HETEROCYCLES, Vol. 92, No. 3, 2016, pp. 485 - 510. © 2016 The Japan Institute of Heterocyclic Chemistry
Received, 11th December, 2015, Accepted, 20th January, 2016, Published online, 4th February, 2016
DOI: 10.3987/COM-15-13394

INTER- AND INTRAMOLECULAR DIELS-ALDER REACTION OF ETHENETRICARBOXYLATE DERIVATIVES

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Abstract – Inter- and intramolecular [4+2] cycloaddition reactions of highly electron-deficient ethenetricarboxylates have been studied. Intermolecular Diels-Alder reaction of ethenetricarboxylate esters and cyclopentadiene proceeded at room temperature or -20 °C to give cycloadducts with 1:1.5-1.9 endo:exo ratio. Lewis acids such as $EtAlCl_2$, $Zn(OTf)_2$ and $Cu(OTf)_2$ catalyzed reaction at room temperature or -40 °C gave cycloadducts with 3.1-5.4:1 endo:exo ratio. Reaction of *N*-benzyl- or *N*-allyl-2-furylmethylamine and 1,1-diethyl 2-hydrogen ethenetricarboxylate in the presence of EDCI/HOBt/Et_3N at room temperature led directly to an intramolecular Diels-Alder adduct stereoselectively. The observed stereoselectivities were explained by the use of DFT calculations.

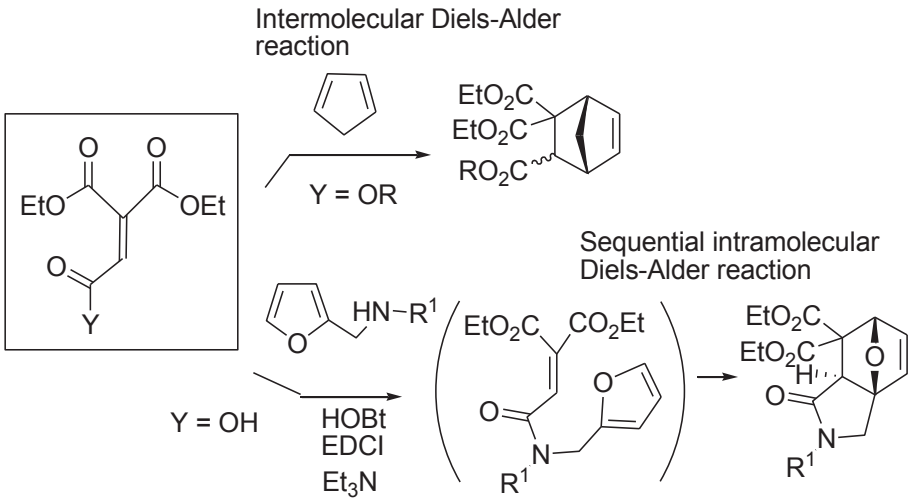
INTRODUCTION

Diels-Alder reaction is one of the most widely used synthetic tools.[1] The alkene component (dienophile) is usually electron-deficient in normal electron-demand Diels-Alder reaction. In general, the greater the number of electron-withdrawing substituents on the double bond, the more reactive is the dienophile, owing to the lowering of the energy of the LUMO of the dienophile by the substituents. Ethenetricarboxylate derivatives bearing three carbonyl groups have been employed as highly electrophilic C=C components in various bond-forming reactions.[2] Although an intramolecular inverse electron demand hetero Diels-Alder reaction of 1-allylic 2,2-dimethyl esters of ethene-1,2,2-tricarboxylate has been studied,[3] only a few normal electron demand Diels-Alder reactions of ethenetricarboxylate related compounds as electron-deficient dienophiles have been reported.[4]

Ethenetricarboxylates allow for the facile derivatization at 2-carboxyl group. The electron-deficient alkene moiety is expected to work as a reactive dienophile in the intramolecular Diels-Alder reaction.

The intramolecular Diels-Alder reaction of furans is used for facile formation of multicyclic skeletons.[5] Furan derivatives can be obtained from renewable resources.[6] The development of new synthetic methods utilizing furans is of considerable interest.[7] Lewis acid-catalyzed reaction of furan derivatives with electron-deficient alkenes also gave Friedel-Crafts/conjugate addition products.[8] The diversity of the reactivity of furans is also of interest.

In this work, intermolecular and sequential intramolecular Diels-Alder reactions of ethenetricarboxylate derivatives with dienes have been studied.



Scheme 1

RESULTS AND DISCUSSION

We have reported Lewis acid-catalyzed intermolecular reaction of ethenetricarboxylates with furan derivatives to give Friedel-Crafts/ conjugate addition products.[9] Both intermolecular Diels-Alder reactions of methylenemalonates /alkylidenemalonates and dienes[10] such as butadiene, cyclopentadiene or 1-methoxy-3-trimethylsiloxy-1,3-butadiene and intramolecular Diels-Alder reactions of alkylidenemalonates and dienes[11] were reported previously. First, intermolecular Diels-Alder reaction of ethenetricarboxylates and reactive dienes has been examined. The reaction of ethenetricarboxylate esters **1** and cyclopentadiene **2** proceeded at room temperature or -20 °C to give cycloadducts **3** with 1:1.5-1.9 endo:exo ratio (eq 1, Table 1). Endo and exo structures were assigned by observed NOEs between C3-*H* and C5-*H* for endo and between C3-*H* and C7-H*H* for exo. Lewis acids such as $Zn(OTf)_2$ and $Cu(OTf)_2$ catalyzed reaction at room temperature gave cycloadducts **3** with 3.1-3.3:1 endo:exo ratio. $EtAlCl_2$ catalyzed reaction at lower temperature increased endo:exo ratio. Thus, the uncatalyzed and Lewis acid-catalyzed Diels-Alder reactions of ethenetricarboxylates **1** and cyclopentadiene **2** showed opposite

preference for stereoselectivity.

Treatment of cycloadduct **3b** (1 : 1.8 endo:exo ratio) obtained by entry 8 reaction condition with $Zn(OTf)_2$ and $Cu(OTf)_2$ at room temperature for 17 h resulted in very little change of the endo:exo ratio. The possible epimerization of cycloadducts **3** by retro-[4+2]/[4+2]-cycloaddition[10c] may be very slow at room temperature in the presence of these Lewis acids.

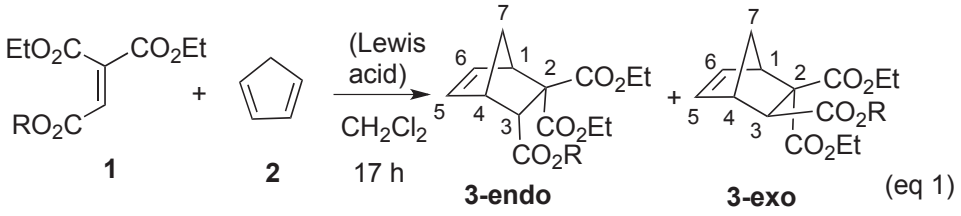


Table 1. Reactions of Ethenetricarboxylate Esters **1** and Cyclopentadine **2**

Entry	**1**	R	Temp.	Lewis Acid	Equiv.	Product	**3-endo**:**3-exo**	**3** Yield (%)
1	**1a**	^{t}Bu	rt	-		**3a**	1 : 1.5	96
2	**1a**	^{t}Bu	-20 °C	-		**3a**	1 : 1.9	62
3	**1a**	^{t}Bu	rt	$Zn(OTf)_2$	0.1	**3a**	3.1 : 1	92
4	**1a**	^{t}Bu	rt	$Cu(OTf)_2$	0.1	**3a**	3.2 : 1	88
5	**1a**	^{t}Bu	rt	$EtAlCl_2$	0.1			decomposed
6	**1a**	^{t}Bu	-20 °C	$EtAlCl_2$	0.1	**3a**	2.8 : 1	100
7	**1a**	^{t}Bu	-40 °C	$EtAlCl_2$	0.1	**3a**	5.4 : 1	100
8	**1b**	Et	rt	-		**3b**	1 : 1.8	73
9	**1b**	Et	rt	$Zn(OTf)_2$	0.1	**3b**	3.3 : 1	97
10	**1b**	Et	-40 °C	$EtAlCl_2$	0.1	**3b**	3.6 : 1	99

In order to explain the observed endo:exo preferences,[12] the reaction mechanism was examined using B3LYP/6-31G*[13,14] calculations including the PCM[15] solvent effect (solvent=CH_2Cl_2). TS geometry was characterized by vibrational analysis, which checked whether the obtained geometry has single imaginary frequencies ($\nu^{\ddagger}$). From TSs, reaction paths were traced by the intrinsic reaction coordinate (IRC) method[16] to obtain the energy-minimum geometries. Relative Gibbs free energies are of RB3LYP/6-31G* SCRF = (PCM, solvent = CH_2Cl_2) (T = 298.15 K, P = 1 atm).

First, the conformations of compound **1** were calculated through the use of model compound trimethyl ethenetricarboxylate **1m**. Stable four conformations of **1m** with respect to s-*cis* and s-*trans* of ester C=O groups were obtained by geometry optimization. In the optimized structures, 1-*syn* ester group to 2-ester is located almost perpendicularly to C=C plane. None of C=O of 1-*syn* ester on the C=C plane was obtained, probably because of steric congestion. The energy differences of C=C−C=O s-*cis* and s-*trans*

are small (within +1.73 kcal/mol) (Figure 1). Using the most stable conformation of **1m**(cc) (cc = 1-anti-s-cis, 2-s-cis), the endo and exo transition states of the intermolecular Diels-Alder reaction of **1m** and cyclopendtadiene (**2**) were calculated (Figure 2). The activation energy $\Delta G^{\ddagger}$ of endo transition state (TS) is 1.03 kcal/mol higher than that of exo TS. The exo preference is in accord with the experimental results.

Although 1-*syn* ester group is perpendicular to C=C plane, it has still an electron-withdrawing effect. C-2 carbon may interact with diene first by the slight asynchronous approach (C2-C1' = 2.168 Å, C1-C4' = 2.327 Å for 2-ester exo TS, C2-C1' = 2.219 Å, C1-C4' = 2.291 Å for 2-ester endo TS). The exo approach on 2-ester and 1-*syn* ester is considered to be endo approach on 1-*anti* ester group. The secondary orbital interaction of 1-*anti* ester carbonyl carbon with diene carbon in 2-ester endo TS may be slightly more effective than that of 2-ester carbonyl carbon in 2-ester endo TS (O*C*-C3' = 2.973 Å for 2-ester exo TS, O*C*-C2' = 2.997 Å for 2-ester endo TS).

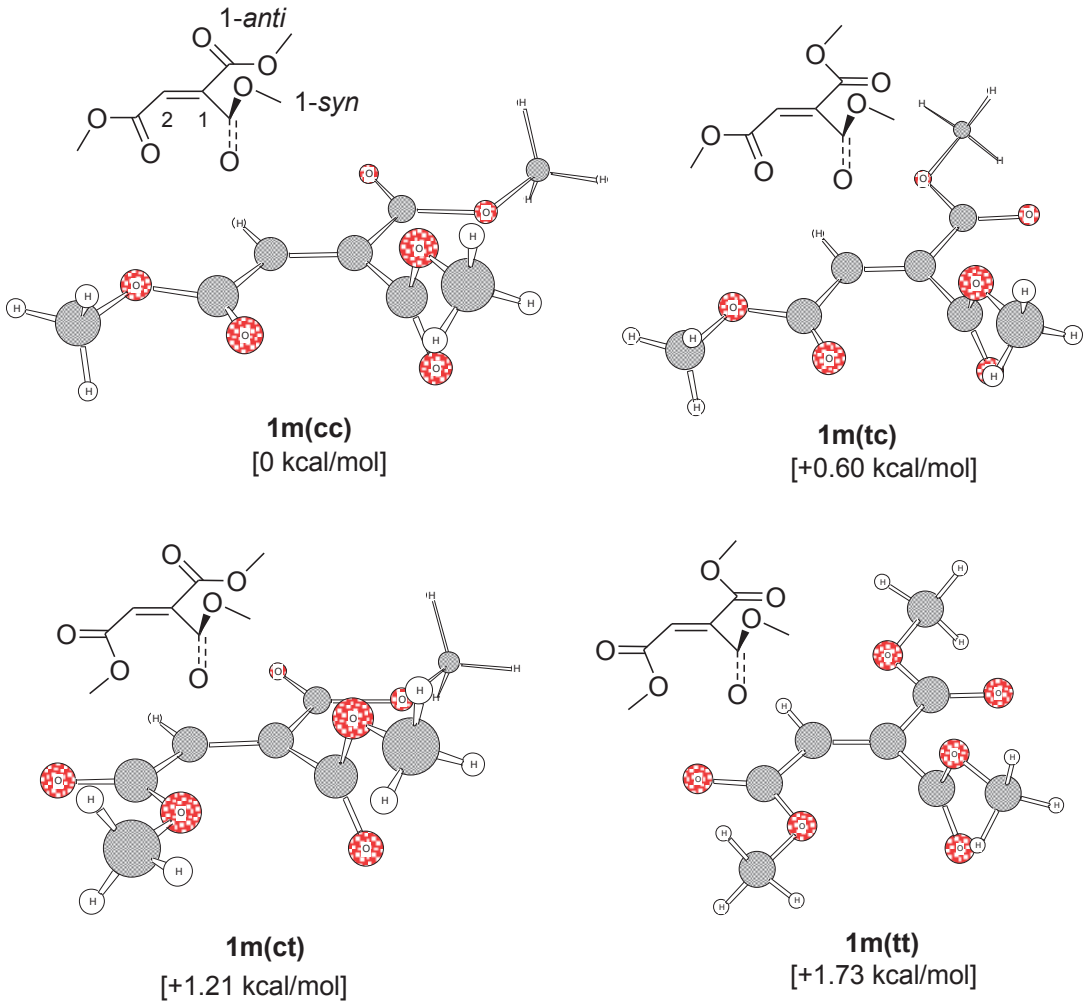


Figure 1. RB3LYP/6-31G* SCRF = (PCM, solvent = CH_2Cl_2) optimized structures for conformational isomers of trimethyl ethenetricarboxylate **1m**. Gibbs free energies are relative to **1m**(cc).

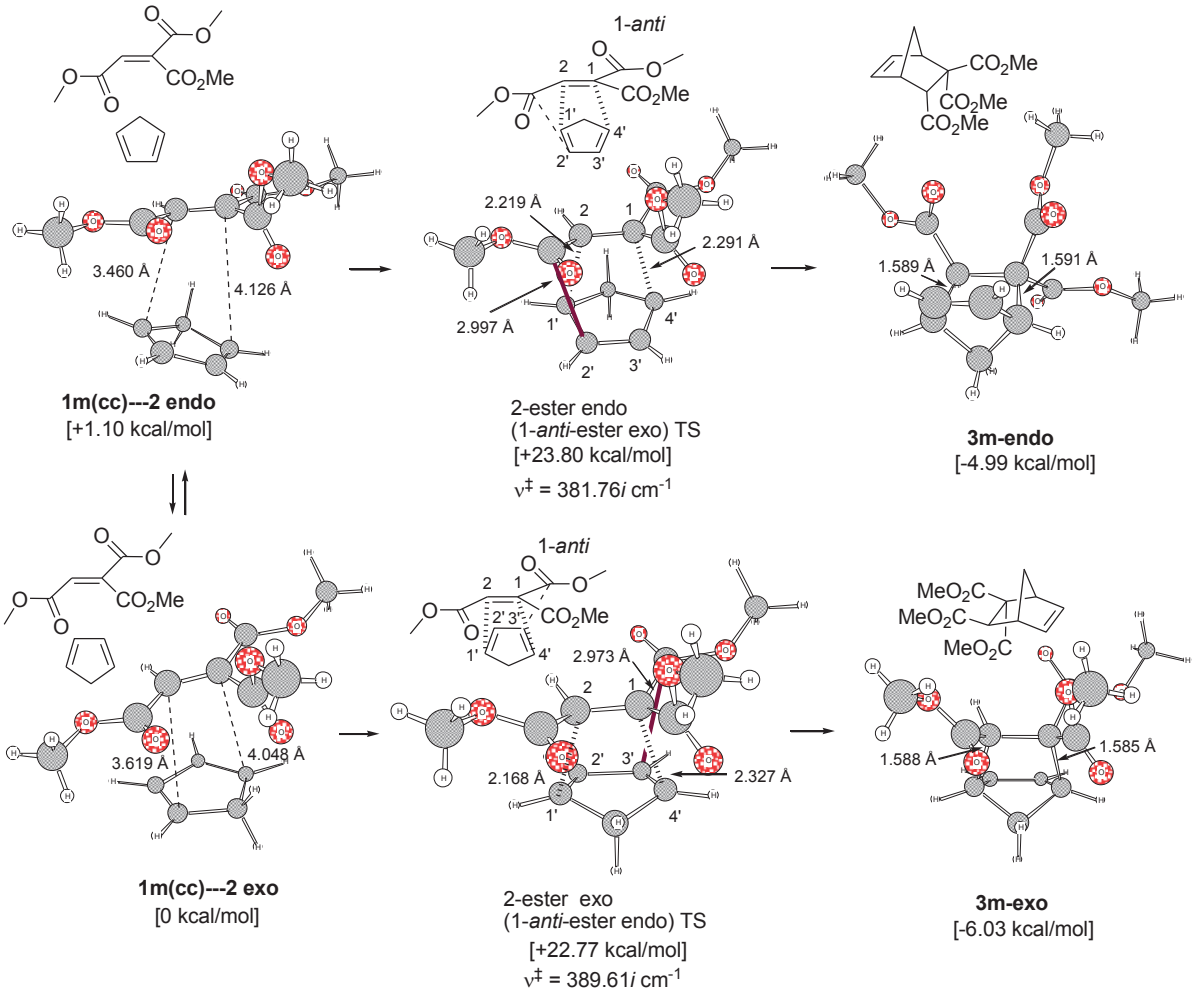


Figure 2. RB3LYP/6-31G* SCRF = (PCM, solvent = CH_2Cl_2) optimized structures for endo:exo Diels-Alder reaction paths of **1m**(cc) and cyclopentadiene (**2**). Gibbs free energies are relative to **1m**(cc)---**2**endo.

Next, Lewis acid-catalyzed Diels-Alder reaction of **1m** and cyclopendtadiene (**2**) was examined using the bidentate $AlCl_3$-coordinated **1m** shown in Figure 3 as a model system.[17,18] In the initial $AlCl_3$-**1m** and **2** complex, 2-ester group is located perpendicularly to C=C plane (1,1-diester C=O groups are both s-trans to C=C). Stepwise mechanism with zwitterionic intermediates was obtained.[19] Lewis acid-catalyzed reaction lowers the activation energies. The activation energy $\Delta G^{\ddagger}$ of endo TS1 is 1.16 kcal/mol lower than that of exo TS1. The endo preference is in accord with the experimental results. The endo preference may arise from the steric congestion of 2-ester group and methylene hydrogen of cyclopentadiene in exo TS. The endo preference in the kinetic product has also been reported in the $TiCl_4$-catalyzed cycloaddition reaction of dimethyl benzylidenemalonate and cyclopentadiene at -78 °C.[10c]

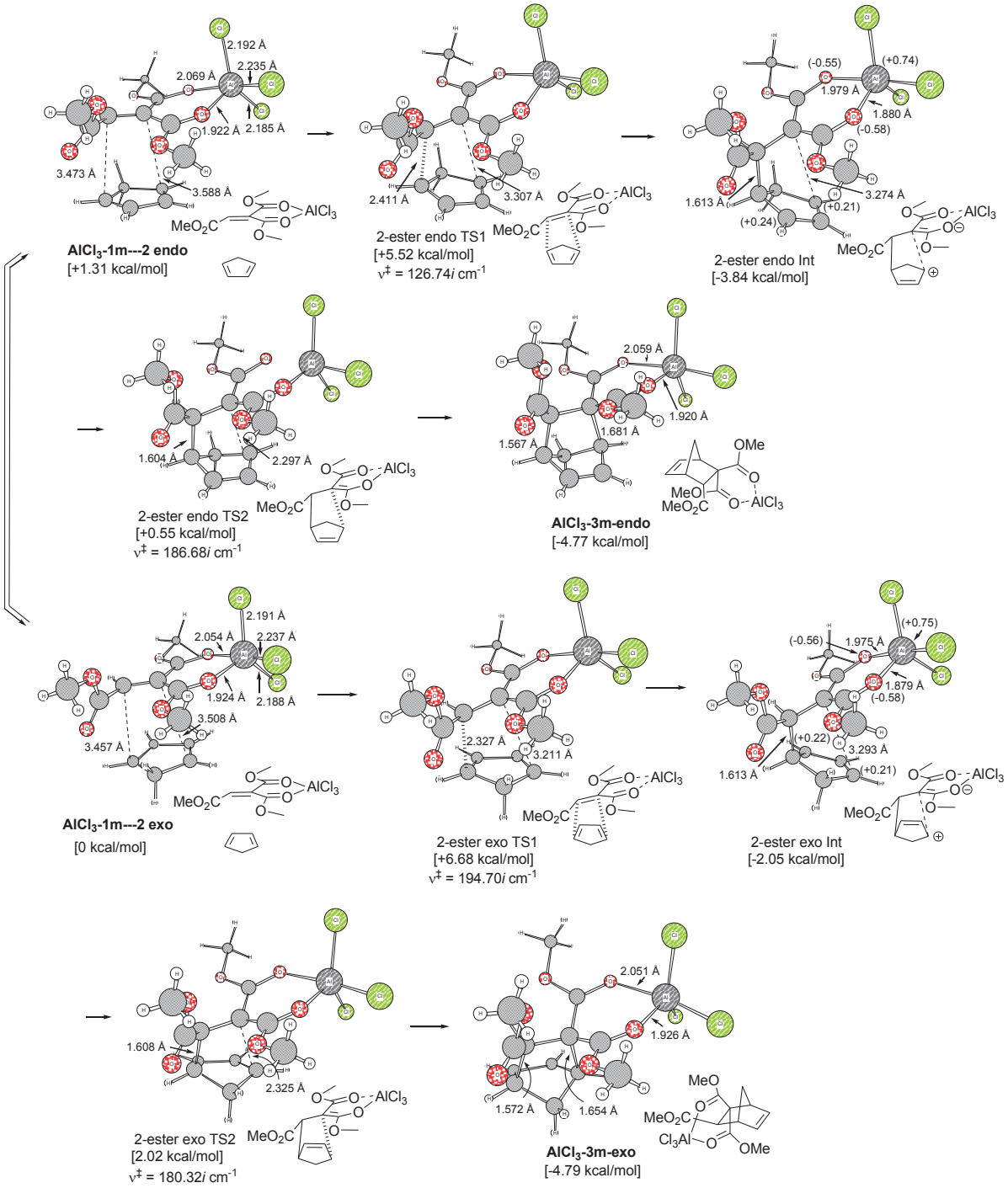
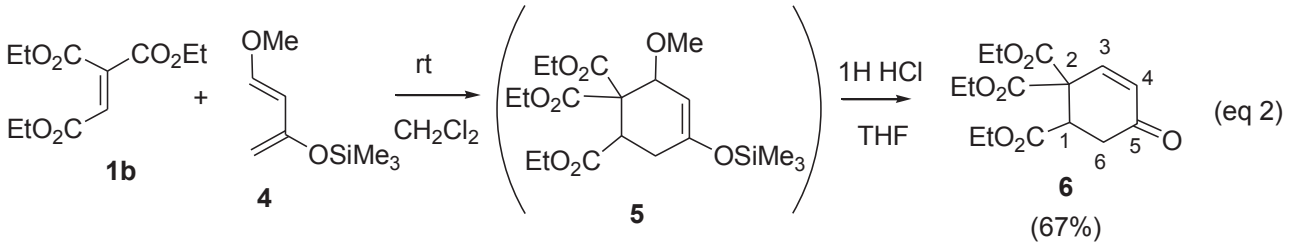


Figure 3. RB3LYP/6-31G* SCRF = (PCM, solvent = CH_2Cl_2) optimized structures for endo:exo Diels-Alder reaction paths of $AlCl_3$-**1m** and cyclopentadiene (**2**). Gibbs free energies are relative to $AlCl_3$-**1m**---**2**exo. Values in parentheses are Mulliken charges with hydrogens summed into heavy atoms.

The reaction of **1b** and Danishefsky's diene has also been carried out. The reaction of **1b** and 1-methoxy-3-trimethylsiloxy-1,3-butadiene **4** in dichloromethane proceeded at room temperature to give the crude adduct **5**, which was hydrolyzed directly with 1 N HCl in THF to give the cyclohexenone **6** in 67% yield regioselectively.



Thus, it was shown that ethenetricarboxylates **1** have high reactivity towards Diels-Alder reaction with reactive dienes such as **2** and **4**.

Next, intramolecular [4+2] cycloaddition reaction of ethenetricarboxylates has been examined. Reaction of *N*-benzyl- or *N*-allyl-2-furylmethylamine **8a,b** and 1,1-diethyl 2-hydrogen ethenetricarboxylate **7** in the presence of EDCI/HOBt/Et_3N at room temperature led directly to an intramolecular Diels-Alder adducts **9a,b** in 65-82% yield (eq 3, Table 2). The possible intermediate **10** could not be observed under the reaction conditions of amide formation (Scheme 2). The reaction of **7** and **8a** in the absence of condensation reagents only gave the mixture of the **7** and **8a**, probably forming a salt. Treatment of the mixture with condensation reagents led to the Diels-Alder adduct **9a** in 75% yield.

The structure of 10-oxa-3-aza-tricyclo[5.2.1.$0^{1,5}$]dec-8-ene **9a** was determined by X-ray analysis (Figure 4).[20] The exo stereochemistry of Diels-Alder adducts **9a-e** with respect to the amide group was also determined by NOEs. NOEs between C5-*H* and C2-H*H* and/or between C5-*H* and C9-*H* were observed (atom numbering is shown in eq 3.).

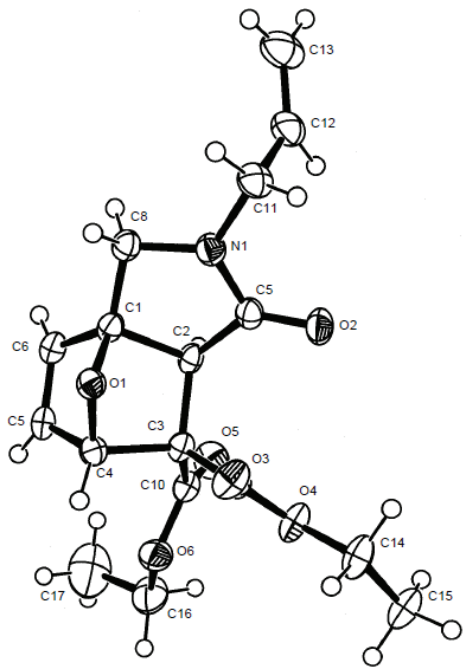


Figure 4. ORTEP drawing of **9a** (thermal ellipsoids are drawn at 50% probability). The atom numbering is different from that in eq 3.

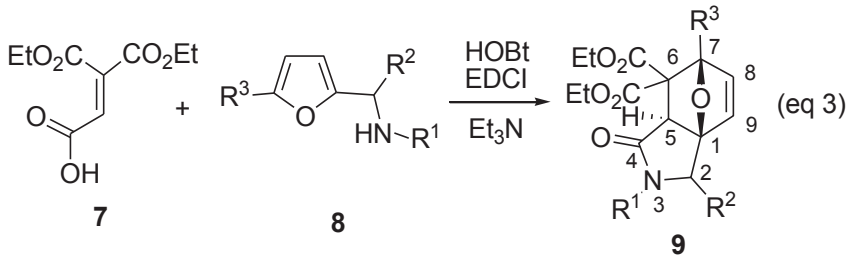
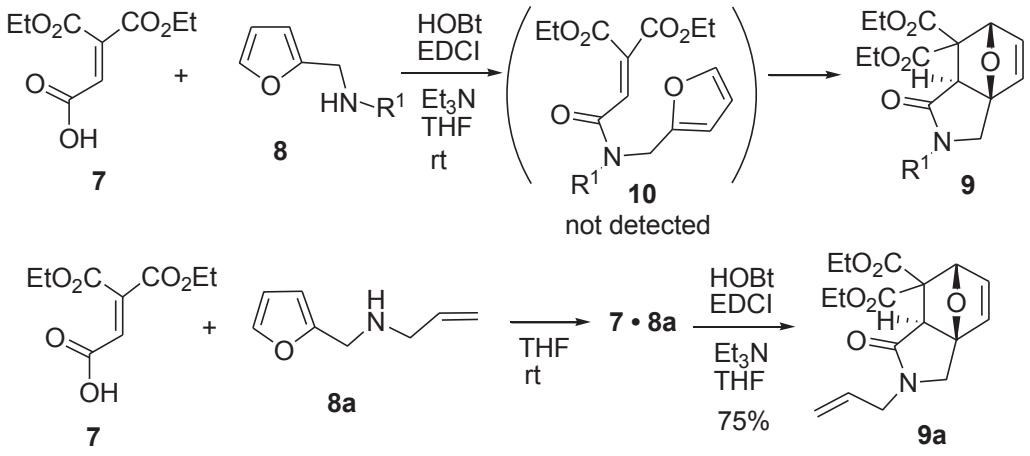


Table 2. Reactions of 1,1-Diethyl 2-hydrogen ethenetricarboxylate **7** and 2-Furylmethylamines **8**

Entry	**8**	R^1	R^2	R^3	Temp,Time	solvent	Product	Yield (%)
1	**8a**	$CH_2CH=CH_2$	H	H	rt 17 h	THF	**9a**	82
2	**8b**	CH_2Ph	H	H	rt 21 h	THF	**9b**	65
3	**8c**	CH_2Ph	Me	H	rt 20 h	THF	**9c**	48 (dr=2:1)
4	**8d**	CHMePh	H	H	rt 20 h	THF	**9d**	43 (dr=1:1)
5	**8e**	CH_2Ph	H	Br	rt 20 h	THF	**9e**	48
6	**8e**	CH_2Ph	H	Br	rt 1 h	THF	**9e**	40
8	**8e**	CH_2Ph	H	Br	60 ˚C, 20 h	THF	**9e**	55
4	**8e**	CH_2Ph	H	Br	80 ˚C, 20 h	CH_2ClCH_2Cl[a]	**9e**	75
6	**8b**	CH_2Ph	H	H	60 ˚C, 20 h	THF	**9b**	46
7	**8b**	CH_2Ph	H	H	80 ˚C, 20 h	CH_2ClCH_2Cl[a]	**9b**	50

[a] The byproducts was removed by column chromatography.[22]



Scheme 2

In order to explain the stereoselectivity of the intramolecular Diels-Alder reaction was examined by B3LYP/6-31G* calculations including the PCM solvent effect (solvent=THF).

The endo and exo intramolecular Diels-Alder reactions from a model compound **10m** as a possible

intermediate were calculated (Figure 5). The activation energy $\Delta G^{\ddagger}$ of endo TS (31.17 kcal/mol) is much higher than that of exo TS (21.41 kcal/mol). The acid-catalyzed intramolecular Diels-Alder reactions of **10m** were also calculated (Figure 6). The protonated six-membered ring intermediates with hydrogen bonding were assumed.[21] The acid *in situ*, possibly generating from EDCI (1-[3-(dimethylamino)propyl]-3-ethylcarbodiimide hydrochloride) or starting material **7** may catalyze the cycloaddition reactions. Stepwise mechanism with zwitterionic intermediates was obtained for the H^+-catalyzed reaction. The acid-catalyzed reaction lowers the activation energies compared to the uncatalyzed reaction. The activation energy $\Delta G^{\ddagger}$ of the second bond formation TS (H^+IM-exo-TS2) (10.10 kcal/mol) is higher than that of the first TS (H^+IM-exo-TS1) (1.51 kcal/mol) for exo addition. The H^+-catalyzed process accelerates the formation of the exo adduct **9**.

The first bond formation TS (H^+IM-endo-TS1) for endo addition was obtained, however the second bond formation TS could not be obtained. Optimization of the initial structure of **endo10m-H$^+$** led to the intermediate (H^+IM- endo-Int). The endo TS and product are highly unstable probably because of the steric constraint. Therefore, the exo adducts **9** produced stereoselectively.

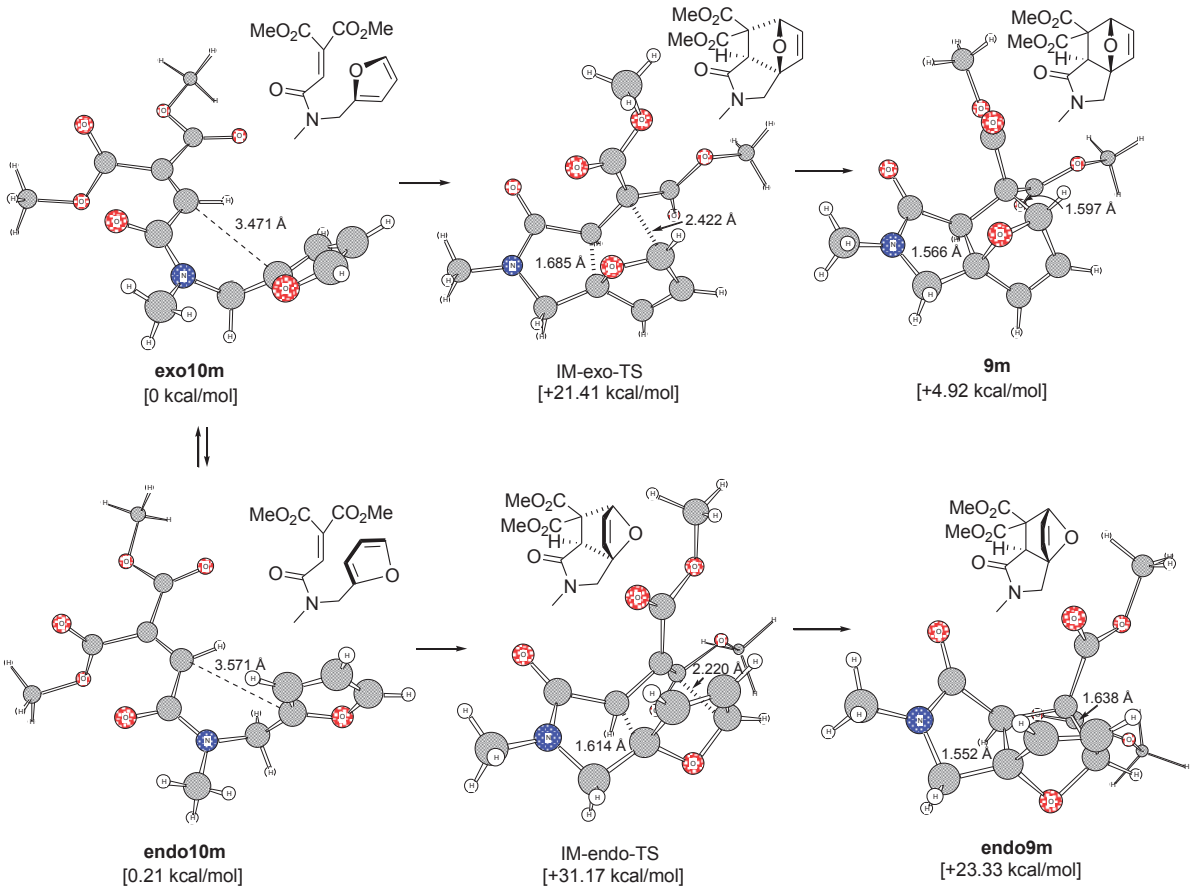


Figure 5. RB3LYP/6-31G* SCRF = (PCM, solvent=THF) optimized structures for endo:exo intramolecular Diels-Alder reaction paths of **10m**.

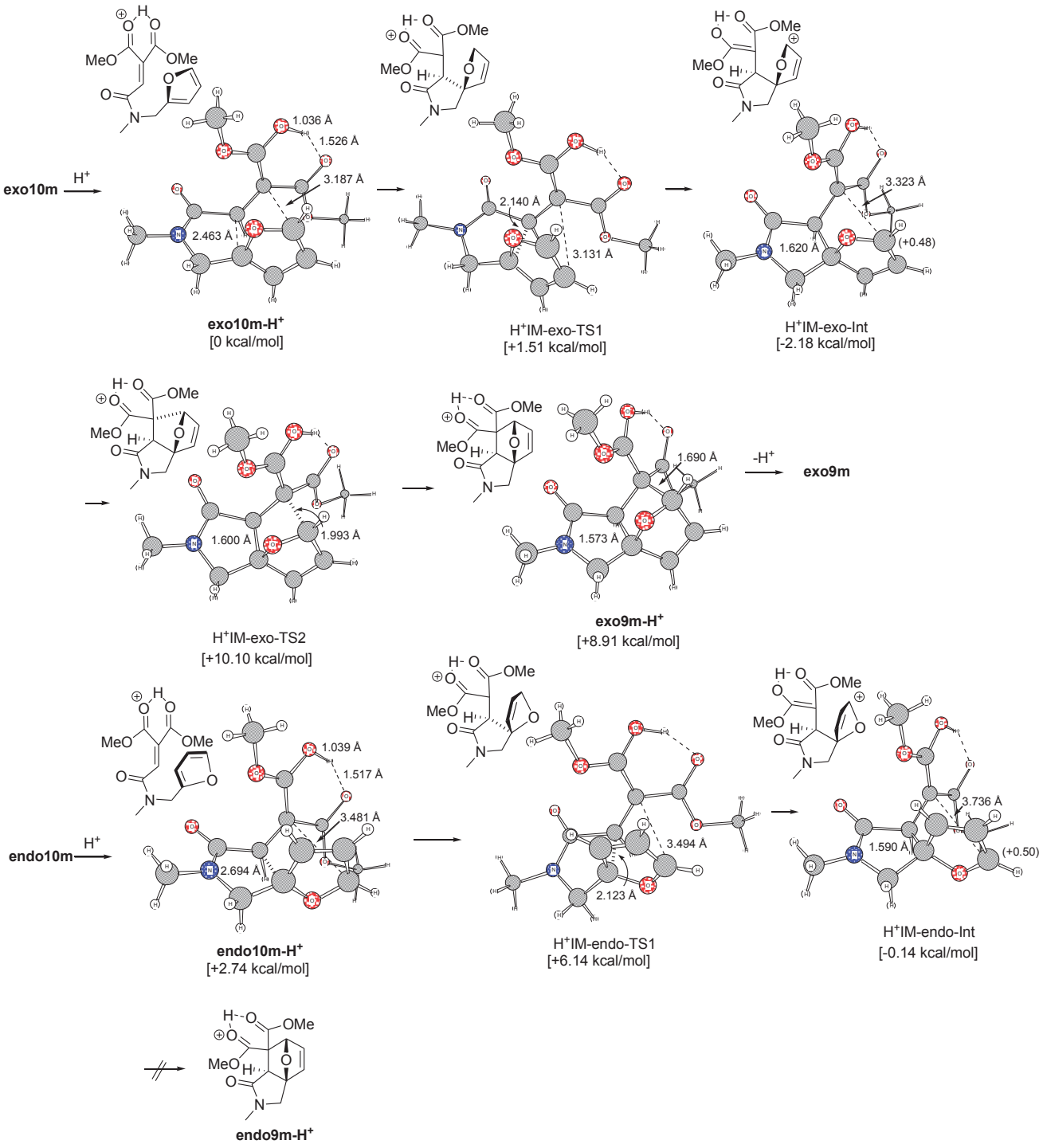
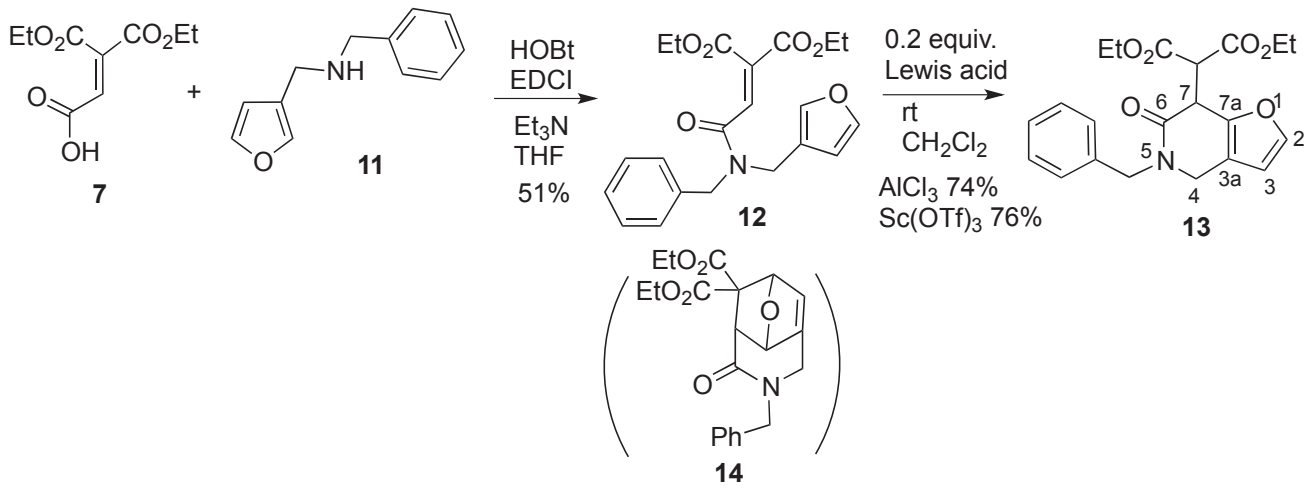


Figure 6. RB3LYP/6-31G* SCRF = (PCM, solvent=THF) optimized structures for endo:exo acid-catalyzed intramolecular Diels-Alder reaction paths of **10m**. Values in parentheses are Mulliken charges with hydrogens summed into heavy atoms.

Reaction of 1-phenylethyl-2-furylmethylamine or benzyl-1-(2-furyl)ethylamine **8c,d** gave Diels-Alder adducts **9c,d** with diastereomer ratios of 2:1-1:1 in 43-48% yield. Reaction of *N*-benzyl-(5-bromofuran-2-yl)methylamine **8e** gave Diels-Alder adduct **9e** at room temperature in THF for 1 h in 40%, for 20 h in 48% and at 80 °C in CH_2ClCH_2Cl[22] for 20 h in 75%. A small amount of

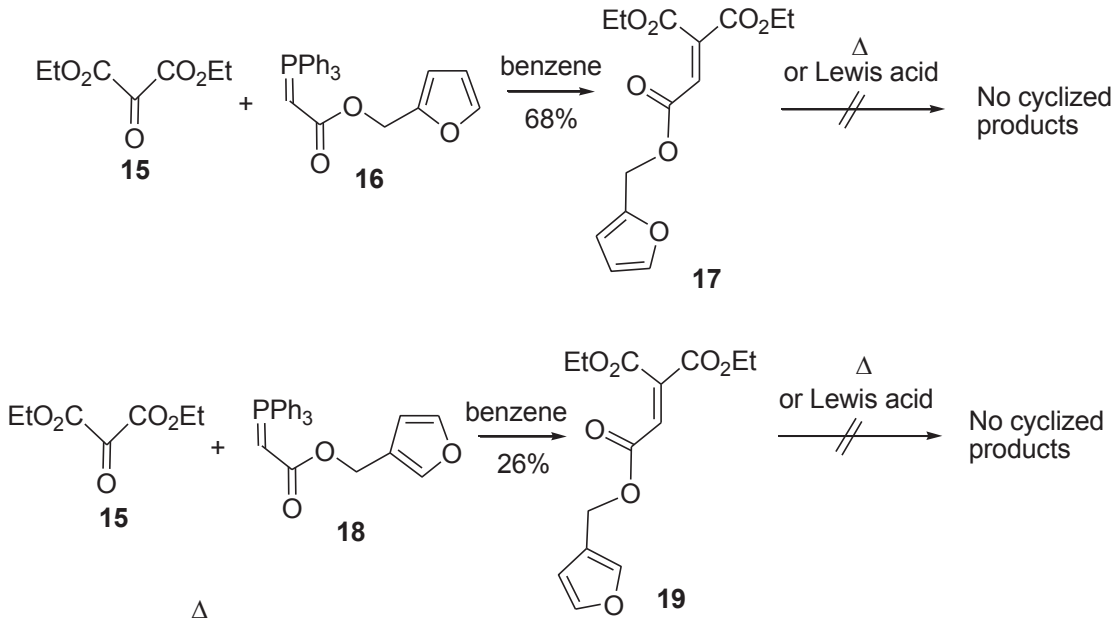
byproducts formed at room temperature possibly contain amine adducts at C=C bond. The reaction of **7** and **8b** with DCC gave a complex mixture containing a small amount of DCU-incorporated byproducts.[23] Next, formation and reaction of 3-substituted amide **12** was examined as a comparison. The 3-substituted amide **12** may not undergo the intramolecular Diels-Alder reaction by the high strain. Although the main objective of this study is to examine Diels-Alder reactions, examination of the selectivity of Diels-Alder vs Friedel-Crafts/Michael addition for furans are also of interest.[8,24] Reaction of benzyl-3-furylmethylamine **11** and ethenetricarboxylate **7** in the presence of EDCI/HOBt/Et_3N gave a non-cyclized amide **12**. Lewis acid-catalyzed reaction of the amide **12** gave the Friedel-Crafts cyclized product **13** selectively in 74-76% yield (Scheme 3), similar to Lewis acid-catalyzed cyclization of phenyl-substituted ethenetricarboxylate derivatives.[25] The highly strained Diels-Alder adduct **14** with 10-oxa-7-aza-tricyclo[3.3.1.$1^{3,9}$]dec-4-ene system was not formed.



Scheme 3

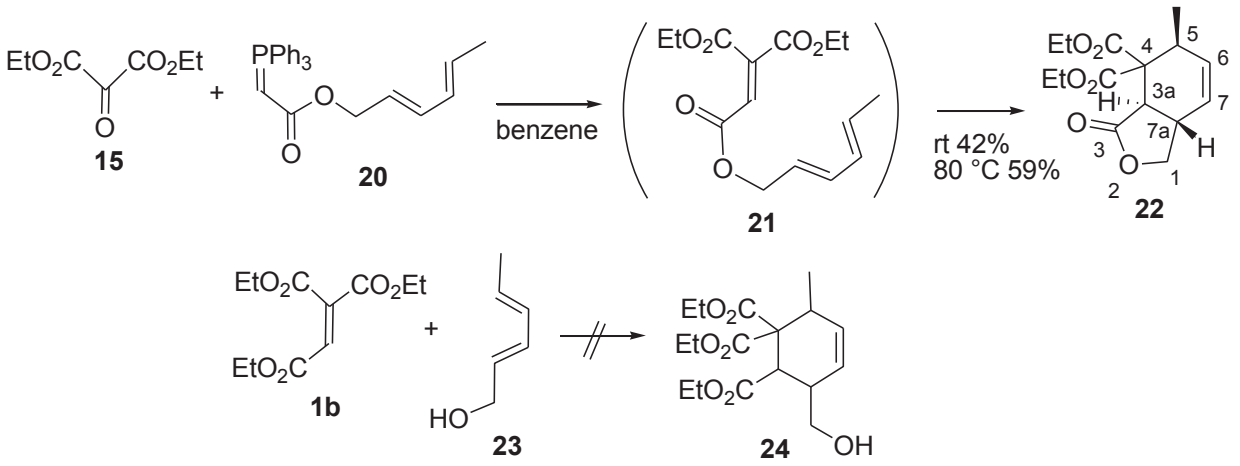
Unlike 2-furylmethylamides of ethenetricarboxylate, 2-furylmethyl ester of ethenetricarboxylate **17** is a stable compound at room temperature and the similar thermal or Lewis acid-catalyzed reaction did not give [4+2] adduct (Scheme 4). The reaction of 3-furylmethyl ester of ethenetricarboxylate **19** under the thermal or Lewis acid-catalyzed reaction only gave starting materials along with decomposed products.

The difference on reactivity between oxygen and nitrogen analogues (intermediate **10** vs **17**, **12** vs **19**) can be explained, similar to the cyclization of other ethenetricarboxylate derivatives.[26] Triesters may be more stable in s-*cis* conformation of O=C−O−CH_2furanyl bond, probably because of the steric repulsion. In diester amides, the energy differences of s-*cis* and s-*trans* conformations of O=C−N−CH_2furanyl may be small. The facile intramolecular reactions of amides probably originates from higher ratio of the reactive s-*trans* conformer.



Scheme 4

On the other hand, in the reaction of diethyl ketomalonate **15** with (2*E*,4*E*)-hexa-2,4-dien-1-yl (triphenylphosphoranylidne)acetate (**20**) in benzene at room temperature or at 80 °C, tandem Wittig reaction/intramolecular Diels-Alder reaction proceeded to give **22** in 42 and 59% yields, respectively (Scheme 5). Intermediate **21** could not be isolated. The corresponding intermolecular Diels-Alder reaction of ester **1b** and (2*E*,4*E*)-hexa-2,4-dien-1-ol **23** in CH_2Cl_2 at room temperature for 20 h did not proceed. The reaction at 80 °C (in 1,2-dichloroethane) or 110 °C (in toluene) caused decomposition of the substrates and did not give the Diels-Alder product.



Scheme 5

In summary, inter- and intramolecular [4+2] cycloaddition reactions of ethenetricarboxylates have been studied. Intermolecular Diels-Alder reaction of ethenetricarboxylate esters and cyclopentadiene

proceeded at room temperature or -20 °C to give cycloadducts with 1:1.5-1.9 endo:exo ratio. Lewis acids such as $EtAlCl_2$, $Zn(OTf)_2$ and $Cu(OTf)_2$ catalyzed reaction at room temperature or -40 °C gave cycloadducts with 3.1-5.4:1 endo:exo ratio. Reaction of benzyl- or allyl-2-furylmethylamine and 1,1-diethyl 2-hydrogen ethenetricarboxylate in the presence of EDCI/HOBt/Et_3N at room temperature led directly to intramolecular Diels-Alder adducts stereoselectively. On the other hand, reaction of benzyl 3-furylmethylamine and 1,1-diethyl 2-hydrogen ethenetricarboxylate under the condensation reaction conditions gave a non-cyclized amide. Lewis acid-catalyzed reaction of the amide gave the Friedel-Crafts cyclized product selectively. The highly functionalized cyclic compounds obtained in this study should be useful synthetic intermediates.

EXPERIMENTAL

General Methods. ^1H Chemical shifts are reported in ppm relative to Me_4Si. ^{13}C Chemical shifts are reported in ppm relative to $CDCl_3$ (77.1 ppm). ^{13}C mutiplicities were determined by DEPT and HSQC. Peak assignments are made by 2D COSY, HSQC, NOESY, and HMBC spectra. Mass analyzer type used for EI is double-focusing in the HRMS measurements. Column chromatography was performed on silica gel (75-150 μm).

Ethenetricarboxylates **1a,b** were prepared according to the literature.[27]

Typical experimental procedure (eq 1, entry 3). A solution of **1a** (272 mg, 1.0 mmol) in CH_2Cl_2 (2 mL) was cooled to 0 °C. $Zn(OTf)_2$ (36 mg, 0.1 mmol) was added to the solution, followed by cyclopentadiene (66 mg, 83 μL, 1.0 mmol; distilled prior to use). The mixture was allowed to warm to room temperature and stirred for 17 h. The reaction mixture was quenched by water and then saturated aqueous $NaHCO_3$. The mixture was extracted with CH_2Cl_2 and the organic phase was dried (Na_2SO_4), and evaporated *in vacuo*. The residue was purified by column chromatography over silica gel with hexane-Et_2O (2 : 1) as eluent to give **3a** (312 mg, 92%, **3a**-endo:**3a**-exo = 3.1 : 1) as an inseparable endo:exo mixture.

2,2-Diethyl 3-*tert*-butyl bicyclo[2.2.1]hept-5-ene-2,2,3-tricarboxylate (3a; endo:exo = 1 : 11): 3a (endo:exo = 1 : 11) was obtained by recrystallization of endo:exo = 1 : 1.5 mixture (entry 1). (**3a; endo:exo = 1 : 11)**: R_f = 0.6 (hexane-Et_2O = 2 : 1); colorless crystals; mp 58-62 °C (EtOAc); ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.22 (t, *J* = 7.1 Hz, 3H), 1.23 (t, *J* = 7.1 Hz, 3H), 1.44 (s, 9H), 1.56 (dddd, *J* = 9.2, 1.8, 1.8, 1.8 Hz, 1H), 2.31 (ddd, *J* = 9.2, 1.6, 1.6 Hz, 1H), 2.98 (bs, 1H), 3.22 (d, *J* = 2.0 Hz, 1H), 3.45 (bs, 1H), 3.96-4.04 (m, 1H), 4.07-4.21 (m, 2H), 4.24-4.33 (m, 1H), 5.99 (dd, *J* = 5.5, 2.8 Hz, 1H), 6.33 (dd, *J* = 5.5, 3.1 Hz, 1H). Selected NOEs are between δ 3.22 (C3-*H*) and δ 6.33 (C5-*H*), 2.98

(C4-*H*). Atom numbering is shown in eq 1.; ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 13.97 (q), 14.14 (q), 28.01 (q), 47.27 (t), 47.74 (d), 50.10 (d), 51.80 (d), 61.43 (t), 61.52 (t), 63.57 (s), 80.92 (s), 135.13 (d), 139.97 (d), 170.08 (s), 170.42 (s), 172.21 (s). Selected HMBC correlations are between δ 2.31 (C7-H*H*) and δ 47.74 (*C*4), 50.10 (*C*1), 135.13 (*C*6), 139.97 (*C*5), and between δ 3.22 (C3-*H*) and δ 47.74 (*C*4), 63.57 (*C*2), 135.13 (*C*6).; IR (neat) 2984, 1735, 1458, 1392, 1365, 1251, 1228, 1191, 1153, 1118, 1063, 1018 cm^{-1}; MS (EI) *m/z* 338 (M^+, 2.7), 282 (14), 264 (54), 237 (47), 217 (81), 171 (100%); HRMS (EI) M^+ 338.1729 (calcd for $C_{18}H_{26}O_6$ 338.1729).

(3a; endo:exo = 3.2 : 1); R_f = 0.6 (hexane-Et_2O = 2 : 1); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) For **3a-endo**, δ (ppm) 1.18 (t, *J* = 7.1 Hz, 3H), 1.26 (t, *J* = 7.1 Hz, 3H), 1.41 (s, 9H), 1.41 (bs, 2H), 3.15 (bs, 1H), 3.37 (bs, 1H), 3.88 (d, *J* = 3.5 Hz, 1H), 3.96-4.04 (m, 1H), 4.09-4.31 (m, 3H), 6.16 (dd, *J* = 5.5, 2.9 Hz, 1H), 6.54 (dd, *J* = 5.5, 3.1 Hz, 1H). Selected NOEs are between δ 3.88 (C3-*H*) and δ 3.15 (C4-*H*), 1.41 (C7-H*H*, overlapped).; ^{13}C NMR (100.6 MHz, $CDCl_3$) For **3a-endo**, δ (ppm) 13.93 (q), 14.03 (q), 28.01 (q), 46.64 (t), 47.29 (d), 51.48 (d), 52.78 (d), 60.94 (t), 61.87 (t), 65.21 (s), 80.57 (s), 135.25 (d), 136.47 (d), 169.55 (s), 171.10 (s), 171.33 (s). Selected HMBC correlations are between δ 1.41 (C7-H*H*) and δ 52.78 (*C*3), 65.21 (*C*2), 135.25 (*C*5), 134.67 (*C*6) and between δ 3.88 (C3-*H*) and δ 47.29 (*C*4), 65.21 (*C*2), 135.25 (*C*5).; IR (neat) 2980, 1732, 1456, 1392, 1366, 1335, 1253, 1152, 1093, 1047 cm^{-1}; MS (EI) *m/z* 338 (M^+, 1.4), 282 (23), 264 (85), 237 (59), 217 (66), 171 (100%); HRMS (EI) M^+ 338.1733 (calcd for $C_{18}H_{26}O_6$ 338.1729).

2,2,3-Triethyl bicyclo[2.2.1]hept-5-ene-2,2,3-tricarboxylate (3b; endo:exo = 1 : 1.8); R_f = 0.7 (hexane-Et_2O = 1 : 2); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) For a major isomer **3b-exo**, δ (ppm) 1.21 (t, *J* = 7.1 Hz, 3H), 1.24 (t, *J* = 7.1 Hz, 3H), 1.27 (t, *J* = 7.1 Hz, 3H), 1.59 (dddd, *J* = 9.2, 1.8, 1.8, 1.8 Hz, 1H), 2.33 (ddd, *J* = 9.2, 1.6, 1.6 Hz, 1H), 3.03 (bs, 1H), 3.31 (d, *J* = 2.2 Hz, 1H), 3.47 (bs, 1H), 3.98-4.31 (m, 6H), 6.02 (dd, *J* = 5.7, 2.8 Hz, 1H), 6.33 (dd, *J* = 5.7, 3.1 Hz, 1H). Selected NOEs are between δ 3.31 (C3-*H*) and δ 6.33 (C5-*H*), 3.03 (C4-*H*).; ^{13}C NMR (100.6 MHz, $CDCl_3$) For a major isomer **3b-exo**, δ (ppm) 13.96 (q), 14.12 (q), 14.21(q), 47.38 (d), 47.56 (t), 50.02 (d), 50.94 (d), 60.92 (t), 61.59 (t), 61.65 (t), 64.03 (s), 135.25 (d), 139.90 (d), 169.91 (s), 170.18 (s), 173.08 (s). Selected HMBC correlations are between δ 2.33 (C7-H*H*) and δ 135.25 (*C*6), 139.90 (*C*5), and between δ 3.31 (C3-*H*) and δ 47.56 (*C*7), 139.90 (*C*5).; IR (neat) 2983, 1735, 1465, 1372, 1254, 1200, 1119, 1096, 1034 cm^{-1}; MS (EI) *m/z* 310 (M^+, 6.8), 264 (11), 199 (27), 91 (51), 66 (100%); HRMS (EI) M^+ 310.1415 (calcd for $C_{16}H_{22}O_6$ 310.1416); Anal. Calcd for $C_{16}H_{22}O_6$: C, 61.92; H, 7.15. Found: C, 61.75; H, 7.39.

(3b; endo:exo = 3.3 : 1); R_f = 0.7 (hexane-Et_2O = 1 : 2); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) For a major isomer **3b-endo**, δ (ppm) 1.19 (t, *J* = 7.1 Hz, 3H), 1.24 (t, *J* = 7.1 Hz, 3H), 1.27 (t, *J* = 7.1 Hz, 3H),

1.43 (ddd, *J* = 9.0, 1.7, 1.7 Hz, 1H), 1.47 (ddd, *J* = 9.0, 1.6, 1.6 Hz, 1H), 3.17 (bs, 1H), 3.40 (bs, 1H), 3.90 (d, *J* = 3.5 Hz, 1H), 4.00-4.30 (m, 6H), 6.24 (dd, *J* = 5.5, 3.0 Hz, 1H), 6.47 (dd, *J* = 5.5, 3.1 Hz, 1H). Selected NOEs are between δ 3.90 (C3-*H*) and δ 3.17 (C4-*H*), 1.47 (C7-H*H*).; ^{13}C NMR (100.6 MHz, $CDCl_3$) For a major isomer **3b-endo**, δ (ppm) 13.96 (q), 14.05 (q), 14.21 (q), 46.81 (t), 46.88 (d), 51.46 (d), 52.25 (d), 60.57 (t), 61.15 (t), 62.00 (t), 65.54 (s), 135.97 (d), 136.19 (d), 169.30 (s), 171.26 (s), 172.00 (s). Selected HMBC correlations are between δ 1.43, 1.47 (C7-H_2) and δ 51.46 (*C*1), 52.25 (*C*3), 135.97 (*C*5), 136.19 (*C*6) and between δ 3.90 (C3-*H*) and δ 46.88 (*C*4), 65.54 (*C*2), 135.97 (*C*5).; IR (neat) 2982, 1733, 1446, 1368, 1335, 1255, 1219, 1094, 1034 cm^{-1}; MS (EI) *m/z* 310 (M^+, 6.8), 264 (47), 237 (50), 199 (58), 91 (62), 66 (100%); HRMS (EI) M^+ 310.1417 (calcd for $C_{16}H_{22}O_6$ 310.1416).

Triethyl 5-oxocyclohex-3-ene-1,2,2-tricarboxylate (6) (eq 2): To a solution of **1b** (244 mg, 1 mmol) in CH_2Cl_2 (2 mL) was added 1-methoxy-3-(trimethylsilyloxy)-1,3-butadiene (**4**) (0.19 mL, 172.3 mg, 1 mmol). The mixture was stirred at room temperature for 22 h. The reaction mixture was concentrated under reduced pressure. To the residue was added THF (1 mL) containing a drop of 1N HCl and the mixture was stirred at room temperature for 10 min. The reaction mixture was concentrated under reduced pressure. The residue was purified by column chromatography over silica gel with hexane-Et_2O (1 : 2) as eluent to give **6** (209 mg, 67%).

6: R_f = 0.6 (hexane-Et_2O = 1 : 2); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.23 (t, *J* = 7.1 Hz, 3H), 1.287 (t, *J* = 7.1 Hz, 3H), 1.293 (t, *J* = 7.1 Hz, 3H), 2.84 (ddd, *J* = 17.6, 6.1, 0.4 Hz, 1H), 2.99 (dd, *J* = 17.6, 5.5 Hz, 1H), 3.91 (ddd, *J* = 6.1, 5.5, 1.1 Hz, 1H), 4.14 (q, *J* = 7.1 Hz, 2H), 4.22-4.30 (m, 4H), 6.11 (dd, *J* = 10.3, 0.4 Hz, 1H), 7.21 (dd, *J* = 10.3, 1.1 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 13.93 (q), 13.98 (q), 37.16 (t), 45.41 (d), 57.08 (s), 61.65 (t), 62.60 (t), 62.94 (t), 129.68 (d), 143.65 (d), 167.32 (s), 170.99 (s), 195.26 (s). Selected HMBC correlations are between δ 2.84, 2.99 (C6-H_2) and δ 195.26 (*C*5), 57.08 (*C*2), 170.99 (CH*C*O_2Et), between δ 6.11 (C4-*H*) and δ 37.16 (*C*6), 57.08 (*C*2) and between δ 7.21 (C3-*H*) and δ 195.26 (*C*5), 45.41 (*C*1), 167.32 (C(*C*O_2Et)$_2$). Atom numbering is shown in eq 2.; IR (neat) 2984, 1738, 1695, 1466, 1446, 1385, 1369, 1277, 1257, 1201, 1097, 1064, 1027 cm^{-1}; MS (EI) *m/z* 312 (M^+, 35), 267 (57), 167 (100%); HRMS (EI) M^+ 312.1208 (calcd for $C_{15}H_{20}O_7$ 312.1209).

N-Allyl-furfurylamine (**8a**) was prepared by reaction of furfurylamine (2 equiv) with allyl bromide in Et_2O according to the literature procedure.[28]

8a: (5.9 mmol scale, 266 mg, 33%): R_f = 0.4 (hexane-Et_2O = 1 : 4); pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.74 (bs, 1H), 3.26 (ddd, *J* = 6.0, 1.6, 1.3 Hz, 2H), 3.79 (s, 2H), 5.12 (ddt, *J* = 10.3, 1.8, 1.3 Hz, 1H), 5.19 (ddt, *J* = 17.2, 1.8, 1.6 Hz, 1H), 5.90 (ddt, *J* = 17.2, 10.3, 6.0 Hz, 1H), 6.18 (ddt, *J* =

3.3, 0.9, 0.7 Hz, 1H), 6.31 (dd, *J* = 3.3, 1.8 Hz, 1H), 7.36 (dd, *J* = 1.8, 0.9 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 45.35 (t), 51.41 (t), 107.09 (d), 110.15 (d), 116.46 (t), 136.36 (d), 141.89 (d), 153.71 (s); IR (neat) 3324, 3078, 2919, 2824, 1644, 1506, 1458, 1148, 1009, 921 cm^{-1}; MS (EI) *m/z* 137 (M^+, 62), 136 (100%); HRMS (EI) M^+ 137.0830 (calcd for $C_8H_{11}NO$ 137.0841).

N-Benzyl-furfurylamines **8b-e** and **11** were prepared by reductive amination according to the literature procedure.[29]

***N*-Benzyl-furfurylamine (8b)**: (8.9 mmol scale, 1.62 g, 97%). **8b** was also prepared by reaction of furfurylamine (2 equiv) with benzyl bromide in Et_2O (5.0 mmol scale, 449 mg, 47%) according to the literature procedure.[28]

^{1}H and ^{13}C NMR of **8b** were in accord with the reported data.[29b]

8b: R_f = 0.2 (hexane-Et_2O = 1 : 1); pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.85 (bs, 1H), 3.78 (s, 4H), 6.18 (bd, *J* = 3.3 Hz, 1H), 6.31 (dd, *J* = 3.3, 1.8 Hz, 1H), 7.22-7.28 (m, 1H), 7.29-7.34 (m, 4H), 7.36 (dd, *J* = 1.8, 0.7 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 45.37 (t), 52.81 (t), 107.12 (d), 110.15 (d), 127.08 (d), 128.32 (d), 128.46 (d), 139.86 (s), 141.88 (d), 153.80 (s).

***N*-Benzyl-1-(furan-2-yl)ethylamine (8c)**: (8.9 mmol scale, 976 mg, 54%): R_f = 0.5 (hexane-Et_2O = 1 : 1); pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.43 (d, *J* = 6.8 Hz, 3H), 1.75 (bs, 1H), 3.66 (d, *J* = 13.1 Hz, 1H), 3.74 (d, *J* = 13.1 Hz, 1H), 3.88 (q, *J* = 6.8 Hz, 1H), 6.16 (ddd, *J* = 3.1, 0.8, 0.6 Hz, 1H), 6.32 (dd, *J* = 3.1, 1.8 Hz, 1H), 7.21-7.26 (m, 1H), 7.29-7.33 (m, 4H), 7.36 (dd, *J* = 1.8, 0.8 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 20.51 (q), 50.60 (d), 51.21 (t), 105.54 (d), 109.95 (d), 126.99 (d), 128.28 (d), 128.46 (d), 140.34 (s), 141.47 (d), 157.85 (s); IR (neat) 3330, 3028, 2972, 2930, 1603, 1505, 1495, 1454, 1371, 1315, 1225, 1150, 1121, 1010 cm^{-1}; MS (EI) *m/z* 201 (M^+, 8.9), 186 (100), 91 (92%); HRMS (EI) M^+ 201.1134 (calcd for $C_{13}H_{15}NO$ 201.1154).

***N*-Furfuryl-1-phenylethylamine (8d)**: (8.9 mmol scale, 1.66 g, 93%): R_f = 0.5 (hexane-Et_2O = 1 : 1); pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.36 (d, *J* = 6.6 Hz, 3H), 1.77 (bs, 1H), 3.58 (d, *J* = 14.5 Hz, 1H), 3.66 (d, *J* = 14.5 Hz, 1H), 3.78 (q, *J* = 6.6 Hz, 1H), 6.10 (dddd, *J* = 3.1, 0.8, 0.6, 0.6 Hz, 1H), 6.29 (dd, *J* = 3.1, 1.8 Hz, 1H), 7.23-7.28 (m, 1H), 7.31-7.36 (m, 5H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 24.30 (q), 44.05 (t), 57.15 (d), 106.90 (d), 110.13 (d), 126.85 (d), 127.12 (d), 128.57 (d), 141.82 (d), 145.08 (s), 154.03 (s); IR (neat) 3331, 3026, 2963, 2925, 1602, 1505, 1492, 1451, 1370, 1147, 1117, 1011 cm^{-1}; MS (EI) *m/z* 201 (M^+, 6.4), 186 (73), 81 (100%); HRMS (EI) M^+ 201.1138 (calcd for $C_{13}H_{15}NO$ 201.1154).

***N*-Benzyl-(5-bromofuran-2-yl)methylamine (8e)**: (9.0 mmol scale, 2.14 g, 89%): R_f = 0.3 (hexane-Et_2O = 1 : 1); pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.75 (bs, 1H), 3.71 (s, 2H), 3.75 (s, 2H), 6.13 (d, *J* = 3.2 Hz, 1H), 6.20 (d, *J* = 3.2 Hz, 1H), 7.21-7.26 (m, 1H), 7.28-7.33 (m, 4H); ^{13}C NMR (100.6

MHz, $CDCl_3$) δ (ppm) 45.28 (t), 52.60 (t), 109.86 (d), 111.72 (d), 120.57 (s), 127.06 (d), 128.20 (d), 128.41 (d), 139.62 (s), 155.94 (s); IR (neat) 3329, 3027, 2917, 2830, 1602, 1505, 1453, 1200, 1125, 1010 cm^{-1}; MS (EI) *m/z* 267 (M^+, 12), 265 (M^+, 12), 186 (11), 161 (21), 159 (22), 106 (23), 91 (100%); HRMS (EI) M^+ 265.0099, 267.0045 (calcd for $C_{12}H_{12}BrNO$ 265.0102, 267.0082).

***N*-Benzyl-furan-3-ylmethylamine (11)**: (9.2 mmol scale, 1.70 g, 99%): R_f = 0.6 (hexane-Et_2O = 1 : 2); pale yellow oil; ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.64 (bs, 1H), 3.65 (dd, *J* = 0.6, 0.4 Hz, 2H), 5.80 (s, 2H), 6.39 (dd, *J* = 1.8, 0.8 Hz, 1H), 7.22-7.28 (m, 1H), 7.30-7.34 (m, 4H), 7.35 (ddd, *J* = 1.6, 0.8, 0.6 Hz, 1H), 7.38 (dd, *J* = 1.8, 1.6 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 43.61 (t), 53.21 (t), 110.51 (d), 127.06 (d), 128.24 (d), 128.46 (s), 128.48 (d), 139.93 (d), 140.17 (s), 143.17 (d); IR (neat) 3315, 3027, 2921, 2823, 1602, 1496, 1453, 1362, 1158, 1108, 1065, 1021, 874 cm^{-1}; MS (EI) *m/z* 187 (M^+, 7.0), 186 (18), 106 (100), 91 (76), 81 (77%); HRMS (EI) M^+ 187.0977 (calcd for $C_{12}H_{13}NO$ 187.0997).

Typical experimental procedure for eq 3 and preparation of 12 in Scheme 3 (eq 3, Table 2, entry 1). To a solution of 1,1-diethyl 2-hydrogen ethenetricarboxylate (**7**) (313 mg, 1.45 mmol) (prepared from 1,1-diethyl 2-*tert*-butyl ethenetricarboxylate (**1a**) upon treatment with CF_3CO_2H)[25] in THF (0.5 mL) were added *N*-allyl-furfurylamine (**8a**) (176 mg, 1.28 mmol) in THF (1.5 mL), Et_3N (0.25 mL, 179 mg, 1.77 mmol), HOBt (1-hydroxybenzotriazole) (430 mg, 3.18 mmol) and EDCI (1-[3-(dimethylamino)propyl]-3-ethylcarbodiimide hydrochloride) (292 mg, 1.52 mmol) at 0 °C. The reaction mixture was stirred for 1 h at 0 °C, and was allowed to warm to room temperature and stirred for 17 h. The reaction mixture was concentrated under reduced pressure and the residue was diluted with CH_2Cl_2. The organic phase was washed with saturated aqueous $NaHCO_3$ solution, 2M aqueous citric acid, saturated aqueous $NaHCO_3$ and water, dried (Na_2SO_4), and evaporated *in vacuo*. The residue was purified by column chromatography over silica gel eluting with hexane-Et_2O to give **9a** (350 mg, 82%).

Diethyl 3-allyl-4-oxo-10-oxa-3-azatricyclo[5.2.1.$0^{1,5}$]dec-8-ene-6,6-dicarboxylate (9a): R_f = 0.3 (hexane-Et_2O = 1 : 2); colorless crystals; mp 100-103 °C (EtOAc); ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.27 (t, *J* = 7.1 Hz, 3H), 1.30 (t, *J* = 7.1 Hz, 3H), 3.44 (s, 1H), 3.67 (d, *J* = 11.7 Hz, 1H), 3.88 (dddd, *J* = 15.6, 5.6, 1.5, 1.5 Hz, 1H), 3.94 (d, *J* = 11.7 Hz, 1H), 3.97 (dd, *J* = 15.6, 5.6 Hz, 1H), 4.11-4.37 (m, 4H), 5.20 (dddd, *J* = 10.1, 1.5, 1.3, 1.3 Hz, 1H), 5.23 (dddd, *J* = 17.0, 1.5, 1.3, 1.3 Hz, 1H), 5.36 (d, *J* = 1.6 Hz, 1H), 5.72 (dddd, *J* = 17.0, 10.1, 5.6, 5.6 Hz, 1H), 6.33 (dd, *J* = 5.7, 1.6 Hz, 1H), 6.61 (d, *J* = 5.7 Hz, 1H). Selected NOEs are between δ 3.44 (C5-*H*) and δ 3.94 (C2-H*H*), 6.61 (C9-*H*), between δ 3.94 (C2-H*H*) and δ 6.61 (C9-*H*), and between δ 6.33 (C8-*H*) and δ 5.36 (C7-*H*), 6.61 (C9-*H*). Atom numbering is shown in eq 3.; ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 13.72 (q), 13.77 (q), 44.87 (t), 47.92 (t), 54.34

(d), 61.60 (t), 61.75 (t), 62.04 (s), 83.20 (d), 89.36 (s), 117.58 (t), 131.43 (d), 135.26 (d), 136.89 (d), 167.86 (s), 168.52 (s), 169.49 (s). Selected HMBC correlations are between δ 3.44 (C5-*H*), 3.94 (C2-H*H*), 5.36 (C7-*H*), 6.33 (C8-*H*) and δ 136.89 (*C*9), between δ 3.94 (C2-H*H*), 5.36 (C7-*H*), 6.33 (C8-*H*) and δ 89.36 (*C*1) and between δ 3.44 (C5-*H*), 6.61 (C9-*H*), 6.33 (C8-*H*) and δ 83.20 (*C*7).; IR (KBr) 2997, 1730, 1691, 1480, 1365, 1266, 1107, 1066, 1039, 1000 cm^{-1}; MS (EI) *m/z* 335 (M^+); HRMS (EI) 335.1358 (calcd for $C_{17}H_{21}NO_6$ M^+ 335.1369); Anal. Calcd for $C_{17}H_{21}NO_6$: C, 60.89; H, 6.31; N, 4.18. Found: C, 60.93; H, 6.08; N, 4.17.

9b: (2.35 mmol scale, 590 mg, 65%): R_f = 0.8 (CH_2Cl_2-Et_2O = 1 : 1); colorless crystals; mp 138-140 °C (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.32 (t, *J* = 7.1 Hz, 3H), 1.33 (t, *J* = 7.1 Hz, 3H), 3.47 (s, 1H), 3.59 (d, *J* = 11.9 Hz, 1H), 3.65 (d, *J* = 11.9 Hz, 1H), 4.11-4.40 (m, 5H), 4.68 (d, *J* = 15.0 Hz, 1H), 5.37 (d, *J* = 1.6 Hz, 1H), 6.32 (dd, *J* = 5.7, 1.6 Hz, 1H), 6.54 (d, *J* = 5.7 Hz, 1H), 7.23-7.36 (m, 5H). Selected NOEs are between δ 3.47 (C5-*H*) and δ 3.65 (C2-H*H*), 6.54 (C9-*H*), between δ 3.65 (C2-H*H*) and δ 3.47 (C5-*H*), and between δ 6.32 (C8-*H*) and δ 5.37 (C7-*H*), 6.54 (C9-*H*).; ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 14.07 (q), 14.09 (q), 46.76 (t), 48.13 (t), 54.69 (d), 61.99 (t), 62.23 (t), 62.38 (t), 83.58 (d), 89.49 (s), 127.74 (d), 128.00 (d), 128.88 (d), 135.73 (d), 135.89 (d), 136.96 (d), 168.20 (s), 168.86 (s), 170.01 (s). Selected HMBC correlations are between δ 3.59 (C2-*H*H), 3.65 (C2-H*H*), 5.37 (C7-*H*) and δ 136.96 (*C*9), between δ 3.59 (C2-*H*H), 6.54 (C9-*H*), 5.37 (C7-*H*), 6.32 (C8-*H*) and δ 89.49 (*C*1) and between δ 3.47 (C5-*H*), 6.54 (C9-*H*), 6.32 (C8-*H*) and δ 83.58 (*C*7).; IR (KBr) 2984, 1756, 1734, 1690, 1478, 1368, 1266, 1192, 1117, 1046 cm^{-1}; MS (EI) *m/z* 385 (M^+, 1.9), 340 (9.4), 295 (11), 248 (19), 221 (25), 200 (40), 186 (100%); HRMS (EI) 385.1521 (calcd for $C_{21}H_{23}NO_6$ M^+ 385.1525); Anal. Calcd for $C_{21}H_{23}NO_6$: C, 65.44; H, 6.02; N, 3.63. Found: C, 65.50; H, 6.06; N, 3.76.

9c: (2 mmol scale, 381 mg, 48%, diastereomer ratio 2 : 1): R_f = 0.5 (hexane-Et_2O = 1 : 3); pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.25-1.34 (m, 9H), 3.43 (s, 1H×0.33), 3.53 (s, 1H×0.67), 3.77 (q, *J* = 6.8 Hz, 1H×0.67), 3.97 (d, *J* = 15.2 Hz, 1H×0.33), 4.00 (q, *J* = 6.5 Hz, 1H×0.33), 4.10-4.41 (m, 4H+1H×0.67), 4.92 (d, *J* = 15.6, 1H×0.67), 5.06 (d, *J* = 15.2 Hz, 1H×0.33), 5.37 (d, *J* = 1.8 Hz, 1H×0.67), 5.39 (d, *J* = 1.8 Hz, 1H×0.33), 6.33 (dd, *J* = 5.7, 1.8 Hz, 1H×0.33), 6.34 (dd, *J* = 5.9, 1.8 Hz, 1H×0.67), 6.49 (d, *J* = 5.7 Hz, 1H×0.33), 6.59 (d, *J* = 5.9 Hz, 1H×0.67), 7.22-7.35 (m, 5H). Selected NOEs are between δ 3.43 (C5i-*H*) and δ 6.49 (C9i-*H*), between δ 3.53 (C5-*H*) and δ 6.59 (C9-*H*), 1.25-1.34 (C2-CH_3, overlapped) and between δ 6.33, 6.34 (C8i,8-*H*) and δ 5.37, 5.39 (C7,7i-*H*). Atom numberings Cx and Cxi denote those of major and minor diastereomers, respectively.; ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 12.97 (q), 14.06 (q), 14.09 (q), 15.77 (q), 43.70 (t), 44.45 (t), 52.52 (d), 53.08 (d), 54.17 (d), 54.48 (d), 61.95 (t), 61.98 (t), 62.18 (t), 62.61 (s), 62.78 (s), 83.35 (d), 83.53 (d), 92.41 (s), 93.29 (s), 127.49 (d), 127.60 (d), 127.89 (d), 128.76 (d), 128.83 (d), 135.55 (d), 135.96 (d), 136.10 (s),

136.21 (d), 136.46 (s), 136.63 (d), 168.25 (s), 168.39 (s), 168.91 (s), 168.94 (s), 169.93 (s), 170.46 (s). Selected HMBC correlations are between δ 5.37, 5.39 (C7,7i-*H*) and δ 135.55, 136.63 (*C*9,9i), between δ 5.37, 5.39 (C7,7i-*H*), 6.33, 6.34 (C8i,8-*H*), 6.49, 6.59 (C9i,9-*H*), 1.25-1.34 (C2,2i-C*H*$_3$, overlapped) and δ 92.41, 93.29 (*C*1i,1) and between δ 6.33, 6.34 (C8i,8-*H*), 6.49, 6.59 (C9i,9-*H*) and δ 83.35, 83.53 (*C*7i,7).; IR (neat) 2979, 1732, 1695, 1496, 1418, 1367, 1262, 1197, 1112, 1068, 1039 cm^{-1}; MS (EI) *m/z* 399 (M$^+$, 1.3), 304 (24), 200 (100%); HRMS (EI) 399.1689 (calcd for $C_{22}H_{25}NO_6$ M$^+$ 399.1682).

9d: (2 mmol scale, 340 mg, 43%, diastereomer ratio 1 : 1): R_f = 0.2 (hexane-Et_2O = 1 : 2); pale yellow viscous oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.26 (t, 7.1 Hz, 3H×0.5), 1.28 (t, *J* = 7.1 Hz, 3H×0.5), 1.30 (t, *J* = 7.1 Hz, 3H×0.5), 1.33 (t, *J* = 7.1 Hz, 3H×0.5), 1.53 (d, *J* = 7.0 Hz, 3H×0.5), 1.57 (d, *J* = 3H×0.5), 3.37 (d, *J* = 11.7 Hz, 1H×0.5), 3.41 (s, 1H×0,5), 3.44 (d, *J* = 11.7 Hz, 1H×0.5), 3.49 (s, 1H×0.5), 3.61 (d, *J* = 11.7 Hz, 1H×0.5), 3.82 (d, *J* = 11.7 Hz, 1H×0.5), 4.09-4.42 (m, 4H), 5.34 (d, *J* = 1.8 Hz, 1H×0.5), 5.35 (d, *J* = 1.8 Hz, 1H×0.5), 5.50 (q, *J* = 7.0 Hz, 1H×0.5), 5.53 (q, *J* = 7.0 Hz, 1H×0.5), 6.29 (dd, *J* = 5.7, 1.6 Hz, 1H×0.5), 6.31 (dd, *J* = 5.7, 1.6 Hz, 1H×0.5), 6.49 (d, *J* = 5.7 Hz, 1H×0.5), 6.56 (d, *J* = 5.7 Hz, 1H×0.5), 7.22-7.38 (m, 5H). Selected NOEs are between δ 3.41 (C5-*H*) and δ 6.49 (C9-*H*), between δ 3.49 (C5i-*H*) and δ 6.56 (C9i-*H*), between δ 3.37 (C2-*H*H) and δ 6.49 (C9-*H*), between δ 3.44 (C2i-*H*H) and δ 6.56 (C9i-*H*), and between δ 6.29, 6.31 (C8,8i-*H*) and δ 5.34, 5.35 (C7,7i-*H*), 6.49, 6.56 (C9,9i-*H*). Atom numberings Cx and Cxi denote those of two diastereomers, respectively.; ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 14.01 (q), 14.05 (q), 15.82 (q), 16.74 (q), 44.02 (t), 44.05 (t), 48.70 (d), 49.30 (d), 55.03 (d), 55.11 (d), 61.91 (t), 62.09 (t), 62.35 (s), 62.49 (s), 83.43 (d), 83.50 (d), 89.28 (s), 89.47 (s), 126.77 (d), 127.25 (d), 127.35 (d), 127.76 (d), 128.63 (d), 128.76 (d), 135.69 (d), 135.79 (d), 136.93 (d), 136.98 (d), 139.36 (s), 139.67 (s), 168.17 (s), 168.31 (s), 168.77 (s), 169.49 (s), 169.71 (s). Selected HMBC correlations are between δ 5.34, 5.35 (C7,7'-*H*) and δ 136.93, 136.98 (*C*9,9'), between δ 5.34, 5.35 (C7,7'-*H*), 6.49, 6.56 (C9,9'-*H*), 6.29, 6.32 (C8,8'-*H*) and δ 89.28, 89.47 (*C*1,1') and between δ 3.41, 3.49 (C5,5'-*H*), 6.49, 6.56 (C9,9'-*H*), 6.29, 6.32 (C8,8'-*H*) and δ 83.43, 83.50 (*C*7,7').; IR (neat) 2980, 1736, 1691, 1496, 1469, 1450, 1423, 1364, 1302, 1261, 1189, 1110, 1064, 1041 cm^{-1}; MS (EI) *m/z* 399 (M$^+$, 2.2), 354 (7.6), 294 (56), 200 (100%); HRMS (EI) 399.1685 (calcd for $C_{22}H_{25}NO_6$ M$^+$ 399.1682).

9e: (1 mmol scale, 227 mg, 48%): R_f = 0.1 (hexane-Et_2O = 1 : 4); pale yellow crystals; mp 127-127.5 °C (EtOAc-Et_2O = 1 : 1); ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.32 (t, *J* = 7.1 Hz, 3H), 1.33 (t, *J* = 7.1 Hz, 3H), 3.54 (s, 1H), 3.66 (d, *J* = 11.9 Hz, 1H), 3.78 (d, *J* = 11.9 Hz, 1H), 4.24-4.41 (m, 4H), 4.43 (d, *J* = 15.0 Hz, 1H), 4.61 (d, *J* = 15.0 Hz, 1H), 6.41 (d, *J* = 5.5 Hz, 1H), 6.54 (d, *J* = 5.5 Hz, 1H), 7.25-7.30 (m, 3H), 7.33-7.37 (m, 2H). Selected NOEs are between δ 3.54 (C5-*H*) and δ 6.54 (C9-*H*), between δ 3.78 (C2-H*H*) and δ 6.54 (C9-*H*), and between δ 6.41 (C8-*H*) and δ 6.54 (C9-*H*).; ^{13}C NMR (100.6 MHz,

$CDCl_3$) δ (ppm) 13.96 (q), 14.05 (q), 46.77 (t), 48.09 (t), 57.80 (d), 62.42 (t), 62.56 (t), 66.86 (s), 87.69 (s), 91.14 (s), 127.86 (d), 128.02 (d), 128.94 (d), 135.50 (s), 137.23 (d), 140.81 (d), 166.06 (s), 167.52 (s), 169.23 (s). Selected HMBC correlations are between δ 3.78 (C2-H*H*) and δ 137.23 (*C*9), between δ 3.66 (C2-*H*H), 6.54 (C9-*H*), 6.41 (C8-*H*) and δ 87.69 (*C*1) and between δ 3.54 (C5-*H*), 6.54 (C9-*H*), 6.41 (C8-*H*) and δ 91.14 (*C*7).; IR (KBr) 2980, 1745, 1718, 1687, 1475, 1440, 1359, 1311, 1288, 1264, 1240, 1213, 1199, 1083, 1037 cm^{-1}; MS (EI) *m/z* 465 (M^+, 0.6), 463 (M^+, 0.6), 438 (4.5), 436 (4.6), 266 (92), 264 (100%); HRMS (EI) 463.0648, 465.0623 (calcd for $C_{21}H_{22}BrNO_6$ M^+ 463.0631, 465.0610); Anal. Calcd for $C_{21}H_{22}BrNO_6$: C, 54.32; H, 4.78; N, 3.02. Found: C, 54.22; H, 4.68; N, 3.05.

12: (3 mmol scale, 598 mg, 51%): R_f = 0.5 (hexane-Et_2O = 1 : 3); pale yellow oil; ^1H NMR (400 MHz, $CDCl_3$) (2 rotamers, ratio 1.3 : 1) δ (ppm) 1.27-1.35 (m, 6H), 4.23-4.38 (m, 4H), 4.28 (s, 2H×0.4, minor rotamer), 4.40 (s, 2H×0.6, major rotamer), 4.49 (s, 2H×0.6), 4.62 (s, 2H×0.4), 6.29 (d, *J* = 0.8 Hz, 1H×0.4), 6.35 (d, *J* = 0.8 Hz, 1H×0.6), 7.19-7.43 (m, 8H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 13.98 (q), 14.02 (q), 14.04 (q), 38.86 (t), 42.17 (t), 47.49 (t), 50.54 (t), 62.00 (t), 62.22 (t), 62.27 (t), 109.68 (d), 110.93 (d), 120.14 (s), 120.35 (s), 127.10 (d), 127.79 (d), 128.14 (d), 128.49 (d), 128.76 (d), 129.10 (d), 134.57 (d), 134.73 (d), 135.25 (s), 135.28 (s), 135.56 (s), 136.30 (s), 140.57 (d), 141.26 (d), 143.49 (d), 144.17 (d), 162.92 (s), 162.97 (s), 164.36 (s), 164.45 (s), 164.47 (s), 164.62 (s); IR (neat) 2983, 1730, 1651, 1497, 1465, 1446, 1374, 1256, 1202, 1069, 1021 cm^{-1}; MS (EI) *m/z* 385 (M^+, 2.5), 340 (9.4), 248 (11), 200 (42), 186 (100%); HRMS (EI) 385.1514 (calcd for $C_{21}H_{23}NO_6$ M^+ 385.1525).

Diethyl 2-(5-benzyl-4,5,6,7-tetrahydro-6-oxofuro[3,2-*c*]pyridin-7-yl)malonate (13). To a solution of **12** (187 mg, 0.49 mmol) in CH_2Cl_2 (1 mL) was added $Sc(OTf)_3$ (50 mg, 0.1 mmol). The mixture was stirred at room temperature overnight. The reaction mixture was quenched by water and then saturated aqueous $NaHCO_3$. The mixture was extracted with CH_2Cl_2 and the organic phase was dried (Na_2SO_4), and evaporated *in vacuo*. The residue was purified by column chromatography over silica gel with hexane-Et_2O (1 : 1) as eluent to give **13** (142 mg, 76%).

13: R_f = 0.3 (hexane-Et_2O = 1 : 1); pale yellow oil; ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.21 (t, *J* = 7.1 Hz, 3H), 1.25 (t, *J* = 7.1 Hz, 3H), 4.15-4.30 (m, 6H), 4.33 (d, *J* = 3.9 Hz, 1H), 4.45 (ddd, *J* = 3.9, 3.9, 3.9 Hz, 1H), 4.75 (d, *J* = 14.8 Hz, 1H), 4.77 (d, *J* = 14.8 Hz, 1H), 6.20 (d, *J* = 1.8 Hz, 1H), 7.24-7.34 (m, 6H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 13.98 (q), 14.01 (q), 41.40 (d), 44.89 (t), 50.89 (t), 52.52 (d), 61.57 (t), 61.66 (t), 107.68 (d), 112.65 (s), 127.60 (d), 128.18 (d), 128.66 (d), 136.61 (s), 143.10 (d), 144.65 (s), 166.99 (s), 167.63 (s), 167.79 (s). Selected HMBC correlations are between δ 4.33 (C*H*(CO_2Et)$_2$), 6.20 (C3-*H*) and δ 144.65 (*C*7a), between δ 4.33 (C*H*(CO_2Et)$_2$) and δ 41.40 (*C*7), and between δ 6.20 (C3-*H*) and δ 112.65 (*C*3a). Atom numberings are shown in Scheme 8.; IR (neat) 2981,

1738, 1645, 1507, 1483, 1454, 1372, 1347, 1263, 1176, 1034 cm^{-1}; MS (EI) *m/z* 385 (M^+, 64), 340 (22), 293 (64), 266 (82), 91 (100%); HRMS (EI) M^+ 385.1531 (calcd for $C_{21}H_{23}NO_6$ 385.1525).

Ethenetricarboxylates **17** and **19** were prepared by the reaction of diethyl ketomalonate with the corresponding (triphenylphosphoranylidne)acetate according to the literature procedure.[27,30] The (triphenylphosphoranylidne)acetate esters for **17** and **19**, and ylide **20** were prepared by the corresponding chloroacetates and triphenylphosphine in benezene and subsequent treatment with NaOH. The chloroacetates were preprared by the reaction of the corresponding alcohols (1 equiv) and chloroacetyl chloride (1 equiv) in the presence of pyridine (1 equiv) in Et_2O at 0 °C. Data of chloroacetates for the (triphenylphosphoranylidne) acetate esters and ethenetricarboxylates **17**, **19** are shown below.

(Furan-2-yl)methyl 2-chloroacetate: (30.4 mmol scale, 5.31 g, 100%); pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 4.08 (s, 2H), 5.17 (s, 2H), 6.38 (dd, *J* = 3.3, 2.0 Hz, 1H), 6.46 (d, *J* = 3.3 Hz, 1H), 7.43 (dd, *J* = 2.0, 0.9 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 40.82 (t), 59.55 (t), 110.77 (d), 111.55 (d), 143.70 (d), 148.53 (s), 167.07 (s); IR (neat) 3126, 2958, 1760, 1501, 1411, 1369, 1309, 1284, 1167, 1079, 1017, 964 cm^{-1}; MS (EI) *m/z* 176 (M^+, 11), 174 (M^+, 34), 98 (19), 81 (100%); HRMS (EI) M^+ 174.0065, 176.0070 (calcd for $C_7H_7ClO_3$ M^+ 174.0083, 176.0054).

(Furan-3-yl)methyl 2-chloroacetate: (30.4 mmol scale, 5.27 g, 99%); pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 4.07 (s, 2H), 5.10 (s, 2H), 6.44 (dd, *J* = 1.8, 0.8 Hz, 1H), 7.41 (dd, *J* = 1.8, 1.8 Hz, 1H), 7.51 (ddd, *J* = 1.8, 0.8, 0.8 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 40.92 (t), 59.39 (t), 110.63 (d), 119.62 (s), 142.15 (d), 143.67 (d), 167.28 (s); IR (neat) 3137, 2959, 1752, 1505, 1412, 1312, 1289, 1159, 1076, 1021, 956, 875 cm^{-1}; MS (EI) *m/z* 176 (M^+, 8.8), 174 (M^+, 27), 98 (100), 81 (63%); HRMS (EI) M^+ 174.0064, 176.0070 (calcd for $C_7H_7ClO_3$ M^+ 174.0084, 176.0054); Anal. Calcd for $C_7H_7ClO_3$: C, 48.16; H, 4.04. Found: C, 48.11; H, 3.79.

(2*E*,4*E*)-Hexa-2,4-dienyl 2-chloroacetate: (15.2 mmol scale, 2.55 g, 96%); colorless oil; bp 78-80 °C/3.6 mmHg; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.77 (bd, *J* = 6.6 Hz, 3H), 4.07 (s, 2H), 4.68 (d, *J* = 6.6 Hz, 2H), 5.62 (dt, *J* = 15.2, 6.6 Hz, 1H), 5.78 (dq, *J* = 15.0, 6.6 Hz, 1H), 6.06 (ddq, *J* = 15.0, 10.5, 1.6 Hz, 1H), 6.29 (dd, *J* = 15.2, 10.5 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 18.16 (q), 40.93 (t), 66.69 (t), 122.48 (d), 130.23 (d), 132.10 (d), 136.08 (d), 167.11 (s); IR (neat) 3024, 2959, 1762, 1737, 1661, 1446, 1413, 1380, 1309, 1168, 990 cm^{-1}; MS (EI) *m/z* 176 (M^+, 13), 174 (M^+, 39), 98 (37), 97 (37), 81 (79), 79 (100%); HRMS (EI) M^+ 174.0431, 176.0431 (calcd for $C_8H_{11}ClO_2$ M^+ 174.0448, 176.0418).

1,1-Diethyl 2-(furan-2-yl)methyl ethene-1,1,2-tricarboxylate (17): (19.2 mmol scale, 3.85 g, 68%); R_f

= 0.6 (hexane-Et_2O = 1 : 1); pale yellow oil; ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.31 (t, *J* = 7.1 Hz, 3H), 1.32 (t, *J* = 7.1 Hz, 3H), 4.29 (q, *J* = 7.1 Hz, 2H), 4.31 (q, *J* = 7.1 Hz, 2H), 5.17 (s, 2H), 6.37 (dd, *J* = 3.3, 1.8 Hz, 1H), 6.45 (bd, *J* = 3.3 Hz, 1H), 6.88 (s, 1H), 7.44 (dd, *J* = 1.8, 0.9 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 13.91 (q), 13.99 (q), 59.11 (t), 62.18 (t), 62.58 (t), 110.77 (d), 111.52 (d), 129.42 (d), 139.47 (s), 143.66 (d), 148.38 (s), 162.20 (s), 163.18 (s), 164.14 (s); IR (neat) 2984, 1781, 1732, 1650, 1502, 1467, 1446, 1377, 1344, 1261, 1177, 1067, 1018 cm^{-1}; MS (EI) *m/z* 296 (M^+, 1.3), 200 (61), 154 (81), 126 (56), 81 (100%); HRMS (EI) M^+ 296.0891 (calcd for $C_{14}H_{16}O_7$ M^+ 296.0896).

1,1-Diethyl 2-(furan-3-yl)methyl ethene-1,1,2-tricarboxylate (19): (16.4 mmol scale, 1.25 g, 26%); R_f = 0.6 (hexane-Et_2O = 1 : 1); colorless oil; ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.311 (t, *J* = 7.1 Hz, 3H), 1.314 (t, *J* = 7.1 Hz, 3H), 4.29 (q, *J* = 7.1 Hz, 2H), 4.31 (q, *J* = 7.1 Hz, 2H), 5.09 (s, 2H), 6.43 (dd, *J* = 1.8, 0.8 Hz, 1H), 6.87 (s, 1H), 7.41 (dd, *J* = 1.8, 1.6 Hz, 1H), 7.50 (ddd, *J* = 1.6, 0.8, 0.8 Hz, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 13.89 (q), 13.97 (q), 58.95 (t), 62.12 (t), 62.57 (t), 110.62 (d), 119.50 (s), 129.65 (d), 139.29 (s), 142.04 (d), 143.63 (d), 162.23 (s), 163.43 (s), 164.18 (s); IR (neat) 2984, 1737, 1651, 1505, 1466, 1447, 1372, 1345, 1257, 1179, 1067, 1023 cm^{-1}; MS (EI) *m/z* 296 (M^+, 3.8), 199 (83), 143 (72), 126 (64), 81 (100%); HRMS (EI) M^+ 296.0880 (calcd for $C_{14}H_{16}O_7$ M^+ 290.0896).

Diethyl 1,3,3a,7a-tetrahydro-5-methyl-3-oxoisobenzofuran-4,4(5*H*)-dicarboxylate (22). To an ice-water-cooled solution of (2*E*,4*E*)-hexa-2,4-dien-1-yl (triphenylphosphoranylidene)acetate (**20**) (2.63 g, 6.57 mmol) in 13 mL of benzene was added diethyl ketomalonate (1.0 mL, 1.14 g, 6.57 mmol). The mixture was stirred for 1 h at 0 °C and then allowed to warm to room temperature and stirred overnight. The benzene was evaporated, and Et_2O was added. The precipitated triphenylphosphine oxide was removed by filtration. The filtrate was concentrated, and the residue was purified by column chromatography over silica gel with hexane-Et_2O (2 : 1) as eluent to give **22** (821 mg, 42%) as an isolable product.

22: R_f = 0.1 (hexane-Et_2O = 2 : 1); colorless oil; ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 1.03 (d, *J* = 7.3 Hz, 3H), 1.25 (t, *J* = 7.1 Hz, 3H), 1.30 (t, *J* = 7.1 Hz, 3H), 2.69-2.80 (m, 2H), 3.40 (qdd, *J* = 7.3, 2.6, 2.2 Hz, 1H), 3.83-3.88 (m, 1H), 4.19-4.36 (m, 4H), 4.43-4.46 (m, 1H), 5.72 (bs, 2H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 13.72 (q), 13.88 (q), 17.72 (q), 36.37 (d), 38.00 (d), 42.65 (d), 57.38 (s), 61.61 (t), 61.88 (t), 69.20 (t), 121.65 (d), 134.73 (d), 167.48 (s), 168.55 (s), 171.52 (s); ^1H NMR (400 MHz, C_6D_6) δ (ppm) 0.860 (d, *J* = 7.5 Hz, 3H), 0.956 (t, *J* = 7.1 Hz, 3H), 0.998 (t, *J* = 7.1 Hz, 3H), 2.46 (m, 1H), 2.58 (d, *J* = 13.9 Hz, 1H), 3.04 (dd, *J* = 11.1, 8.0 Hz, 1H), 3.51 (m, 1H), 3.68 (dd, *J* = 8.0, 6.7 Hz, 1H), 3.93-4.10 (m, 4H), 5.11 (ddd, *J* = 9.9, 1.7, 1.7 Hz, 1H), 5.32 (ddd, *J* = 9.9, 3.8, 2.7 Hz, 1H). Selected NOEs are between δ 0.860 (C5-C*H*$_3$) and δ 2.58 (C3a-*H*), 5.32 (C6-*H*), between δ 2.46 (C7a-*H*) and δ

3.68 (C1-H*H*), and between δ 2.58 (C3a-*H*) and δ 3.04 (C1-*H*H). Atom numbering is shown in Scheme 10.; ^{13}C NMR (100.6 MHz, C_6D_6) δ (ppm) 13.83 (q), 13.99 (q), 18.01 (q), 36.89 (d), 38.25 (d), 43.22 (d), 57.92 (s), 61.61 (t), 61.82 (t), 68.68 (t), 121.99 (d), 134.85 (d), 167.93 (s), 168.81 (s), 170.95 (s). Selected HMBC correlations are between δ 3.04, 3.68 (C1-H_2) and δ 121.99 (*C*7), 38.25 (*C*7a), 43.22 (*C*3a), between δ 2.58 (C3a-*H*) and δ 38.25 (*C*7a), 57.92 (*C*4), and between δ 5.11 (C7-*H*) and δ 43.22 (*C*3a), 36.89 (*C*5), between δ 2.58 (C3a-*H*), 5.32 (C6-*H*) and δ 36.89 (*C*5).; IR (neat) 2980, 1799, 1733, 1465, 1368, 1265, 1209, 1185, 1099, 1002 cm^{-1}; MS (EI) *m/z* 296 (M^+, 41), 251 (29), 223 (100%); HRMS (EI) M^+ 296.1261 (calcd for $C_{15}H_{20}NO_6$ 296.1260); Anal. Calcd for $C_{15}H_{20}O_6$: C, 60.80; H, 6.80. Found: C, C, 61.05; H, 7.02.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan and JSPS KAKENHI Grant Number 26410048. This work was partly supported by Nanotechnology Platform Program of MEXT. We thank Nara Institute of Science and Technology (NAIST) and Prof. K. Kakiuchi (NAIST) for mass spectrometry. We also thank Ms E. Hirai and Mr. K. Ueda (Nara University of Education) for experimental help.

Supporting Information available: Cartesian coordinates of the optimized geometries, Crystallographic data, ^{1}H and ^{13}C NMR spectral data, and 2D NOESY spectra.

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