriate dienophile (0.60 mmol). The resulting solution was heated in a sealed tube at 190 °C. The reaction mixture was allowed to cool to room temperature, and the solvent was removed under reduced pressure. Chromatography of the residue eluted with hexanes/ethyl acetate mixtures gave analytically pure adducts **7**−**9**.

2-Azetidinone 7a: From diene **1a** (72 mg, 0.296 mmol) and dimethyl acetylenedicarboxylate (54 mg, 0.36 mmol), after heating at 190 °C

for 18 h, adduct **7a** (78 mg, 66%) was obtained as a pale yellow oil after purification by flash chromatography (hexanes/ethyl acetate, 1:1). − ^{1}H NMR: δ = 1.41 (d, *J* = 7.7 Hz, 3 H), 2.32 (ddt, *J* = 23.5, 8.0, 1.9 Hz, 1 H), 2.76 (ddd, *J* = 23.5, 6.2, 3.7 Hz, 1 H), 3.55 (qd, *J* = 7.7, 5.9 Hz, 1 H), 3.72 (m, 1 H), 3.77 and 3.78 (s, each 3 H), 3.80 (s, 3 H), 4.41 (dd, *J* = 5.9, 1.5 Hz, 1 H), 5.66 (s, 2 H), 6.80 and 7.26 (d, *J* = 9.0 Hz, each 2 H). − ^{13}C NMR: δ = 168.1, 167.8, 167.6, 155.9, 134.9, 134.6, 131.2, 125.5, 122.6, 119.2, 114.0, 56.9, 55.4, 52.6, 52.3, 47.1, 36.7, 27.5, 9.1. − IR ($CHCl_3$): ṽ = 1740, 1725, 1720 cm^{-1}. − MS (CI): *m*/*z* (%) = 386 (100) [M^+ + 1], 385 (38) [M^+]. − $C_{21}H_{23}NO_6$ (385.4): calcd. C 65.44, H 6.02, N 3.63; found C 65.34, H 6.10, N 3.71.

2-Azetidinone 7b: From diene **2a** (75 mg, 0.20 mmol) and dimethyl acetylenedicarboxylate (37 mg, 0.24 mmol), after heating at 190 °C for 16 h, adduct **7b** (98 mg, 97%), with approximately 5% of a minor isomer, was obtained as a colourless oil after purification by flash chromatography (hexanes/ethyl acetate 6:4, containing 10% of triethylamine). − ^{1}H NMR: δ = −0.07 and 0.00 (s, each 3 H), 0.77 (s, 9 H), 1.20 (d, *J* = 7.1 Hz, 3 H), 2.46 (dd, *J* = 22.5, 6.1 Hz, 1 H), 2.71 (dd, *J* = 22.4, 7.8 Hz, 1 H), 3.54 (dd, *J* = 7.7, 6.0 Hz, 1 H), 3.75 and 3.76 (s, each 3 H), 3.77 (m, 1 H), 3.79 (s, 3 H), 4.38 (dd, *J* = 6.0, 1.5 Hz, 1 H), 4.69 (dd, *J* = 4.1, 1.7 Hz, 1 H), 6.78 and 7.20 (d, *J* = 9.0 Hz, each 2 H). − ^{13}C NMR: δ = 168.4, 167.8, 166.8, 156.0, 148.9, 136.4, 132.8, 131.1, 119.1, 114.1, 98.4, 57.0, 55.5, 52.7, 52.4, 47.1, 38.9, 31.4, 25.5, 17.8, 9.0. − IR ($CHCl_3$): ṽ = 1743, 1726, 1718 cm^{-1}. − MS (EI): *m*/*z* (%) = 515 (16) [M^+], 295 (100). − $C_{27}H_{37}NO_7Si$ (517.7): calcd. C 62.89, H 7.23, N 2.72, Si 5.45; found C 62.48, H 7.53, N 2.60, Si 5.40.

2-Azetidinone 7c: From diene **2a** (75 mg, 0.20 mmol) and dimethyl fumarate (35 mg, 0.24 mmol), after heating at 190 °C for 20 h, adduct **7c** (83 mg, 80%), with approximately 8% of a minor isomer, was obtained as a colourless oil after purification by flash chromatography [hexanes/ethyl acetate (3:1) containing 10% of triethylamine]. − ^{1}H NMR: δ = −0.16 and −0.14 (s, each 3 H), 0.81 (s, 9 H), 1.28 (d, *J* = 7.5 Hz, 3 H), 2.23 (m, 2 H), 2.85 (t, *J* = 10.2 Hz, 1 H), 3.44 (dd, *J* = 7.8, 5.8 Hz, 1 H), 3.68 (s, 6 H), 3.75 (s, 3 H), 4.25 (dd, *J* = 5.8, 2.9 Hz, 1 H), 4.66 (s, 1 H), 6.84 (d, *J* = 9.0 Hz, 2 H), 7.30 (d, *J* = 9.0 Hz, 2 H). − ^{13}C NMR: δ = 174.4, 173.7, 168.6, 156.3, 149.4, 131.5, 119.8, 114.4, 101.5, 56.0, 55.5, 52.3, 52.2, 46.9, 46.4, 42.9, 37.4, 31.3, 25.5, 17.7, 9.3, −4.5, −4.9. − IR ($CHCl_3$): ṽ = 1748, 1742, 1738 cm^{-1}. − MS (EI): *m*/*z* (%) = 517 (18) [M^+], 295 (100). − $C_{27}H_{39}NO_7Si$ (512.66): calcd. C 62.64, H 7.59, N 2.71, Si 5.43; found C 62.51, H 7.69, N 2.82, Si 5.33.

2-Azetidinone 7d: From diene **2a** (75 mg, 0.20 mmol) and methyl propiolate (168 mg, 2.0 mmol), after heating at 190 °C for 18 h, adduct **7d** (75 mg, 82%) was obtained as a colourless oil after purification by flash chromatography [hexanes/ethyl acetate (5:1) containing 10% of triethylamine]. − ^{1}H NMR: δ = 0.00 and 0.14 (s, each 3 H), 1.00 (s, 9 H), 1.53 (d, *J* = 7.5 Hz, 3 H), 2.43 (dd, *J* = 23.5, 7.5 Hz, 1 H), 2.74 (td, *J* = 18.1, 5.6 Hz, 1 H), 3.65 (m, 1 H), 3.88 (s, 3 H), 3.91 (m, 1 H), 3.94 (s, 3 H), 4.44 (d, *J* = 6.0 Hz, 1 H), 4.87 (d, *J* = 4.3 Hz, 1 H), 6.89 (d, *J* = 9.0 Hz, 2 H), 7.10 (dd, *J* = 7.3, 3.6 Hz, 1 H), 7.37 (d, *J* = 9.0 Hz, 2 H). − ^{13}C NMR: δ = 168.3, 166.7, 155.7, 148.6, 138.3, 131.9,. 131.1, 118.9, 113.8, 100.1, 58.4, 55.5, 52.0, 47.0, 35.6, 31.3, 25.6, 17.7, 9.3, −4.5, −4.9. − IR ($CHCl_3$): ṽ = 1745, 1740 cm^{-1}. − MS (CI): *m*/*z* (%) = 458 (100) [M^+ + 1], 457 (56) [M^+]. − $C_{25}H_{35}NO_5Si$ (457.6): calcd. C 65.61, H 7.71, N 3.06, Si 6.14; found C 65.21, H 7.57, N 3.26, Si 6.34.

2-Azetidinone (−)-7e: From diene **(+)-1b** (75 mg, 0.19 mmol) and dimethyl acetylenedicarboxylate (35 mg, 0.23 mmol), after heating at 190 °C for 16 h, adduct **(−)-7e** (84 mg, 77%) was obtained as a colourless oil after purification by flash chromatography (hexanes/ethyl acetate, 2:1). − $[\alpha]_D$ = −1.8 (*c* = 1.0, $CHCl_3$). − ^{1}H NMR: δ = 2.03 (dd, *J* = 23.5, 7.5 Hz, 1 H), 2.70 (td, *J* = 23.5, 4.8 Hz, 1 H), 3.65 (s, 3 H), 3.76 (m, 1 H), 3.77 (s, 6 H), 3.86 (s, 3 H), 4.63 (d, *J* = 5.4 Hz, 1 H), 4.67 (d, *J* = 9.8 Hz, 1 H), 5.81 (td, *J* = 10.7, 3.2 Hz, 1 H), 6.77 and 7.32 (d, *J* = 9.0 Hz, each 2 H). − ^{13}C NMR: δ = 168.3, 167.5, 164.7, 156.2, 135.1, 134.7, 130.4, 125.3, 123.3, 119.6, 113.9, 82.8, 59.6, 59.2, 55.4, 52.5, 52.2, 37.2, 27.2. − IR ($CHCl_3$): ṽ = 1745, 1730, 1725 cm^{-1}. − MS (CI): *m*/*z* (%) = 378 (100) [M^+ + 1], 377 (12) [M^+]. − $C_{21}H_{23}NO_7$ (401.4): calcd. C 62.84, H 5.78, N 3.49; found C 62.68, N 5.94, N 3.61.

2-Azetidinone (+)-7f: From diene **(+)-2b** (75 mg, 0.19 mmol) and dimethyl fumarate (33 mg, 0.23 mmol), after heating at 190 °C for 18 h, adduct **(+)-7f** (58 mg, 57%), with approximately 17% of a minor isomer, was obtained as a colourless oil after purification by flash chromatography [hexanes/ethyl acetate (2:1) containing 10% of triethylamine]. − $[\alpha]_D$ = +43.4 (*c* = 1.0, $CHCl_3$). − ^{1}H NMR: δ = −0.05 and 0.05 (s, each 3 H), 0.85 (s, 9 H), 2.13 (dd, *J* = 13.7, 2.5 Hz, 1 H), 2.28 (dd, *J* = 18.8, 5.6 Hz, 1 H), 3.03 (m, 2 H), 3.60 (s, 3 H), 3.67 and 3.68 (s, each 3 H), 3.79 (s, 3 H), 4.42 (dd, *J* = 5.4, 2.4 Hz, 1 H), 4.56 (dd, *J* = 5.4, 0.7 Hz, 1 H), 4.82 (s, 1 H), 6.87 and 7.42 (d, *J* = 8.3 Hz, each 2 H). − ^{13}C NMR: δ = 174.4, 173.7, 165.4, 156.5, 149.3, 130.8, 119.8, 114.3, 101.7, 82.9, 56.5, 58.9, 55.4, 52.1, 52.0, 45.6, 43.1, 37.6, 31.6, 25.5, 17.8, −4.6, −5.0. − IR ($CHCl_3$): ṽ = 1745, 1740, 1738 cm^{-1}. − MS (EI): *m*/*z* (%) = 534 (100) [M^+ + 1], 533 (28) [M^+]. − $C_{27}H_{39}NO_8Si$ (533.7): calcd. C 60.76, H 7.37, N 2.62, Si 5.26; found C 60.56, N 7.35, N 2.52, Si 5.13.

2-Azetidinone (+)-7g: From diene **(+)-2b** (79 mg, 0.20 mmol) and methyl propiolate (168 mg, 2.0 mmol), after heating at 190 °C for 16 h, adduct **(+)-7g** (84 mg, 89%) was obtained as a colourless oil after purification by flash chromatography [hexanes/ethyl acetate (8:2) containing 10% of triethylamine]. − $[\alpha]_D$ = +79.4 (*c* = 1.0, $CHCl_3$). − ^{1}H NMR: δ = −0.03 and 0.08 (s, each 3 H), 0.92 (s, 9 H), 2.18 (m, 1 H), 2.57 (td, *J* = 23.4, 5.1 Hz, 1 H), 3.66 (s, 3 H), 3.76 (s, 3 H), 3.78 (d, *J* = 1.2 Hz, 1 H), 4.57 (dd, *J* = 5.4, 0.7. Hz, 1 H), 4.62 (d, *J* = 5.4, Hz, 1 H), 4.96 (dd, *J* = 4.6, 2.2 Hz, 1 H), 6.76 (d, *J* = 9.0 Hz, 2 H), 6.83 (m, 1 H), 7.13 (d, *J* = 9.0 Hz, 2 H). − ^{13}C NMR: δ = 166.7, 164.8, 156.1, 148.5, 139.3, 130.9, 130.2, 119.4, 113.7, 100.5, 82.9, 60.8, 59.5, 55.4, 51.9, 36.1, 31.3, 25.4, 17.7, −4.4, −4.7. − IR ($CHCl_3$): ṽ = 1745, 1739 cm^{-1}. − MS (EI): *m*/*z* (%) = 473 (28) [M^+], 175 (100). − $C_{25}H_{35}NO_6Si$ (473.65): calcd. C 63.40, H 7.45, N 2.96, Si 5.93; found C 63.30, N 7.39, N 3.04, Si 5.85.

2-Azetidinone (−)-7h: From diene **(+)-1c** (94 mg, 0.35 mmol) and dimethyl acetylenedicarboxylate (73.9 mg, 0.52 mmol), after heating at 190 °C for 12 h, adduct **(−)-7h** (71 mg, 50%) was obtained as a colourless oil after purification by flash chromatography (hexanes/ethyl acetate 2:1). − ^{1}H NMR: δ = 0.85 (d, *J* = 9.5 Hz, 6 H), 1.83 (m, 1 H), 2.94 (d, *J* = 7.8 Hz, 2 H), 3.59 and 3.71 (s, each 3 H), 3.76 (m, 1 H), 3.77 (s, 3 H), 3.90 (m, 3 H), 4.17 (dd, *J* = 5.1, 2.2 Hz, 1 H), 4.32 (d, *J* = 18.0 Hz, 1 H), 4.63 (d, *J* = 5.1 Hz, 1 H), 5.83 (d, *J* = 1.6 Hz, 2 H). − ^{13}C NMR: δ = 168.3, 167.7, 167.6, 167.3, 135.9, 132.9, 124.8, 124.1, 116.1, 84.5, 71.6, 59.9, 59.7, 52.4, 41.9, 37.3, 27.6, 27.4, 19.0. − IR ($CHCl_3$): ṽ = 1760, 1742, 1725, 1722 cm^{-1}. − MS (CI): *m*/*z* (%) = 410 (100) [M^+ + 1], 409 (42) [M^+]. − $C_{20}H_{27}NO_8$ (409.44): calcd. C 58.67, H 6.65, N 3.42; found C 58.77, H 6.57, N 3.38.

2-Azetidinones 8b/9b: From diene **2a** (75 mg, 0.20 mmol) and *N*-methylmaleimide (27 mg, 0.24 mmol), after flash chromatography eluting with hexanes/ethyl acetate (1:2, containing 10% of triethyl-

amine), the less-polar compound **8b** (43 mg, 44%) as a colourless solid and the more-polar compound **9b** (29 mg, 29%) as a colourless oil were obtained.

2-Azetidinone 8b: Colourless solid; m.p. 172−174 °C (hexanes/ethyl acetate). − ^{1}H NMR: δ = 0.04 and 0.08 (s, each 3 H), 0.79 (s, 9 H), 1.25 (d, *J* = 7.5 Hz, 3 H), 2.46 (m, 2 H), 2.92 (s, 3 H), 3.01 (m, 2 H), 3.53 (dd, *J* = 7.6, 5.6 Hz, 1 H), 3.78 (s, 3 H), 4.25 (dd, *J* = 5.8, 2.9 Hz, 1 H), 4.56 (dd, *J* = 1.5, 2.9 Hz, 1 H), 5.18 (dd, *J* = 16.5, 8.4 Hz, 1 H), 6.84 (d, *J* = 9.0 Hz, 2 H), 7.54 (d, *J* = 9.0 Hz, 2 H). − ^{13}C NMR: δ = 179.0, 178.4, 169.4, 157.2, 151.5, 130.7, 122.5, 114.4, 101.6, 56.0, 55.6, 46.8, 42.3, 40.2, 39.5, 31.1, 25.6, 25.1, 18.1, 9.6, −4.5, −4.9. − IR ($CHCl_3$): ṽ = 1750, 1740, 1711 cm^{-1}. − MS (CI): *m*/*z* (%) = 485 (100) [M$^+$ + 1], 484 (42) [M$^+$]. − $C_{26}H_{36}N_2O_5Si$ (484.67): calcd. C 64.43, H 7.49, N 5.78, Si 5.79; found C 64.34, N 7.45, N 5.86, Si 5.72.

2-Azetidinone 9b: Colourless oil. − ^{1}H NMR: δ = −0.34 and −0.27 (s, each 3 H), 0.69 (s, 9 H), 1.39 (d, *J* = 7.8 Hz, 3 H), 2.24 (d, *J* = 14.8 Hz, 1 H), 2.50 (d, *J* = 15.8 Hz, 1 H), 2.62 (d, *J* = 10.7 Hz, 1 H), 2.89 (s, 3 H), 3.63 (m, 1 H), 3.70 (s, 3 H), 4.58 (s, 1 H), 4.66 (s, 1 H), 4.93 (dd, *J* = 10.7, 5.4 Hz, 1 H), 6.79 (d, *J* = 9.0 Hz, 2 H), 7.15 (d, *J* = 9.0 Hz, 2 H). − ^{13}C NMR: δ = 178.9, 177.8, 169.8, 157.6, 151.8, 130.2, 123.5, 114.7, 101.7, 56.2, 55.5, 46.8, 41.4, 40.3, 37.8, 29.8, 25.4, 25.0, 17.8, 9.8, −5.2, −5.4. − IR ($CHCl_3$): ṽ = 1747, 1739, 1708 cm^{-1}. − MS (EI): *m*/*z* (%) = 484 (11) [M$^+$], 149 (100). − $C_{27}H_{36}N_2O_5Si$: (496.68): calcd. C 64.43, H 7.49, N 5.78, Si 5.79; found C 64.51, H 7.53, N 5.86, Si 5.84.

2-Azetidinones (+)-8c/(+)-9c: From diene **(+)-1b** (75 mg, 0.20 mmol) and *N*-phenylmaleimide (42 mg, 0.24 mmol), after flash chromatography eluting with dichloromethane/ethyl acetate (10:1), the less polar compound **(+)-9c** (30 mg, 25%) as a colourless oil and the more polar compound **(+)-8c** (71 mg, 61%) as a colourless oil were obtained.

2-Azetidinone (+)-9c: Colourless oil. − $[\alpha]_D$ = +18.9 (*c* = 1.0, $CHCl_3$). − ^{1}H NMR: δ = 2.26 (dd, *J* = 13.6, 7.1 Hz, 1 H), 2.76 (m, 1 H), 3.26 (m, 2 H); 3.54 (s, 3 H), 3.79 (s, 3 H), 4.70 (d, *J* = 5.4 Hz, 1 H), 5.28 (dd, *J* = 8.7, 5.4 Hz, 1 H), 5.96 (d, *J* = 3.9 Hz, 2 H), 6.88 (d, *J* = 9.0 Hz, 2 H), 7.22 (m, 3 H), 7.50 (m, 4 H). − ^{13}C NMR: δ = 178.4, 177.3, 165.9, 157.0, 131.8, 129.9, 129.1, 128.7, 126.4, 125.9, 121.0, 114.4, 83.6, 59.6, 57.8, 55.4, 41.9, 40.0, 37.4, 24.6. − IR ($CHCl_3$): ṽ = 1748, 1737, 1711 cm^{-1}. − MS (EI): *m*/*z* (%) = 408 (19) [M$^+$], 149 (100). − $C_{23}H_{24}N_2O_5$ (408.46): calcd. C 67.63, H 5.92, N 6.86; found C 67.71, N 5.84, N 6.77.

2-Azetidinone (+)-8c: Colourless oil. − $[\alpha]_D$ = +57.0 (*c* = 1.0, $CHCl_3$). − ^{1}H NMR: δ = 2.23 and 2.78 (m, each 1 H), 2.88 (m, 1 H), 3.35 (td, *J* = 7.5, 1.5 Hz, 1 H), 3.66 (s, 3 H), 3.72 (s, 3 H), 3.84 (dd, *J* = 9.0, 5.4 Hz, 1 H), 4.77 (d, *J* = 5.2 Hz, 1 H), 5.22 (dd, *J* = 10.7, 5.4 Hz, 2 H), 5.90 (d, *J* = 3.9 Hz, 2 H), 6.88 (d, *J* = 9.0 Hz, 2 H), 7.23 (m, 4 H), 7.39 (m, 3 H). − ^{13}C NMR: δ = 178.7, 177.8, 166.1, 157.3, 131.7, 130.3, 129.6, 129.1, 128.7, 128.5, 114.4, 83.5, 59.5, 57.8, 55.4, 40.9, 40.1, 38.0, 24.5. − IR ($CHCl_3$): ṽ = 1746, 1740, 1707 cm^{-1}. − MS (CI): *m*/*z* (%) = 409 (100) [M$^+$ + 1], 408 (30) [M$^+$]. − $C_{23}H_{24}N_2O_5$ (408.46): calcd. C 67.63, H 5.92, N 6.86; found C 67.53, N 5.86, N 6.80.

General Procedure for the Preparation of Diels−Alder Adducts 10a−c: To a solution of the appropriate 3-furyl-β-lactam **3a−c** (0.30 mmol), and hydroquinone (cat.) in toluene (6 mL) was added dimethyl acetylenedicarboxylate (0.60 mmol), and the reaction was heated for 16 hours at reflux temperature. The reaction mixture was allowed to cool to room temperature, and the solvent was removed under reduced pressure. Chromatography of the residue eluted with hexanes/ethyl acetate mixtures gave adducts **10a−c**.

2-Azetidinones 10a: From 3-furyl-β-lactam **3a** (50 mg, 0.15 mmol) and dimethyl acetylenedicarboxylate (46 mg, 0.30 mmol), after flash chromatography eluted with hexanes/ethyl acetate (2:1), the less polar compound **10a**(*major*) (41 mg, 57%) as a colourless solid and the more polar compound **10a**(*minor*) (12 mg, 17%) as a colourless solid were obtained.

2-Azetidinone 10a(*major*): Colourless solid; m.p. 126−127 °C (hexanes/ethyl acetate). − ^{1}H NMR: δ = 3.63 (s, 3 H), 3.69 (s, 3 H), 3.73 (s, 3 H), 5.25 (dd, *J* = 5.0, 1.2 Hz, 1 H), 5.39 (d, *J* = 5.0 Hz, 1 H), 5.47 (d, *J* = 1.7 Hz, 1 H), 5.53 (dd, *J* = 2.2, 1.7 Hz, 1 H), 6.84 (d, *J* = 9.0 Hz, 2 H), 6.93 (m, 3 H), 7.03 (dd, *J* = 2.5, 0.9 Hz, 1 H), 7.19 (m, 2 H), 7.34 (d, *J* = 9.0 Hz, 2 H). − ^{13}C NMR: δ = 162.9, 161.5, 161.4, 156.7, 156.3, 153.4, 153.2, 151.2, 141.7, 130.4, 129.2, 122.4, 118.2, 115.4, 114.6, 86.2, 85.3, 82.1, 56.3, 55.5, 53.2, 52.2. − IR ($CHCl_3$): ṽ = 1741, 1725 cm^{-1}. − MS (CI): *m*/*z* (%) = 478 (100) [M$^+$ + 1], 477 (42) [M$^+$]. − $C_{26}H_{23}NO_8$ (477.47): calcd. C 65.40, H 4.86, N 2.93; found C 65.30, N 4.98, N 2.90.

2-Azetidinone 10a(*minor*): Colourless solid; m.p. 129−130 °C (hexanes/ethyl acetate). − ^{1}H NMR: δ = 3.31 (s, 3 H), 3.69 (s, 3 H), 3.76 (s, 3 H), 5.18 (d, *J* = 5.1 Hz, 1 H), 5.49 (d, *J* = 5.1 Hz, 1 H), 5.53 (t, *J* = 1.9 Hz, 1 H), 5.91 (d, *J* = 1.9 Hz, 1 H), 6.74 (d, *J* = 9.0 Hz, 2 H), 7.02 (m, 3 H), 7.19 (m, 5 H). − ^{13}C NMR: δ = 162.1, 161.4, 161.1, 157.1, 156.6, 154.2, 153.6, 150.8, 143.5, 130.9, 126.5, 122.6, 118.0, 115.7, 114.5, 86.1, 85.9, 81.8, 56.0, 55.5, 52.4, 52.1. − IR ($CHCl_3$): ṽ = 1746, 1721 cm^{-1}. − MS (CI): *m*/*z* (%) = 478 (100) [M$^+$ + 1], 477 (26) [M$^+$]. − $C_{26}H_{23}NO_8$ (477.47): calcd. C 65.40, H 4.86, N 2.93; found C 65.47, H 4.81, N 2.97.

General Procedure for the Retro-Diels−Alder Reaction of Adducts 10: A solution of the Diels−Alder adducts **10** (0.25 mmol), and dimethyl acetylenedicarboxylate (76 mg, 0.50 mmol) in toluene (10 mL) was heated in a sealed tube at 190 °C for 20 hours. The reaction mixture was allowed to cool to room temperature, and the solvent was removed under reduced pressure. Chromatography of the residue eluting with hexanes/ethyl acetate mixtures gave the analytically pure products **11**.

4-Ethynyl-2-azetidinone (11a): From Diels−Alder adduct **10b** (75 mg, 0.25 mmol) and dimethyl acetylenedicarboxylate (46 mg, 0.30 mmol), after flash chromatography eluted with hexanes/ethyl acetate (3:1), the less-polar compound **11a** (40 mg, 62%) as a colourless oil and the more-polar compound **14** (48 mg) (mixture of isomers) as a colourless oil were obtained.

(3*RS*,4*SR*)-4-Ethynyl-1-(methoxycarbonylmethyl)-3-(phenoxy)-2-azetidinone (11a): Colourless oil. − ^{1}H NMR: δ = 2.41 (dd, *J* = 2.2, 0.5 Hz, 1 H), 3.73 (s, 3 H), 3.79 and 4.40 (d, *J* = 18.3 Hz, each 1 H), 4.83 (dd, *J* = 4.4, 2.2 Hz, 1 H), 5.36 (d, *J* = 4.4 Hz, 1 H), 6.96 (m, 2 H), 7.24 (m, 3 H). − ^{13}C NMR: δ = 168.1, 164.7, 157.2, 129.8, 122.6, 115.7, 86.4, 77.9, 75.3, 52.6, 50.6, 41.0. − IR ($CHCl_3$): ṽ = 3300, 1755, 1746 cm^{-1}. − MS (EI): *m*/*z* (%) = 260 (18) [M$^+$ + 1], 259 (100) [M$^+$]. − $C_{14}H_{13}NO_4$ (259.26): calcd. C 64.86, H 5.05, N 5.40; found C 64.82, H 5.11, N 5.37.

Compound 14: Colourless oil. − ^{1}H NMR: δ = 3.76 (s, 2 H), 3.79 (s, 3 H), 3.85 (m, 11 H), 3.95 and 4.24 (s, each 3 H). − ^{13}C NMR: δ = 162.1, 151.3, 87.2, 58.7, 52.6, 52.3, 51.9. − IR ($CHCl_3$): ṽ = 1734 cm^{-1}.

4-Ethynyl-2-azetidinone (11b): From Diels−Alder adduct **10c** (50 mg, 0.11 mmol) and dimethyl acetylenedicarboxylate (31 mg, 0.22 mmol), after flash chromatography eluted with hexanes/ethyl acetate (2:1), the less-polar compound **11b** (20 mg, 64%) as a colourless oil and the more-polar compound **14** (28 mg) (mixture of isomers) as a colourless oil were obtained.

(3*RS*,4*SR*)-1-Allyl-4-ethynyl-3-phthalimido-2-azetidinone (11b): Colourless oil. − ^{1}H NMR: δ = 2.31 (d, *J* = 2.1 Hz, 1 H), 3.68

(m, 1 H), 4.20 (dd, J = 15.2, 5.3 Hz, 1 H), 4.54 (dd, J = 5.1, 2.1 Hz, 1 H), 5.28 (m, 2 H), 5.45 (d, J = 5.1 Hz, 1 H), 5.77 (m, 1 H), 7.70 and 7.85 (m, each 2 H). – ^{13}C NMR: δ = 167.2, 166.5, 163.4, 148.8, 134.5, 131.7, 130.6, 123.8, 119.5, 116.1, 78.1, 58.1, 52.0, 48.7, 43.9. – IR ($CHCl_3$): $\tilde{\nu}$ = 3300, 1755, 1740 cm^{-1}. – MS (CI): *m/z* (%) = 281 (100) [M^+ + 1], 280 (14) [M^+]. – $C_{16}H_{12}N_2O_3$ (280.28): calcd. C 68.57, H 4.32, N 9.99; found C 68.70, H 4.29, N 9.93.

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[15] In reference 11 it has been claimed, on the basis of a COSY experiment, that by reaction of racemic *trans*-3-butadienyl-2-azetidinones with dimethyl acetylenedicarboxylate, a conjugate diene was formed. However, NOE irradiation of vinylic protons on compounds **7a**, **7b** and **7e** resulted, respectively, in 5, 6 and 5% enhancements of the signals corresponding to H1′, which is in agreement with the proposed nonconjugated structure.

[16] Considering the diversity of the nomenclature which is used to define facial stereoselectivity in Diels–Alder reactions with chiral dienes with a stereogenic allylic substituent, it is necessary to indicate our choice. In the depicted conformation (see Figure 2), which could not be the reactive one, *syn* addition refers to the *unlike* addition, following the Seebach–Prelog convention.

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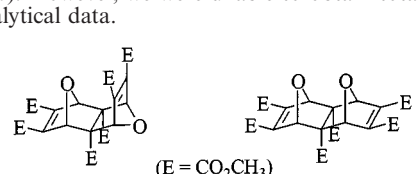
[19] The structure of cycloadducts **14** was tentatively assigned on the basis of NMR techniques as the *exo-endo* and the *exo-exo* isomers, and is in good agreement with previous reports (see reference 20). However, we were unable to obtain totally satisfactory analytical data.



(E = CO_2CH_3)

14 *exo-endo* **14** *exo-exo*

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[22] X-ray data for **8b**: Crystallised from *n*-hexane at 20 °C; $C_{26}H_{36}N_2O_5Si$ (M_r = 484.67); monoclinic; space group = $P2_1/c$; a = 10.2756(8) Å, b = 11.5914(8) Å; c = 22.5143(3) Å; α =

90°; β = 92.800(10)°; γ = 90°; V = 2678.4(3) Å^3; Z = 4; $d_{calcd.}$ = 1.202 mg m^{-3}; ac = 1.075 mm^{-1}; F(000) = 1040. A transparent crystal of 0.17 × 0.17 × 0.17 mm was used. 2504 Independent reflections were collected on a Seifert XRD 3000S diffractometer. The structure was solved by direct methods (SIR97 and difference Fourier techniques); no absorption correction was applied (μ = 1.075 mm^{-1}). All calculations were carried out with the program SHELX-97 on a VAX 6410 computer. The structure was refined using full-matrix least-squares procedures on F^2. Crystallographic data (excluding structure factors) for the structure included in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-150137. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [Fax: (internat.) + 44-1223/336-033; Email: deposit@ccdc.cam.ac.uk].

[23] Full spectroscopic and analytical data for compounds not included in the Experimental Section are provided in the Supporting Information (see footnote on the first page of this article).

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