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A Diels–Alder route to angularly functionalized bicyclic structures

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We dedicate this paper to Professor Steven Ley on the occasion of his receipt of the Tetrahedron Prize for Creativity in Organic Chemistry, honoring his pioneering accomplishments in organic synthesis

ABSTRACT

A Diels–Alder-based route to *trans*-fused angularly functionalized bicyclic structures has been developed. This transformation features the use of a tetrasubstituted dienophile in the cycloaddition step.

1. Introduction

The development of improved methods for the stereoselective construction of substituted decalin and hydrindane systems remains an important focus of organic synthesis.[1] Over the years, our laboratory has been exploring extensions of the Diels–Alder reaction, with a view to gaining access to substructural patterns, which are not traditionally filed under Diels–Alder logic. Toward this end, we recently developed a two-step '*trans*-Diels–Alder' paradigm, which provides access to *trans*-fused decalin and hydrindane systems from 1-nitrocycloalkene dienophiles (**2**) and simple dienes (**1**). As is shown in Figure 1, cycloaddition provides a *cis*-fused bicyclic adduct, bearing a nitro group in the ring junction (**3**). Subsequent radical denitration furnishes the target *trans*-fused system (**4**) with good selectivity.[2] In the case of the hydrindane series, the Diels–Alder step, per se, is even more straightforward; however, denitration results in nearly 1:1 mixtures of diastereomeric products.

To further expand upon this concept, we considered the possibility of achieving cycloaddition between a tetrasubstituted dienophile of the type **5** and a diene (**1**).[3] It was hoped that the *cis*-fused nitro-substituted Diels–Alder adduct, **6**, following radical-induced denitration, might progress to a *trans*-fused system bearing substitution (A) at the ring junction (cf. **7**). Alternatively, **6** could be converted to a *cis*-fused angular amine product (cf. **8**) through reduction of the nitro functionality. We were not unmindful of the challenges inherent in this proposed sequence. Indeed, tetrasubstituted olefins are known to act as poor dienophiles in the Diels–Alder reaction,[4] and relatively few examples of tetrasubstituted cyclic dienophiles bearing nitro functionality have been reported.[5] To our knowledge, compound **5** had not been demonstrated to function as a competent Diels–Alder dienophile. We were hopeful that by installing a second electron-withdrawing group (i.e., CN) as substituent A, we could realize the desired cycloaddition. We describe herein the development of two-step, Diels–Alder-based routes to *trans*-fused adducts containing angular substitution, such as **7**, and to disubstituted, *cis*-fused adducts of the type **8**.[6]

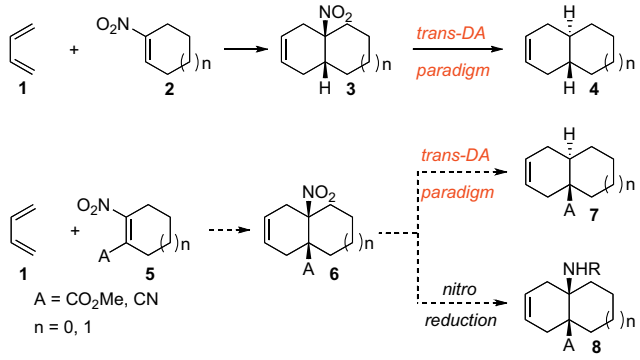

Figure 1.

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† These authors contributed equally to this work.

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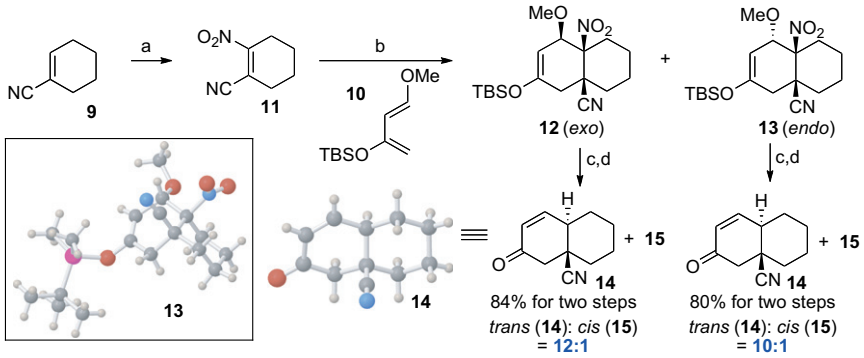
2. Results and discussion

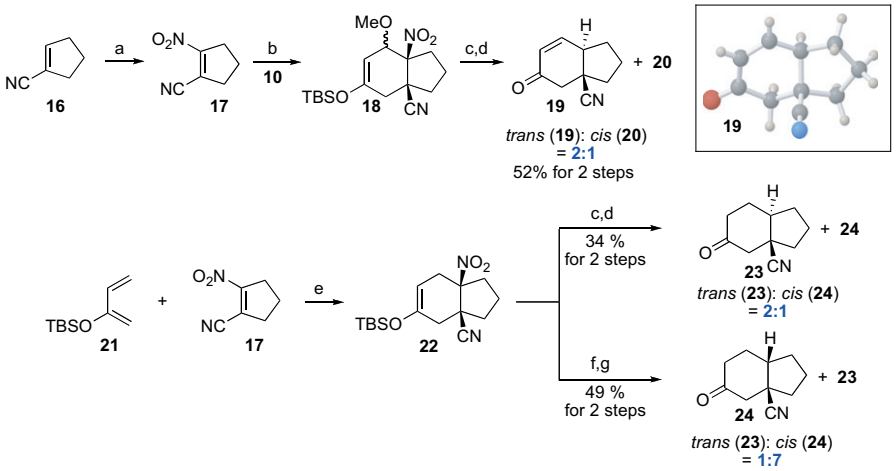
We first examined the cycloaddition–denitration sequence in the context of dienophile **11**[7] (itself prepared in one step from **9**, as shown) and synergistic diene **10** (Scheme 1).[8] In the event, **10** and **11** did undergo cycloaddition to afford a 1:1 (*exo*/*endo*) mixture of the readily separable adducts **12** and **13**. The structure of **13** (*endo*) was confirmed by X-ray crystallographic analysis. Each adduct was then separately subjected to conditions, which favor radical-mediated denitration.[9] Following hydrolysis, *trans*-fused adduct **14** was isolated as the predominant product; its structure was also unambiguously determined by X-ray crystallography. The slightly higher levels of stereocontrol achieved in the denitration of *exo* cycloadduct **12** (12:1 vs 10:1) can perhaps be attributed to the axial disposition of the methoxy group, which serves to more effectively shield the 'front' face of the transient free radical, leaving the back face exposed to attack by the hydrogen-donor agent.

Having explored the cycloaddition–denitration sequence with activated diene coupling partners, we next investigated the use of less reactive hydrocarbon-based dienes in the Diels–Alder step. Our initial efforts to effect Diels–Alder reaction between 2,3-dimethyl-1,3-butadiene and dienophile **11** were unsuccessful. Under moderate thermal conditions (<130 °C), no reaction was observed (Scheme 3). At higher temperatures (150 °C), compound **25** was formed in 25–40% yield.[12] The structure of adduct **25** was confirmed by X-ray crystallography. It was eventually determined that

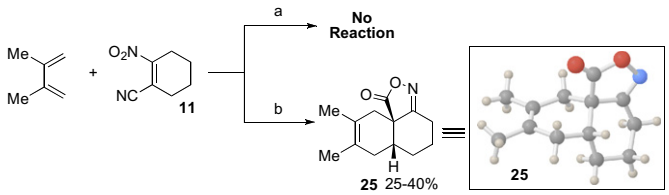


Scheme 1. Reagents and conditions: (a) $NaNO_2$, CAN, CH_3CN, rt, 24 h, 56%; (b) toluene, 100 °C, 80 h, 78%; (c) *n*-Bu_3SnH, AIBN, benzene, reflux, 2 h; (d) HF, CH_3CN, 1 h.

We next examined the two-step sequence in the context of a cyclopentenyl dienophile. Here, the tetrasubstituted dienophile, **17**, was prepared from compound **16**, as shown (Scheme 2). Under thermal conditions, **17** underwent cycloaddition with diene **10** to afford the *cis*-fused adduct, **18**, as a mixture of *endo* and *exo* isomers, in 95% yield. Upon denitration and subsequent hydrolysis, a 2:1 mixture of *trans*-fused **19** and *cis*-fused **20** was isolated. Obviously, this lack of stereocontrol would compromise the value of the cycloadduct **26** could be generated in moderate yield at 100 °C, through the addition of 5.0 M $LiClO_4$ in THF,[13] which serves to accelerate the Diels–Alder reaction (Table 1, entry 1). In contrast to the moderate Diels–Alder yields obtained with cyclohexenyl dienophile, **11** (Table 1, entries 1 and 2), the cyclopentenyl dienophile, **17**, readily undergoes cycloaddition with hydrocarbon dienes, furnishing *cis*-fused hydrindane adducts in excellent yields (Table 1, entries 3 and 4).

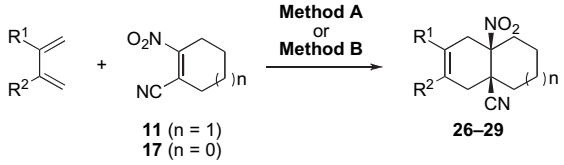


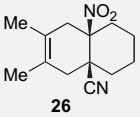
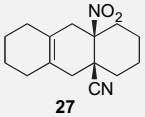
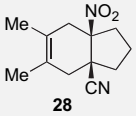
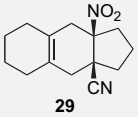
Scheme 2. Reagents and conditions: (a) $NaNO_2$, CAN, CH_3CN, rt, 24 h, 61%; (b) toluene, 100 °C, 10 h, 95%; (c) *n*-Bu_3SnH, AIBN, benzene, reflux, 2 h; (d) HF, CH_3CN, 1 h; (e) toluene, 100 °C, 36 h, 63%, *p*-directed/*m*-directed = 4:1; (f) HF, CH_3CN, rt, 8 h; (g) *n*-Bu_3SnH, AIBN, benzene, reflux, 1.5 h, 48% for two steps.



Scheme 3. Reagents and conditions: (a) 2,6-di-*tert*-butyl-4-methylphenol, toluene, 130 °C, 24 h. (b) 2,6-di-*tert*-butyl-4-methylphenol, toluene, 150 °C, 24 h.

Table 1



Entry	Diene	Dienophile	Method	Adduct	Yield (%)
1		**11**	A	 **26**	26
2		**11**	A	 **27**	35
3		**17**	B	 **28**	95
4		**17**	B	 **29**	91

Key: Method A: 2,6-di-*tert*-butyl-4-methylphenol, 5.0 M $LiClO_4$ in THF, 100 °C, 60 h; Method B: 2,6-di-*tert*-butyl-4-methylphenol, toluene, 100 °C, 24 h.

We now turned to an assessment of the feasibility of the denitration step, which we hoped would provide access to substituted, *trans*-fused hydrindane and decalin systems. As outlined in Table 2, entries 1 and 2, the *cis*-fused decalin systems (**26** and **27**) underwent radical-based denitration to provide the corresponding *trans*-fused adducts in good yield and with excellent levels of diastereocontrol (>20:1 *trans*/*cis*).[14] However, denitration of hydrindanes **28** and **29** proceeded with quite poor levels of stereoselectivity (Table 2, entries 3 and 4).[15]

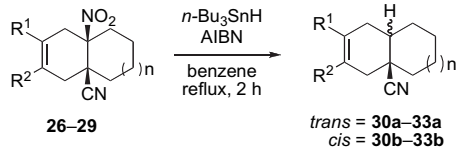
Finally, we sought to accomplish reduction of the *cis*-fused Diels–Alder adducts (**26** and **28**), to provide the corresponding *cis*-fused amine derivatives. As outlined in Scheme 4, treatment[16] of compounds **26** and **28** with zinc dust in the presence of AcOH, followed by Alloc protection of the resultant angular amines, provided compounds **34** and **35** in good yield, and with the cyanide functionality intact. The two-step Diels–Alder/reduction sequence represents a straightforward synthesis of angular amines.

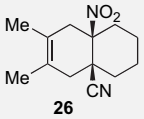
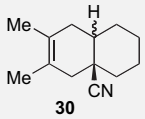
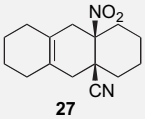
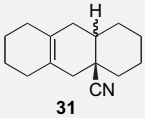
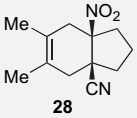
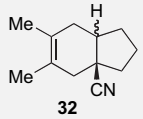
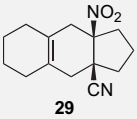
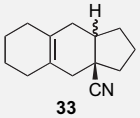
3. Experimental section

3.1. General

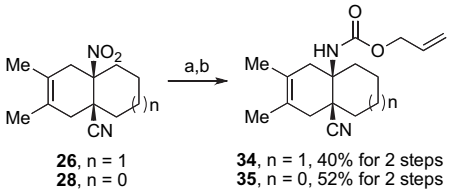
Experiments involving moisture- and/or air-sensitive compounds were performed in oven- or flame-dried glassware with

Table 2



Entry	Substrate	Product	Yield (%)	trans/cis (**a**/**b**)
1	 **26**	 **30**	89	>20:1
2	 **27**	 **31**	85	>20:1
3	 **28**	 **32**	77	~1.5:1
4	 **29**	 **33**	89	~1.7:1

rubber septa under a positive pressure of nitrogen or argon using standard Schlenk techniques. Heating was accomplished by heating mantle or silicon oil bath using a temperature controller. Organic solutions were concentrated under reduced pressure using a Büchi rotatory evaporator, unless otherwise noted. Reactions were magnetically stirred and monitored by thin-layer chromatography (TLC) carried out on 0.25 mm E. Merck silica gel plates (60-F_{254}) using UV light as a visualizing agent and a $KMnO_4$ solution, a vanillin solution, an anisaldehyde solution, or a ceric ammonium molybdate (CAM) solution, and heat as developing agent. Flash chromatography was carried out with EM silica gel 60 (230–240 mesh) or Sorbent Technology silica gel 60 (particle size 32–63 μm) according to the method of Still.[17] Yields refer to chromatographically and spectroscopically (^1H NMR) homogeneous materials, unless otherwise stated. Unless otherwise noted, all reagents were purchased at the highest commercial quality from commercial suppliers and used without further purification. Lithium perchlorate (battery grade, dry, 99.99%) was purchased from Aldrich and dried under high vacuum at 130 °C for at least 12 h just prior to use. Tetrahydrofuran (THF) was freshly distilled from sodium/benzophenone ketyl under an atmosphere of argon. Benzene, dichloromethane (CH_2Cl_2), and toluene were freshly distilled over CaH_2 or filtered



Scheme 4. Reagents and conditions: (a) Zn dust, THF/AcOH (2:1), −20 °C, 3 h; (b) AllocCl, THF, satd $NaHCO_3$, rt, 3 h.

through a column of activated alumina under an atmosphere of argon. Diethyl ether was filtered through a column of activated alumina under an atmosphere of argon. Microwave reactions were performed on a Biotage microwave reactor. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker DRX-400, a Bruker DRX-500 or a Bruker DRX-600 spectrometer at ambient temperature (300 K), unless otherwise stated. Chemical shifts of the ^{1}H NMR ($CDCl_3$: 7.26 ppm) and ^{13}C NMR ($CDCl_3$: 77.0 ppm) spectra were referenced to residual solvent peaks. ^{1}H NMR spectra are reported as follows: chemical shift, multiplicity (br=broad, s=singlet, d=doublet, m=multiplet), coupling constant, and integration. ^{13}C NMR spectra were recorded with ^{1}H decoupling. The multiplicities of the carbons of *trans*-3,4-dimethylbicyclo[4.4.0]dec-3-en-1-carbonitrile (**30a**) and *trans*-1,2,3,4,4a,5,6,7,8,9,9a,10-dodecahydroanthracene-4a-carbonitrile (**31a**) were determined by DEPT (Distortionless Enhancement by Polarization Transfer) experiments. IR spectra were recorded on a Jasco FT/IR-6100 or a Nicolet AVATAR 370 DTGS spectrometer and are reported in terms of frequency of absorption (cm^{-1}). Melting points were measured using MEL-TEMP® and are uncorrected. Low resolution mass spectra were acquired on a ZQ Micromass spectrometer using the technique of ESI (electrospray ionization). High-resolution mass spectra (HRMS) were obtained from the Columbia University Mass Spectral Core Facility on a JEOL HX 110 mass spectrometer using the technique of EI (electron impact ionization) or FAB (fast atom bombardment).

3.2. General procedure

*3.2.1. General procedure for the nitration of cyloalkenecarbonitriles (**9** and **16**)*[7]. To a stirred solution of cycloalkenecarbonitrile (20.0 mmol, 1.0 equiv) in anhydrous CH_3CN (100 mL) at 0 °C was added $NaNO_2$ (4.14 g, 60.0 mmol, 3.0 equiv) followed by ammonium cerium nitrate (32.8 g, 60.0 mmol, 3.0 equiv). The reaction mixture was stirred at room temperature for 24 h, diluted with H_2O, and extracted with EtOAc (20 mL×3). The organic layer was treated with a saturated solution of $NaHCO_3$ (100 mL) and the resulting mixture was stirred at room temperature for 12 h. The mixture was diluted with H_2O and extracted with EtOAc (20 mL×3). The combined extract was dried over anhydrous $MgSO_4$, filtered, and concentrated on a rotatory evaporator. Purification of the residue by flash column chromatography on silica gel gave the title compound.

*3.2.1.1. 2-Nitrocyclohexenecarbonitrile (**11**).* Prepared using cyclohexenecarbonitrile (**9**, 2.14 g, 20.0 mmol), $NaNO_2$ (4.14 g, 60.0 mmol) and ammonium cerium nitrate (32.8 g, 60.0 mmol) in CH_3CN (100 mL), **11** was isolated as a yellow oil (1.70 g, 56%) after column chromatography (hexanes/EtOAc=4:1). ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.75–2.72 (m, 2H), 2.61–2.59 (m, 2H), 1.86–1.82 (m, 2H), 1.77–1.72 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 157.9, 115.1, 114.2, 29.4, 25.7, 20.7, 20.3; IR (neat) 2952, 2869, 2221, 1652, 1528, 1427, 1342, 1331 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_7H_8N_2O_2$) required *m*/*z* 152.0586, found *m*/*z* 152.0583.

*3.2.1.2. 2-Nitrocyclopentenecarbonitrile (**17**).* Prepared using cyclopentenecarbonitrile (**16**, 3.00 g, 32.2 mmol), $NaNO_2$ (6.67 g, 96.6 mmol), and ammonium cerium nitrate (53.0 g, 96.6 mmol) in CH_3CN (200 mL), **17** was isolated as a yellow oil (2.70 g, 61%) after column chromatography (hexanes/EtOAc=4:1). ^{1}H NMR (600 MHz, $CDCl_3$) δ 3.08–3.04 (m, 2H), 2.96–2.92 (m, 2H), 2.24–2.19 (m, 2H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 160.4, 117.2, 112.4, 34.6, 31.2, 20.7; IR (neat) 2964, 2919, 2850, 2229, 1644, 1521, 1435, 1348, 1321, 1177 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_6H_6N_2O_2$) required *m*/*z* 138.0429, found *m*/*z* 138.0432.

*3.2.2. General procedure for the Diels–Alder reaction of 2-nitrocycloalkenecarbonitriles (**11** and **17**) with electron-rich dienes (**10** and **21**).* A sealable vial reactor equipped with a magnetic stirring bar was charged with 2-nitrocycloalkenecarbonitriles (1.0 equiv), an electron-rich diene (2.0 equiv), and anhydrous toluene. The reactor was sealed and the mixture was stirred at 100 °C in a pre-heated oil bath for 10–80 h. At this point, the mixture was cooled to room temperature and the solvent was evaporated. The resulting residue was purified by flash column chromatography on silica gel to afford the desired Diels–Alder adduct as a mixture of *endo* and *exo* diastereomers.

*3.2.2.1. A 1:1 mixture of silyl enol ethers **12** and **13**.* Prepared using **11** (200 mg, 1.31 mmol) and *trans*-2-(*tert*-butyldimethylsilyloxy)-4-methoxy-1,3-butadiene (**10**, 564 mg, 2.63 mmol) in toluene (3.0 mL) at 100 °C for 80 h, an approximate 1:1 mixture of **12** and **13** was isolated as a pale yellow oil (350 mg, 78%) after column chromatography (hexanes/EtOAc=12:1). Diastereomers **12** and **13** were separated by careful column chromatography. *exo* Isomer **12**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 5.14 (d, *J*=4.7 Hz, 1H), 4.04 (d, *J*=4.9 Hz, 1H), 3.32 (s, 3H), 2.61 (br s, 2H), 2.45–2.44 (m, 1H), 2.37–2.34 (m, 1H), 1.89–1.85 (m, 1H), 1.74–1.71 (m, 2H), 1.65–1.56 (m, 2H), 1.25 (br s, 1H), 0.94 (s, 9H), 0.23 (s, 3H), 0.21 (s, 3H); IR (neat) 2951, 2932, 2884, 2859, 2239, 1752, 1673, 1554, 1454, 1370, 1254, 1230, 1210, 1089 cm^{-1}; MS (ESI) 389.3 $[M+Na]^+$. *endo* Isomer **13**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 4.93 (d, *J*=1.7 Hz, 1H), 4.58 (s, 1H), 3.36 (s, 3H), 2.81 (d, *J*=17.9 Hz, 1H), 2.66 (d, *J*=15.4 Hz, 1H), 2.42 (d, *J*=17.9 Hz, 1H), 1.93–1.90 (m, 2H), 1.77–1.75 (m, 1H), 1.67–1.58 (m, 3H), 1.52–1.46 (m, 1H), 0.93 (s, 9H), 0.22 (s, 3H), 0.20 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.8, 121.8, 102.3, 92.1, 81.0, 58.5, 39.3, 38.1, 30.6, 29.5, 19.4, 18.5, 17.9, −4.4; IR (neat) 2953, 2932, 2884, 2858, 2237, 1674, 1548, 1455, 1366, 1254, 1226, 1198, 1096, 914 cm^{-1}; HRMS (FAB) exact mass calculated for $[M+1]^+$ ($C_{18}H_{31}N_2O_4Si$) required *m*/*z* 367.2053, found *m*/*z* 367.2063. The structure of **13** was also confirmed by X-ray crystallographic analysis (see Supplementary data).

*3.2.2.2. A 1.8:1 mixture of silyl enol ethers **18** and **18′**.* Prepared using **17** (500 mg, 3.62 mmol) and *trans*-2-(*tert*-butyldimethylsilyloxy)-4-methoxy-1,3-butadiene (**10**, 1.55 g, 7.24 mmol) in toluene (4.0 mL) at 100 °C for 10 h, an approximate 1.8:1 mixture of **18** and **18′** was isolated as a pale yellow oil (1.21 g, 95%) after column chromatography (hexanes/EtOAc=10:1). Diastereomers **18** and **18′** were separated by careful column chromatography. Compound **18**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 4.96–4.93 (m, 1H), 4.91–4.88 (m, 1H), 3.32 (s, 3H), 2.73–2.69 (m, 1H), 2.62–2.59 (m, 1H), 2.32–2.28 (m, 1H), 2.14–2.01 (m, 4H), 1.95–1.89 (m, 1H), 0.90 (s, 9H), 0.19 (s, 3H), 0.17 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 147.5, 119.7, 101.0, 100.7, 78.6, 57.7, 45.0, 38.3, 35.8, 28.6, 25.4, 20.0, 17.8, −4.6, −4.7; IR (neat) 2955, 2931, 2887, 2858, 2830, 2241, 1675, 1547, 1462, 1363, 1255, 1218, 1094, 835 cm^{-1}; HRMS (FAB) exact mass calculated for $[M+1]^+$ ($C_{17}H_{29}N_2O_4Si$) required *m*/*z* 353.1897, found *m*/*z* 353.1918. Compound **18′**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 5.11 (d, *J*=4.9 Hz, 1H), 4.26 (d, *J*=5.0 Hz, 1H), 3.32 (s, 3H), 2.79 (d of AB pattern, *J*=18.3 Hz, 1H), 2.62–2.51 (m, 2H), 2.26 (d of AB pattern, *J*=18.3 Hz, 1H), 2.17–2.12 (m, 1H), 2.06–2.01 (m, 1H), 1.93–1.88 (m, 2H), 0.91 (s, 9H), 0.20 (s, 3H), 0.18 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 149.7, 120.8, 99.2, 98.7, 75.6, 57.3, 40.9, 39.8, 35.7, 33.5, 25.4, 18.6, 17.8, −4.6, −4.7; IR (neat) 2955, 2931, 2893, 2858, 2825, 2243, 1671, 1553, 1461, 1369, 1256, 1221, 1087, 835 cm^{-1}; HRMS (FAB) exact mass calculated for $[M+1]^+$ ($C_{17}H_{29}N_2O_4Si$) required *m*/*z* 353.1897, found *m*/*z* 353.1880.

*3.2.2.3. A 4:1 mixture of silyl enol ethers **22** and **22′**.* Prepared using **17** (75.0 mg, 0.543 mmol) and 2-(*tert*-butyldimethylsilyloxy)-1,3-butadiene (**21**, 200 mg, 1.08 mmol) in toluene (1.0 mL) at 100 °C

for 36 h, an approximate 4:1 regioisomeric mixture of **22** and **22′** was isolated as a pale yellow oil (110 mg, 63%) after column chromatography (hexanes/EtOAc=14:1). Regioisomers **22** and **22′** were inseparable and characterization was carried out in the next step. ^{1}H and ^{13}C NMR spectra of the mixture of **22** and **22′** are available in Supplementary data.

*3.2.3. General procedure for the preparation of bicyclic ketones (**14**, **15**, **19**, **20**, **23**, and **24**).* To a stirred solution of a *cis*-fused silyl enol ether (1.0 equiv) in anhydrous benzene was added tri-*n*-butyltin hydride (2.0 equiv) followed by azobisisobutyronitrile (0.5 equiv) and the mixture was heated under reflux for 2 h. At this point, the mixture was cooled to room temperature and the solvent was evaporated. In a separate Falcon® tube, the resulting residue was dissolved in CH_3CN and treated with HF (48% in H_2O) and the mixture was stirred at room temperature for 1 h. The mixture was cooled in an ice-water bath and the reaction was quenched by dropwise addition of saturated $NaHCO_3$ solution. The precipitate thus formed was filtered off and the filtrate was diluted with H_2O and extracted with CH_2Cl_2 (3×30 mL). The combined extract was dried over anhydrous Na_2SO_4, filtered, and concentrated on a rotatory evaporator. The residue was purified by flash column chromatography on silica gel to give the title compound.

*3.2.3.1. A 12:1 mixture of trans-3-oxobicyclo[4.4.0]dec-4-enecarbonitrile (**14**) and cis-3-oxobicyclo[4.4.0]dec-4-enecarbonitrile (**15**).* Prepared using an *exo* isomer **12** (35.0 mg, 95.5 μmol), tri-*n*-butyltin hydride (55.3 mg, 190 μmol), azobisisobutyronitrile (8.0 mg, 48 μmol) in benzene (4.0 mL), a 12:1 mixture of *trans*-fused **14** and *cis*-fused **15** was isolated as a pale yellow oil (13 mg, 78% over two steps) after column chromatography (hexanes/EtOAc=4:1). The *trans*-fused **14** was isolated in pure form by careful column chromatography. Compound **14**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 6.68 (dd, J=10.1, 1.5 Hz, 1H), 6.14–6.12 (m, 1H), 2.79 (d of AB pattern, J=16.7 Hz, 1H), 2.41 (d of AB pattern, J=16.7 Hz, 1H), 2.38–2.37 (m, 1H), 2.04–2.02 (m, 1H), 1.98–1.94 (m, 2H), 1.83–1.80 (m, 1H), 1.78–1.63 (m, 2H), 1.55–1.50 (m, 1H), 1.48–1.46 (m, 1H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 194.4, 151.4, 130.0, 120.8, 48.3, 43.6, 43.6, 35.9, 28.2, 25.5, 22.0; IR (neat) 2936, 2861, 2232, 1683, 1448, 1384, 1244, 1159, 982 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{11}H_{13}NO$) required m/z 175.0997, found m/z 175.0998. The structure of **14** was also confirmed by X-ray crystallographic analysis (see Supplementary data).

*3.2.3.2. A 10:1 mixture of trans-3-oxobicyclo[4.4.0]dec-4-enecarbonitrile (**14**) and cis-3-oxobicyclo[4.4.0]dec-4-enecarbonitrile (**15**).* Prepared using an *endo* isomer **13** (50.0 mg, 0.136 mmol), tri-*n*-butyltin hydride (78.6 mg, 0.270 mmol), azobisisobutyronitrile (11.0 mg, 68.0 μmol) in benzene (5.0 mL), a 10:1 mixture of *trans*-fused **14** and *cis*-fused **15** was isolated as a pale yellow oil (19 mg, 80% over two steps) after column chromatography (hexanes/EtOAc=4:1).

*3.2.3.3. A 2:1 mixture of trans-3-oxobicyclo[4.3.0]non-4-enecarbonitrile (**19**) and cis-3-oxobicyclo[4.3.0]non-4-enecarbonitrile (**20**).* Prepared using a distereomeric mixture of **18** and **18′** (200 mg, 0.567 mmol), tri-*n*-butyltin hydride (329 mg, 1.13 mmol), azobisisobutyronitrile (47.0 mg, 0.284 mmol) in benzene (6.0 mL), a 2:1 mixture of *trans*-fused **19** and *cis*-fused **20** was isolated as a pale yellow oil (47 mg, 51% over two steps) after column chromatography (hexanes/EtOAc=8:1). Diastereomers **19** and **20** were separated by careful column chromatography. Compound **19**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.04 (dd, J=10.0, 1.3 Hz, 1H), 6.14 (dd, J=10.0, 2.8 Hz, 1H), 3.05 (d of AB pattern, J=16.7 Hz, 1H), 2.63–2.59 (m, 1H), 2.39 (d of AB pattern, J=16.7 Hz, 1H), 2.30–2.26 (m, 1H), 2.18–2.12 (m, 1H), 2.11–2.05 (m, 1H), 2.01–1.93 (m, 1H), 1.86–1.80 (m, 1H), 1.77–1.71 (m, 1H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 195.3, 147.9, 130.8, 121.6, 48.1, 47.4, 47.4, 35.6, 26.2, 21.0; IR (neat) 2960, 2879, 2231, 1683, 1455, 1381, 1240, 1159 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{10}H_{11}NO$) required m/z 161.0841, found m/z 161.0850. The structure of **19** was also confirmed by X-ray crystallographic analysis (see Supplementary data). Compound **20**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 6.73 (dd, J=10.3, 3.7 Hz, 1H), 6.05 (dd, J=10.3, 1.9 Hz, 1H), 3.17–3.14 (m, 1H), 2.83 (d of AB pattern, J=16.6 Hz, 1H), 2.73 (d of AB pattern, J=16.6 Hz, 1H), 2.35–2.23 (m, 2H), 2.00–1.93 (m, 1H), 1.90–1.82 (m, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 193.8, 149.5, 128.5, 123.3, 44.8, 42.0, 41.9, 35.9, 31.0, 23.0; IR (neat) 2923, 2853, 1679, 1446, 1386, 1244, 1151, 1055, 842 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{10}H_{11}NO$) required m/z 161.0841, found m/z 161.0836.

*3.2.3.4. A 2:1 mixture of trans-3-oxobicyclo[4.3.0]nonanecarbonitrile (**23**) and cis-3-oxobicyclo[4.3.0]nonanecarbonitrile (**24**).* Prepared using a silyl enol ether **22** (60.0 mg, 0.186 mmol), tri-*n*-butyltin hydride (81.2 mg, 0.279 mmol), azobisisobutyronitrile (10.0 mg, 56.0 μmol) in benzene (3.0 mL), a 2:1 mixture of *trans*-fused **23** and *cis*-fused **24** was isolated as a pale yellow oil (10.3 mg, 34% over two steps) after column chromatography (hexanes/EtOAc=4:1). Diastereomers **23** and **24** were separated by careful column chromatography. Compound **23**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 2.93–2.90 (m, 1H), 2.59–2.56 (m, 1H), 2.35–2.26 (m, 3H), 2.19–2.16 (m, 1H), 2.08–1.87 (m, 5H), 1.70–1.61 (m, 2H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 206.3, 120.9, 49.7, 48.3, 47.7, 39.8, 37.0, 27.6, 25.7, 21.9; IR (neat) 2960, 2873, 2229, 1715, 1457, 1423, 1187, 913 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{10}H_{13}NO$) required m/z 163.0997, found m/z 163.0988. Compound **24**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.71 (d of AB pattern, J=18.0 Hz, 1H), 2.65–2.60 (m, 1H), 2.53 (d of AB pattern, J=18.0 Hz, 1H), 2.42–2.33 (m, 2H), 2.28–2.22 (m, 1H), 2.18–2.10 (m, 2H), 1.92–1.83 (m, 2H), 1.77–1.70 (m, 2H), 1.66–1.56 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 207.3, 124.3, 45.2, 43.5, 42.2, 38.2, 37.0, 30.4, 26.0, 23.0; IR (neat) 2957, 2872, 2231, 1719, 1526, 1373, 1350, 1241, 1045 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{10}H_{13}NO$) required m/z 163.0997, found m/z 163.0988.

*3.2.3.5. Stereochemical confirmation of cis-3-oxobicyclo[4.3.0]nonanecarbonitrile (**24**).* To a solution of **20** (20.0 mg, 0.124 mmol) in degassed CH_3OH (4.0 mL) was added $Pd(OH)_2$ (20.0 mg, 20% w/w). A hydrogen-filled balloon (1 atm) was placed over the solution and the mixture was stirred at room temperature for 2 h. At this point, TLC analysis indicated that the reaction was completed. The mixture was filtered through a pad of Celite®, washed thoroughly with EtOAc, and the solvents were evaporated. The crude mixture was purified by flash column chromatography (hexanse/EtOAc=2:1) on silica gel to afford *cis*-fused **24** (19 mg, 94%), whose spectroscopic properties were in complete accord with the authentic sample.

*3.2.4. Preparation of a 1:7 mixture of trans-3-oxobicyclo[4.3.0]nonanecarbonitrile (**23**) and cis-3-oxobicyclo[4.3.0]nonanecarbonitrile (**24**).* A Falcon® tube was charged with a silyl enol ether **22** (10.0 mg, 31.0 μmol) and CH_3CN (2.0 mL) and HF (48% in H_2O, 0.010 mL) was added dropwise. The mixture was stirred at room temperature for 8 h. The mixture was cooled in an ice-water bath and the reaction was quenched by dropwise addition of saturated $NaHCO_3$ solution. The mixture was diluted with H_2O and extracted with CH_2Cl_2 (3×4 mL). The combined extract was dried over anhydrous Na_2SO_4, filtered, and concentrated on a rotatory evaporator. The residue was purified by flash column chromatography (hexanes/EtOAc=4:1) on silica gel to afford *cis*-6-nitro-3-oxobicyclo[4.3.0]nonanecarbonitrile (4.1 mg, 64%) as a pale yellow oil. *cis*-6-Nitro-3-oxobicyclo[4.3.0]nonanecarbonitrile: ^{1}H NMR (500 MHz,

$CDCl_3$) δ 3.32 (d of AB pattern, J=18.8 Hz, 1H), 2.84–2.78 (m, 1H), 2.72 (d of AB pattern, J=18.8 Hz, 1H), 2.70–2.59 (m, 2H), 2.50–2.45 (m, 1H), 2.44–2.38 (m, 1H), 2.35–2.14 (m, 3H), 1.97–1.88 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 203.0, 119.6, 93.5, 47.5, 43.9, 36.0, 35.7, 34.4, 32.3, 18.1; IR (neat) 2962, 2919, 2889, 2850, 2239, 1724, 1675, 1539, 1419 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{10}H_{12}N_2O_3$) required m/z 208.0848, found m/z 208.0855. To a stirred solution of *cis*-6-nitro-3-oxobicyclo[4.3.0]nonanecarbonitrile (27.0 mg, 0.130 mmol, 1.0 equiv) in anhydrous benzene (2.0 mL) was added tri-*n*-butyltin hydride (75.7 mg, 0.260 mmol, 2.0 equiv) followed by azobisisobutyronitrile (11.0 mg, 70.0 μmol, 0.5 equiv) and the mixture was heated under reflux for 1.5 h. At this point, the mixture was cooled to room temperature and the solvent was evaporated. The residue was purified by flash column chromatography (hexanes/EtOAc=6:1) on silica gel to give a 1:7 mixture of *trans*-fused **23** and *cis*-fused **24** (16 mg, 75%).

*3.2.5. Preparation of tricyclic compound **25**.* A sealable vial reactor equipped with a magnetic stirring bar was charged with 2-nitrocyclohexenecarbonitrile (**11**, 70.0 mg, 0.460 mmol, 1.0 equiv), 2,3-dimethyl-1,3-butadiene (379 mg, 4.60 mmol, 10 equiv), 2,6-di-*tert*-butyl-4-methylphenol (10.1 mg, 46.0 μmol, 0.1 equiv), and anhydrous toluene (2.0 mL). The reactor was sealed and the mixture was stirred at 150 °C in a pre-heated oil bath for 24 h. At this point, the mixture was cooled to room temperature and the solvent was evaporated. The resulting residue was purified by flash column chromatography (hexanes/EtOAc=14:1) on silica gel to afford the title compound (32.0 mg, 33%) as a tan/orange sticky solid. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.81–2.74 (m, 1H), 2.67–2.64 (m, 1H), 2.41–2.29 (m, 2H), 2.12–1.88 (m, 5H), 1.70 (s, 3H), 1.65 (s, 3H), 1.56–1.54 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 180.0, 172.2, 124.2, 117.1, 47.4, 38.3, 32.4, 30.5, 27.7, 26.3, 24.2, 19.4, 18.5; IR (neat) 2931, 2863, 1785, 1715, 1452, 1386, 1086 cm^{-1}; mp 80–86 °C; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{13}H_{17}NO_2$) required m/z 219.1259, found m/z 219.1250. The structure of **25** was also confirmed by X-ray crystallographic analysis (see Supplementary data).

*3.2.6. General procedure for the Diels–Alder reaction of 2-nitrocyclohexenecarbonitriles (**11**) with simple dienes.* A sealable tube equipped with a magnetic stirring bar was charged with 2-nitrocyclohexenecarbonitrile (**11**, 76.1 mg, 0.500 mmol, 1.0 equiv), a simple diene (5–10 equiv), 2,6-di-*tert*-butyl-4-methylphenol (5.5 mg, 25 μmol, 5.0 mol %), and anhydrous lithium perchlorate (532 mg, 5.00 mmol, 10 equiv). Under an atmosphere of argon, the mixture was cooled at 0 °C and anhydrous THF (1.0 mL) was added slowly. After stirring of the mixture for 10 min, the cooling bath was removed and the tube was sealed. The mixture was then stirred at 100 °C in a pre-heated oil bath for 60 h. At this point, the mixture was cooled to room temperature, diluted with H_2O, and extracted with CH_2Cl_2 (3×15 mL). The combined extract was washed with brine, dried over anhydrous Na_2SO_4, filtered, and concentrated on a rotatory evaporator. The resulting residue was purified by gradient column chromatography (hexanes/EtOAc=9:1→8:1) on silica gel to afford the title compound.

*3.2.6.1. cis-3,4-Dimethyl-6-nitrobicyclo[4.4.0]dec-3-en-1-carbonitrile (**26**).* Prepared using **11** (76.1 mg, 0.500 mmol) and 2,3-dimethyl-1,3-butadiene (410 mg, 5.00 mmol), **26** was isolated as an off-white solid (30.5 mg, 26%) after careful column chromatography. ^{1}H NMR ($CDCl_3$, 400 MHz, 333.15 K) δ 2.85 (d, J=18.0 Hz, 1H), 2.76 (d of AB pattern, J=18.8 Hz, 1H), 2.60 (d of AB pattern, J=18.8 Hz, 1H), 2.32–2.24 (m, 2H), 2.10–2.02 (m, 2H), 1.86–1.55 (m, 5H), 1.64 (s, 6H); ^{13}C NMR ($CDCl_3$, 100 MHz, 333.15 K) δ 121.8, 121.4, 120.8, 90.4, 40.5, 39.7, 37.1, 33.9, 32.7, 22.0, 20.9, 18.4, 18.2; IR (KBr) 2933, 2865, 2232, 1789, 1544, 1455, 851 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{13}H_{18}NO_2$) required m/z 234.1368, found m/z 234.1383.

*3.2.6.2. cis-9a-Nitro-1,2,3,4,4a,5,6,7,8,9,9a,10-dodecahydroanthracene-4a-carbonitrile (**27**).* Prepared using **11** (76.1 mg, 0.500 mmol) and 1,2-dimethylenecyclohexane[18] (270 mg, 2.50 mmol), **27** was isolated as an off-white solid (45.6 mg, 35%) after careful column chromatography. ^{1}H NMR ($CDCl_3$, 400 MHz, 333.15 K) δ 2.79 (d, J=17.6 Hz, 1H), 2.68 (d of AB pattern, J=18.8 Hz, 1H), 2.54 (d of AB pattern, J=18.8 Hz, 1H), 2.31–2.24 (m, 1H), 2.20 (d, J=18.0 Hz, 1H), 2.10–2.02 (m, 2H), 1.92–1.56 (m, 13H); ^{13}C NMR ($CDCl_3$, 100 MHz, 333.15 K) δ 124.2, 123.1, 121.5, 90.4, 39.7, 39.4, 36.1, 34.0, 32.8, 29.7, 29.5, 29.3, 22.6, 22.1, 21.0; IR (KBr) 2930, 2236, 1789, 1546, 1439, 851 cm^{-1}; HRMS (EI) exact mass calculated for $[M+1]^+$ ($C_{15}H_{21}N_2O_2$) required m/z 261.1603, found m/z 261.1607.

*3.2.7. General procedure for the Diels–Alder reaction of 2-nitrocyclopentenecarbonitriles (**17**) with simple dienes.* A sealable vial reactor equipped with a magnetic stirring bar was charged with 2-nitrocyclopentenecarbonitriles (**17**, 34.5 mg, 0.250 mmol, 1.0 equiv), a simple diene (0.750 mmol, 3.0 equiv), 2,6-di-*tert*-butyl-4-methylphenol (2.8 mg, 13 μmol, 5.0 mol %), and anhydrous toluene (0.5 mL). The reactor was sealed and the mixture was stirred at 100 °C in a pre-heated oil bath for 24 h. At this point, the mixture was cooled to room temperature and the solvent was evaporated. The resulting residue was purified by column chromatography (hexanes/EtOAc=9:1) on silica gel to afford the title compound.

*3.2.7.1. cis-3,4-Dimethyl-6-nitrobicyclo[4.3.0]non-3-en-1-carbonitrile (**28**).* Prepared using **17** (34.5 mg, 0.250 mmol) and 2,3-dimethyl-1,3-butadiene (61.6 mg, 0.750 mmol), **28** was isolated as a pale yellow oil (52.3 mg, 95%) after column chromatography. ^{1}H NMR (600 MHz, $CDCl_3$) δ 2.80 (d of AB pattern, J=18.4 Hz, 1H), 2.72 (d of AB pattern, J=18.0 Hz, 1H), 2.64–2.60 (m, 1H), 2.49 (d of AB pattern, J=18.4 Hz, 1H), 2.35–2.31 (m, 1H), 2.28 (d of AB pattern, J=18.0 Hz, 1H), 2.15–2.10 (m, 1H), 2.09–1.02 (m, 1H), 1.99–1.94 (m, 1H), 1.91–1.85 (m, 1H), 1.66 (s, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 121.4, 121.3, 121.2, 95.0, 43.4, 38.8, 37.6, 35.0, 34.5, 18.5, 18.3; IR (neat) 2986, 2964, 2915, 2891, 2861, 2237, 1537, 1457, 1431, 1354, 1133 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{12}H_{16}N_2O_2$) required m/z 220.1212, found m/z 220.1214.

*3.2.7.2. cis-9a-Nitro-2,3,3a,4,5,6,7,8,9,9a-decahydro-1H-cyclopenta[b]naphthalene-3a-carbonitrile (**29**).* Prepared using **17** (34.5 mg, 0.250 mmol) and 1,2-dimethylenecyclohexane[18] (81.1 mg, 0.750 mmol), **29** was isolated as a pale yellow oil (56.0 mg, 91%) after column chromatography. ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.75 (d of AB pattern, J=18.0 Hz, 1H), 2.70–2.60 (m, 2H), 2.44 (d of AB pattern, J=18.0 Hz, 1H), 2.38–2.31 (m, 1H), 2.23 (d, J=17.6 Hz, 1H), 2.19–1.82 (m, 8H), 1.67–1.57 (m, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 123.6, 123.5, 121.3, 94.8, 43.2, 37.8, 36.6, 35.0, 34.5, 29.3, 29.2, 22.5, 22.5, 18.4; IR (neat) 2924, 2239, 1726, 1549, 1439, 1361, 845 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{14}H_{18}N_2O_2$) required m/z 246.1368, found m/z 246.1383.

*3.2.8. General procedure for the radical denitration of cis-fused decalin (**26** and **27**) and hydrindane (**28** and **29**) systems.* A 15-mL Schlenk-type flask equipped with a magnetic stirring bar and a reflux condenser was charged with a *cis*-fused decalin or hydrindane derivative (1.0 equiv), tri-*n*-butyltin hydride (2.0 equiv), azobisisobutyronitrile (0.3–0.5 equiv), and anhydrous benzene. The mixture was heated under reflux for 2 h. At this point, the mixture was cooled to room temperature and the solvent was evaporated. The resulting residue was purified by gradient column

chromatography (hexanes/EtOAc=1:0→97:3→19:1) on silica gel to afford the title compound.

*3.2.8.1. trans-3,4-Dimethylbicyclo[4.4.0]dec-3-en-1-carbonitrile (**30a**).* Prepared using **26** (41.0 mg, 0.175 mmol), tri-*n*-butyltin hydride (102 mg, 0.350 mmol), and azobisisobutyronitrile (8.6 mg, 52 μmol) in benzene (1.8 mL), *trans*-fused **30a** was isolated as a pale yellow oil (29.5 mg, 89%) after column chromatography. The minor isomer, *cis*-fused **30b** was not detected within the limits of ^{1}H and ^{13}C NMR. ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.21 (d, J=16.8 Hz, 1H), 2.05–1.89 (m, 3H), 1.80–1.75 (m, 1H), 1.72–1.58 (m, 3H), 1.62 (s, 6H), 1.49–1.41 (m, 1H), 1.37–1.23 (m, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 125.8, 122.6, 121.9, 43.2 (CH_2), 39.9 (CH), 39.6, 36.9 (CH_2), 36.6 (CH_2), 29.9 (CH_2), 25.5 (CH_2), 23.1 (CH_2), 18.7 (CH_3), 18.6 (CH_3); IR (neat) 2926, 2230, 1738, 1448, 1382 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{13}H_{19}N$) required m/z 189.1517, found m/z 189.1516.

*3.2.8.2. trans-1,2,3,4,4a,5,6,7,8,9,9a,10-Dodecahydroanthracene-4a-carbonitrile (**31a**).* Prepared using **27** (21.0 mg, 80.7 μmol), tri-*n*-butyltin hydride (47 mg, 161 μmol), and azobisisobutyronitrile (6.6 mg, 40 μmol) in benzene (0.8 mL), *trans*-fused **31a** was isolated as an off-white solid (14.8 mg, 85%) after column chromatography. The minor isomer, *cis*-fused **31b** was not detected within the limits of ^{1}H and ^{13}C NMR. ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.15 (d, J=16.8 Hz, 1H), 2.05–1.95 (m, 2H), 1.88–1.45 (m, 14H), 1.37–1.24 (m, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 128.0, 124.3, 122.7, 42.1 (CH_2), 39.8 (CH), 39.4, 36.8 (CH_2), 35.7 (CH_2), 30.0 (CH_2), 29.7 (CH_2), 29.6 (CH_2), 25.5 (CH_2), 23.2 (CH_2), 22.8 (CH_2), 22.7 (CH_2); IR (KBr) 2925, 2830, 2228, 1738, 1449, 1320 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{15}H_{21}N$) required m/z 215.1674, found m/z 215.1658.

*3.2.8.3. A 1.5:1 mixture of trans-3,4-dimethylbicyclo[4.3.0]non-3-enecarbonitrile (**32a**) and cis-3,4-dimethylbicyclo[4.3.0]non-3-enecarbonitrile (**32b**).* Prepared using **28** (30.8 mg, 0.140 mmol), tri-*n*-butyltin hydride (81.5 mg, 0.280 mmol), and azobisisobutyronitrile (11.5 mg, 70.0 μmol) in benzene (1.4 mL), an inseparable 1.5:1 mixture of *trans*-fused **32a** and *cis*-fused **32b** was isolated as an pale yellow oil (18.9 mg, 77%) after column chromatography. The relative stereochemistry of the major isomers was assigned according to Casadevall's observation and our previous study.[2] Diastereomeric ratios were estimated by the integration of the methine carbon signals. ^{1}H and ^{13}C NMR spectra of the mixture of **32a** and **32b** are available in Supplementary data. IR (neat) 2959, 2914, 2836, 2231, 1727, 1452, 1275, 1124, 1073 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{12}H_{17}N$) required m/z 175.1361, found m/z 175.1358.

*3.2.8.4. A 1.7:1 mixture of trans-2,3,3a,4,5,6,7,8,9,9a-decahydro-1H-cyclopenta[b]naphthalene-3a-carbonitrile (**33a**) and cis-2,3,3a,4,5,6,7,8,9,9a-decahydro-1H-cyclopenta[b]naphthalene-3a-carbonitrile (**33b**).* Prepared using **29** (34.5 mg, 0.140 mmol), tri-*n*-butyltin hydride (81.5 mg, 0.280 mmol), and azobisisobutyronitrile (11.5 mg, 70.0 μmol) in benzene (1.4 mL), an inseparable 1.7:1 mixture of *trans*-fused **33a** and *cis*-fused **33b** was isolated as an pale yellow oil (25.2 mg, 89%) after column chromatography. The relative stereochemistry of the major isomers was assigned according to Casadevall's observation and our previous study.[2] Diastereomeric ratios were estimated by the integration of the methine carbon signals. ^{1}H and ^{13}C NMR spectra of the mixture of **32a** and **32b** are available in Supplementary data. IR (neat) 2927, 2833, 2230, 1729, 1440, 1312 cm^{-1}; HRMS (EI) exact mass calculated for $[M]^+$ ($C_{14}H_{19}N$) required m/z 201.1517, found m/z 201.1523.

3.2.9. General procedure for the preparation of cis-fused angular amine derivatives. To a stirred solution of a *cis*-fused decalin or hydrindane (1.0 equiv) in a mixture of glacial acetic acid and THF (1:2, v/v) at −20 °C was added Zn dust (10 equiv). After stirring for 3 h, the mixture was filtered through a pad of Celite® and the filtrate was concentrated on a rotatory evaporator. The resulting residue was dissolved in THF and the mixture was treated successively with a saturated solution of $NaHCO_3$ and allyl chloroformate (2.5 equiv). The mixture was stirred for 3 h, diluted with H_2O, and extracted with EtOAc (3×10 mL). The combined extract was washed with brine, dried over anhydrous $MgSO_4$, filtered, and concentrated on a rotatory evaporator. The resulting residue was purified by gradient column chromatography on silica gel to afford the title compound.

*3.2.9.1. cis-Allyl 8a-cyano-6,7-dimethyl-1,2,3,4,4a,5,8,8a-octahydronaphthalen-4a-ylcarbamate (**34**).* Prepared using **26** (20.0 mg, 85.4 μmol), Zn dust (55.8 mg, 854 μmol), and allyl chloroformate (25.7 mg, 214 μmol), **34** was isolated as a pale yellow oil (10 mg, 40%) after column chromatography. ^{1}H NMR (600 MHz, $CDCl_3$) δ 5.95–5.88 (m, 1H), 5.32–5.28 (m, 1H), 5.23–5.21 (m, 1H), 4.92 (s, 1H), 4.54–4.48 (m, 2H), 2.67 (d of AB pattern, J=17.9 Hz, 1H), 2.50–2.42 (m, 2H), 2.25 (d of AB pattern, J=17.9 Hz, 1H), 2.12–1.98 (m, 2H), 1.81–1.77 (m, 1H), 1.72–1.62 (m, 4H), 1.63 (s, 3H), 1.62 (s, 3H), 1.52–1.47 (m, 1H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 154.4, 132.8, 123.2, 126.7, 119.3, 117.8, 65.3, 55.0, 41.5, 38.5, 36.2, 31.3, 30.2, 29.7, 21.2, 18.7, 18.3; IR (neat) 3346, 2933, 2865, 2232, 1724, 1509, 1450, 1294, 1231, 1111, 1046, 985 cm^{-1}; HRMS (FAB) exact mass calculated for $[M+1]^+$ ($C_{17}H_{25}N_2O_2$) required m/z 289.1916, found m/z 289.1919.

*3.2.9.2. cis-Allyl 7a-cyano-5,6-dimethyl-2,3,3a,4,7,7a-hexahydro-1H-inden-3a-ylcarbamate (**35**).* Prepared using **28** (20.0 mg, 90.8 μmol), Zn dust (59.4 mg, 908 μmol), and allyl chloroformate (27.4 mg, 227 μmol), **35** was isolated as a pale yellow oil (13 mg, 52%) after column chromatography. ^{1}H NMR (600 MHz, $CDCl_3$) δ 5.95–5.89 (m, 1H), 5.33–5.30 (m, 1H), 5.23 (dd, J=10.4, 1.3 Hz, 1H), 5.01 (s, 1H), 4.54 (d, J=5.5 Hz, 2H), 2.50–2.39 (m, 4H), 2.25–2.16 (m, 2H), 2.05–1.91 (m, 2H), 1.88–1.75 (m, 2H), 1.63 (s, 3H), 1.62 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 155.0, 132.6, 123.9, 122.7, 119.8, 118.0, 65.5, 62.5, 45.2, 37.7, 37.6, 34.7, 29.7, 19.3, 18.8, 18.4; IR (neat) 3332, 2916, 2886, 2849, 2233, 1724, 1510, 1445, 1274, 1238, 1086, 916 cm^{-1}; HRMS (FAB) exact mass calculated for $[M+1]^+$ ($C_{16}H_{23}N_2O_2$) required m/z 275.1760, found m/z 275.1772.

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Supplementary data

^{1}H and ^{13}C NMR spectra of all new compounds are available. Crystallographic data for the structures reported in this article have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC-763857 (**13**), CCDC-763854 (**14**), CCDC-763855 (**19**), and CCDC-763856 (**25**). Copies of the data can be obtained free of charge at www.ccdc.cam.ac.uk/conts/retrieving.html or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK [Tel.: +44 1223 336 408, fax: +44 1223 336 033 or e-mail: deposit@ccdc.cam.ac.uk].

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2010.04.094.

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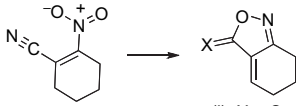

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