Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron
Tetrahedron 63 (2007) 9605–9613

DBU-mediated Ireland–Claisen rearrangement of allyl alk-3-enoates: an efficient synthesis of 2-ethylidene-γ,δ-unsaturated carboxylic acids

Yunxia Li,[a] Andreas Goeke,[b,c] Ruiyao Wang,[a] Quanrui Wang[a,*] and Georg Fráter[c,*]

[a]*Department of Chemistry, Fudan University, 200433 Shanghai, PR China*
[b]*Shanghai Givaudan Ltd, Fragrances, 201203 Shanghai, PR China*
[c]*Givaudan Schweiz AG, Fragrance Research, Überlandstraße 138, 8600 Dübendorf, Switzerland*

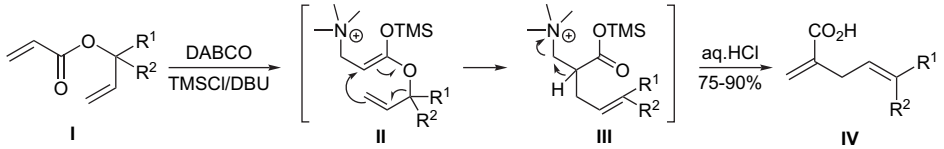
Received 16 May 2007; revised 12 July 2007; accepted 13 July 2007
Available online 19 July 2007

Abstract—Ireland–Claisen rearrangement, triggered by silyl enolization of allylic but-3-enoates **2**, has been developed using DBU as the base in the presence of an excess amount of TMSCl under reflux in acetonitrile for a couple of hours. The procedure allows the synthesis of a range of 2-ethylidene-γ,δ-unsaturated carboxylic acids **5** in moderate to high yields. It is further revealed that the rearrangement proceeds equally well with allylic (*E*)-hexa-3,5-dienoates **10** derived from sorbic acid under similar conditions to provide 2-allyl substituted hexa-2,4-dienoic acids **13**.

1. Introduction

Numerous significant variants of the Claisen [3,3]-sigmatropic rearrangement have been developed in the past decades, which have increased its versatility and made it a powerful tool to synthesize γ,δ-unsaturated carbonyl compounds.[1] Especially in 1972, Ireland and Mueller found that esters of allylic alcohols can be rearranged to γ,δ-unsaturated carboxylic acids in the presence of strong bases (like LDA) and the reaction has been generally referred to as Ireland–Claisen rearrangement.[2,3] This rearrangement usually occurs below ambient temperatures via the silylketene acetals prepared by reaction of allylic ester enolates with a silylating agent such as trimethylsilyl chloride.

We have recently established a DABCO-catalyzed Ireland–Claisen [3,3]-rearrangement of allylic acrylates **I** in the presence of an excess of TMSCl and 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) in refluxing acetonitrile (Scheme 1).[4] In this procedure, the silylketene acetals **II** were generated by a Baylis–Hillman-like addition of DABCO to the acrylate and subsequent silylation of the zwitterionic intermediate. After rearrangement of this intermediate followed by the elimination of DABCO, α-methylene-γ,δ-unsaturated carboxylic acids **IV** were obtained in good yields. However, this pathway applies only to non-substituted acrylates, as it becomes increasingly difficult to add Baylis–Hillman bases to β-substituted and β-disubstituted acrylates. Working along this line, we surprisingly found that the combination of DBU and TMSCl[5] is reactive enough to promote the silylketene acetal formation and subsequent Claisen rearrangement/isomerization reactions of a range of allylic but-3-enoates or related vinylogous systems. Herein, we present the results of our mild and effective variant of the Ireland–Claisen rearrangement.



Scheme 1. The DABCO promoted Ireland–Claisen rearrangement of allyl acrylates **I**.[4]

Keywords: Ireland–Claisen rearrangement; DBU; 2-Ethylidene-γ,δ-unsaturated carboxylic acids.
* Corresponding authors. E-mail addresses: qrwang@fudan.edu.cn; georg.frater@givaudan.com

0040–4020/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.tet.2007.07.031

2. Results and discussion

The synthetic sequence is illustrated in Scheme 2. First, we prepared the corresponding allylic esters easily in good yields by the reaction of crotonoyl chloride with alcohols **1** in the presence of stoichiometric amounts of triethylamine.[6] It was found that, in most cases, the β,γ-unsaturated esters **2** were formed as the major products along with varying amounts of crotonates **3**. Since both products provided the same ester enolates during the following step, separation of **2** and **3** was not necessary.

In preliminary experiments, we investigated the enolization of **2a/3a** (98:2) with Et_3N, DBU, DMAP (4-dimethylaminopyridine), and *N*-ethyldiisopropylamine (Hünig's base) as a base. After exploring a range of reaction conditions, we were pleased to discover that DBU can serve as an efficient base in promoting the formation of the ester enolates. Thus, **2a/3a** (1.0 equiv) were treated with DBU (2.0 equiv) and trimethylsilyl chloride (TMSCl, 3.0 equiv) in acetonitrile under reflux. The [3,3]-rearrangement (via chair-form transient state **A** to give **4**) and subsequent isomerization reaction proceeded smoothly and were completed after 5 h. Acidic work-up provided 2-ethylidene-pent-4-enoic acid **5a** in 90% isolated yield and 97% (*E*)-selectivity for the α-ethylidene double bond.

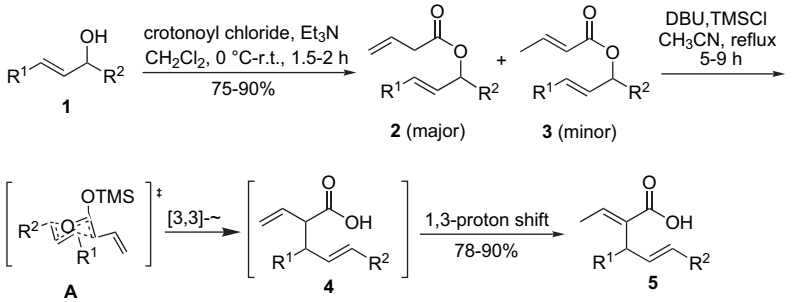
Ireland–Claisen rearrangements of conjugated silylketene acetals are scarce but have been described starting from α, β-unsaturated or β,γ-unsaturated allyl esters.[7] In the total syntheses of (−)-grandinolide and (−)-sapranthin by asymmetric Sharpless dihydroxylation of methyl *trans*-3-pentenoate, Rank and her co-workers conducted the Ireland–Claisen rearrangement of the β,γ-unsaturated allyl ester **2a** using LHMDS as the base at −78 °C for the initial deprotonation. The product was reported to be an 87:13 mixture of the deconjugated acid **4a** and the conjugated acid **5a**.[8]

DBU was initially introduced as a reagent for dehydrohalogenation in a vitamin A synthesis during 1960s along with the other bicyclic amidine compound DBN.[9] DBU has been recognized as a strong hindered organic base with low nucleophilicity and it finds increasing use in the synthetic works.[10,11] To the best of our awareness, there are no literature precedents for using DBU as the base in generation of silylketene acetals derived from allyl but-3-enoates or but-2-enoates. The use of DBU is evidently advantageous over the commonly used strong bases like LDA or LHMDS with which low temperatures must be employed. Inspired by the ease of carrying out this protocol, we performed a series of experiments with different allylic esters of type **2/3** to probe the scope of the reaction.

As shown in Table 1, this reaction tolerates a wide range of substitution patterns at both the carboxylate as well as the allylic alcohol moiety to afford the tandem rearranged/isomerized products in good yields.[12] It was found that for the (*E*)-3-monosubstituted allyl but-3-enoates **2b** and **2c** the reaction furnished the 3-substituted 2-ethylidene-γ,δ-unsaturated acids **5b** and **5c**, respectively, as a mixture of *E* and *Z* products with the former ones predominating (Table 1, entries 2 and 3), both in high yields. The remote 6(*Z*)-double bond in **2c** did not isomerize during the reaction. For allyl but-3-enoate **2d** bearing a substituent at the 2′-position, the reaction proceeded equally smoothly to provide **5d** in 78% yield (Table 1, entry 4). Similar results were observed for the 1,1-dimethyl substituted ester **2e** and the 1-phenyl substituted ester **2f** (Table 1, entries 5 and 6). As a trend, substitution at the 3′-position of the allyl unit renders (*E*)-configured products **5** less selectively, due to the increased allylic strain caused by the bulkier residue at the 2-position of the crotonic acid (Fig. 1).

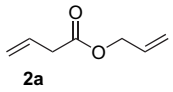
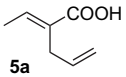
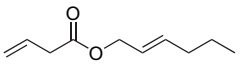
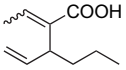
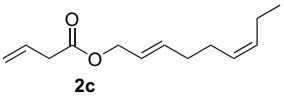
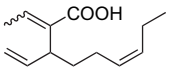
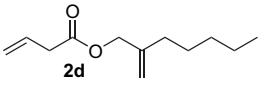
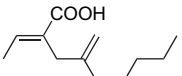
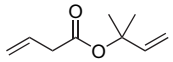
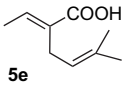
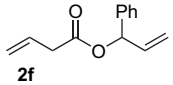
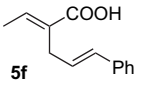
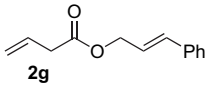
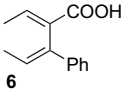
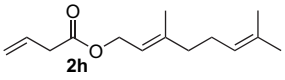
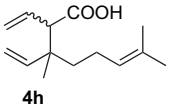
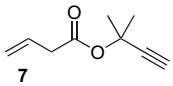
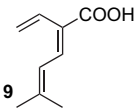
Worthy of note is that the rearrangement of cinnamyl but-3-enoate **2g** occurred under our conditions without difficulty. However, the isolated product was proved to be the fully conjugated carboxylic acid **6**. Apparently, isomerization of the 4-double bond of the initially formed 2-ethylidene-3-phenyl-pent-4-enoic acid **5g** was involved under our conditions (Table 1, entry 7). A NOE experiment allowed establishment of the *Z* configuration of the C-3 double bond for **6**. On the other hand, when the 3,3-disubstituted but-3-enoates **2h** was subjected to the standard reaction conditions, a mixture comprised of 2-vinyl and 2-ethylidene substituted γ,δ-unsaturated acids **4h/5h** (>98:2; de of **4h**: 50%) were produced (Table 1, entry 8). Again, the higher preference for non-conjugated isomer **4h** can be accounted for by the large allylic strain of compound **5h**.

In order to further assess the scope of our protocol, the propargyl but-3-enoate **7** was subjected to the rearrangement. Apparently, the silylketene acetal could be easily generated with DBU/TMSCl and did undergo the [3,3]-rearrangement to give, after an isomerization of the initially formed allene **8** (Scheme 3), 2,4-dienoic acid **9** in moderate yield (Table 1, entry 9). It is important to note that due to the deprotonation of terminal alkynes, this reaction cannot be performed under classical Ireland–Claisen conditions. The *E* configuration at the C-2 double bond was established by NOE experiment.



Scheme 2. Rearrangement of allylic but-3-enoates.

Table 1. Synthesis of 2-ethylidene or 2-vinyl γ,δ-unsaturated carboxylic acids based on Ireland–Claisen rearrangement[a]

Entry	Substrate (major isomer)	Product (major isomer)	Time (h)	Yield[b,c] (%)	Ratio[d] (*E*/*Z*)
1	 **2a**	 **5a**	5	90[b]	>97:3
2	 **2b**	 **5b**	7.5	82[b]	78:22
3	 **2c**	 **5c**	7.5	84[b]	83:17
4	 **2d**	 **5d**	7	78[b]	>97:3
5	 **2e**	 **5e**	6	80[b]	>96:4
6	 **2f**	 **5f**	8	78[c]	>97:3
7	 **2g**	 **6**	9	78[c]	>93:7
8	 **2h**	 **4h**	9	79[e]	
9	 **7**	 **9**	8	47[c]	

[a] Reactions were carried out with **2/3** (1.0 equiv) (GC content of **3** ≤5%), DBU (2.0 equiv), and TMSCl (3.0 equiv) in CH_3CN (10 mL/g of **2/3**) under reflux for the specified period of time.
[b] Isolated yield by bulb-to-bulb distillation.
[c] Isolated yield by column chromatography (hexane/acetone=10:1).
[d] *E*/*Z* by GC.
[e] de 50%; amount of **5h** <2%.

Finally, to test if the rearrangement occurs when the conjugated system is extended by one more double bond, several allylic (*E*)-hexa-3,5-dienoates **10** (containing a minor amount of the regioisomers **11**), which were readily attainable from sorboyl chloride and allylic alcohols,[6a] were subjected to the standard reaction conditions (Scheme 4). As illustrated in Table 2, all the reaction proceeded equally well to offer the tandem rearranged/isomerized hexa-2,4-dienoic acids **13** in high yields, demonstrating that the principle of vinylogy[13] is applicable to our protocol. The initially formed products **12** were not isolated from the mixture. An NOE experiment for **13e** indicated a predominant *E* configuration at the C-2 and C-4 double bonds.

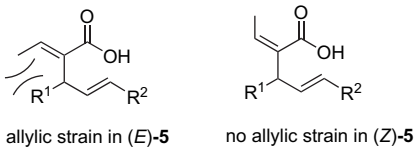
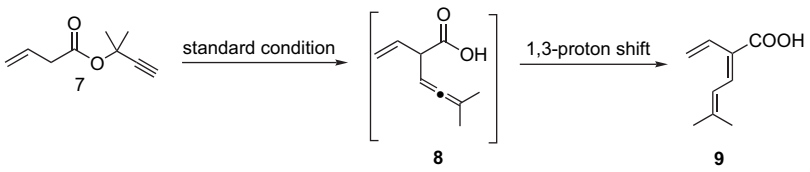
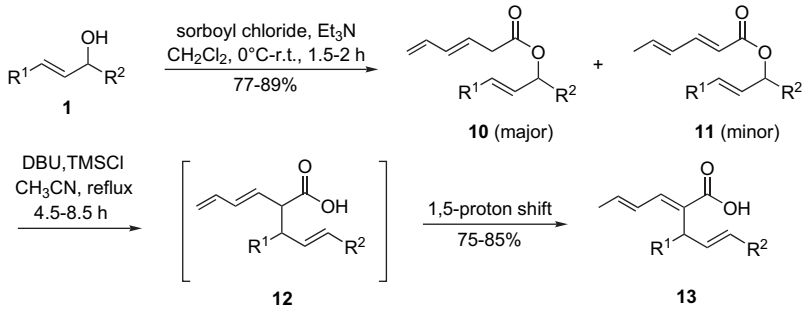


Figure 1.



Scheme 3. Rearrangement of 2-methylbut-3-yn-2-yl but-3-enoate **7**.



Scheme 4. Rearrangement of allylic (*E*)-hexa-3,5-dienoates **10**.

Table 2. Synthesis of 2-allyl substituted hexa-2,4-dienoic acids based on Ireland–Claisen rearrangement of allylic (*E*)-hexa-3,5-dienoates[a]

Entry	Substrate	Product (major isomer)	Time (h)	Yield[b] (%)	Ratio[c]
1	**10a**	**13a**	4.5	91	>90:10
2	**10b**	**13b**	8	81	72:28
3	**10c**	**13c**	8.5	79	88:12
4	**10d**	**13d**	7	80	>97:3
5	**10e**	**13e**	6	85	>97:3
6	**10f**	**13f**	7.5	87	>98:2

[a] Reactions were carried out with **10** (1.0 equiv), DBU (2.0 equiv), and TMSCl (3.0 equiv) in CH_3CN (10 mL/g of **10**) under reflux for the specified period of time.
[b] Isolated yield by column chromatography (hexane/acetone=10:1).
[c] 2*E*,4*E*/2*E*,4*Z* by GC.

In summary, we have disclosed that DBU and TMSCl system can be used for the Ireland–Claisen rearrangement for a range of allylic alk-3 (2)-enoates to give 2-ethylene-γ,δ-unsaturated acids **5** and 2-butenylidene-γ,δ-unsaturated acids **13** in high yields. The superiority of the present protocol lies in its easy operation, cheaper reagents, wide substrate scope, and mild conditions while the presence of carbon–carbon multiple bonds in the acid products enables further transformations.

3. Experimental

3.1. General information

Melting points are uncorrected and expressed in degree Celsius. IR spectral data were obtained for liquid film or KBr discs with a Bruker Tensor 27 spectrophotometer and absorptions are given in wavenumbers (cm^{-1}). NMR spectra were recorded in $CDCl_3$ solutions with a Bruker AMX-300 or Jeol ECA 400 or Bruker Avance DMX 500 spectrometer using TMS as an internal reference. Coupling constant (J) values are given in Hertz. Mass spectra were determined with Agilent Technologies 5975 inert Mass Selective Detector. High-resolution mass spectra were determined with a Varian MAT 44S with EI ionization. Silica gel Merck 60 (200–300 mesh) was used for flash column chromatography with hexane/acetone mixtures for elution. A Glass Oven B-585 kügelrohr apparatus was used for bulb-to-bulb distillation.

3.2. General procedure for esterification: synthesis of the allylic esters 2a–h, 7, and 10a–f

To a stirred 0 °C solution of the appropriate allylic alcohol **1** (100 mmol) in CH_2Cl_2 (500 mL) was added triethylamine (17.0 mL, 120 mmol), followed by freshly distilled crotonoyl chloride (11.6 mL, 120 mmol) or sorboyl chloride (16.0 mL, 120 mmol). After 30 min the reaction was allowed to warm to room temperature and stirred further for 1–1.5 h. Then, saturated aqueous $NaHCO_3$ (150 mL) was added to quench the reaction. The organic layer was separated and washed sequentially with saturated aqueous $NaHCO_3$ (150 mL), 5% aqueous HCl (2×100 mL), and saturated aqueous NaCl (100 mL), and dried over $MgSO_4$. The solution was filtered and concentrated in vacuo. Purification by bulb-to-bulb distillation provided the allylic esters as colorless oil.

3.2.1. Allyl but-3-enoate (2a).[6a] Yield: 89%; colorless oil. IR (neat, ν/cm^{-1}): 3007, 2963, 1740, 1264, 1173, 1004, 970. ^1H NMR (300 MHz, $CDCl_3$): δ 5.99–5.92 (m, 1H), 5.91–5.84 (m, 1H), 5.29 (dd, J_1=17.4 Hz, J_2=1.5 Hz, 1H), 5.23 (dd, J_1=10.5 Hz, J_2=1.5 Hz, 1H), 5.17 (dd, J_1=16.5 Hz, J_2=1.5 Hz, 1H), 5.16 (dd, J_1=11.1 Hz, J_2=1.5 Hz, 1H), 4.59 (d, J=5.7 Hz, 2H), 3.12 (d, J=7.2 Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 171.13, 132.06, 130.16, 118.62, 118.28, 65.30, 39.08.

3.2.2. (*E*)-Hex-2-enyl but-3-enoate (2b). Yield: 89%; colorless oil. IR (neat, ν/cm^{-1}): 3084, 2961, 2875, 1738, 1645, 1458, 1327, 1171, 976. ^1H NMR (300 MHz, $CDCl_3$): δ 5.97–5.86 (m, 1H), 5.76 (dt, J_1=15.3 Hz, J_2=6.9 Hz, 1H), 5.56 (dt, J_1=16.5 Hz, J_2=6.3 Hz, 1H), 5.17 (dd, J_1=17.4 Hz, J_2=1.5 Hz, 1H), 5.16 (dd, J_1=11.1 Hz, J_2=1.5 Hz, 1H), 4.53 (d, J=6.3 Hz, 2H), 3.10 (d, J=7.2 Hz, 2H), 2.03 (dt, J_1=7.2 Hz, J_2=7.2 Hz, 2H), 1.47–1.35 (m, 2H), 0.90 (t, J=7.5 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 171.31, 136.53, 130.33, 123.81, 118.48, 65.50, 39.17, 34.30, 22.03, 13.62. HRMS (EI): m/z calcd for $C_{10}H_{16}O_2$ [M^+]: 168.1150; found: 168.1156.

3.2.3. (2*E*,6*Z*)-Nona-2,6-dienyl but-3-enoate (2c). Yield: 87%; colorless oil. IR (neat, ν/cm^{-1}): 3297, 2990, 2943, 1749, 1129, 973. ^1H NMR (300 MHz, $CDCl_3$): δ 5.98–5.84 (m, 1H), 5.76 (dt, J_1=15.6 Hz, J_2=5.1 Hz, 1H), 5.56 (dt, J_1=15.0 Hz, J_2=6.3 Hz, 1H), 5.37 (dt, J_1=10.5 Hz, J_2=7.5 Hz, 1H), 5.28 (dt, J_1=10.8 Hz, J_2=6.3 Hz, 1H), 5.16 (dd, J_1=15.6 Hz, J_2=1.5 Hz, 1H), 5.15 (dd, J_1=10.2 Hz, J_2=1.5 Hz, 1H), 4.52 (d, J=6.6 Hz, 2H), 3.08 (d, J=7.2 Hz, 2H), 2.10–2.09 (m, 4H), 2.01 (dq, J_1=7.2 Hz, J_2=6.9 Hz, 2H), 0.93 (t, J=7.5 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 171.20, 135.88, 132.29, 130.31, 127.86, 124.05, 118.43, 85.34, 39.12, 32.31, 26.49, 20.54, 14.26. HRMS (EI): m/z calcd for $C_{13}H_{20}O_2$ [M^+]: 208.1463; found: 208.1467.

3.2.4. 2-Methyleneheptyl but-3-enoate (2d). Yield: 86%; colorless oil. IR (neat, ν/cm^{-1}): 3083, 2932, 1744, 1650, 1458, 1326.83, 1166, 993, 918. ^1H NMR (300 MHz, $CDCl_3$): δ 5.99–5.85 (m, 1H), 5.15 (dd, J_1=15.9 Hz, J_2=1.5 Hz, 1H), 5.14 (dd, J_1=11.4 Hz, J_2=1.5 Hz, 1H), 4.99 (s, 1H), 4.90 (s, 1H), 4.52 (s, 2H), 3.11 (d, J=6.9 Hz, 2H), 2.03 (t, J=7.8 Hz, 2H), 1.48–1.38 (m, 2H), 1.31–1.25 (m, 4H), 0.87 (t, J=6.9 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 171.06, 143.97, 130.19, 118.49, 112.01, 69.93, 39.11, 33.17, 31.47, 27.17, 22.46, 13.96. HRMS (EI): m/z calcd for $C_{12}H_{20}O_2$ [M^+]: 196.1463; found: 196.1459.

3.2.5. 2-Methylbut-3-en-2-yl but-3-enoate (2e). Yield: 77%; colorless oil. IR (neat, ν/cm^{-1}): 3088, 2983, 2938, 1736, 1644, 1189, 1128, 920, 842. ^1H NMR (300 MHz, $CDCl_3$): δ 6.06 (dd, J_1=18.0 Hz, J_2=10.8 Hz, 1H), 5.96–5.83 (m, 1H), 5.16 (d, J=17.4 Hz, 1H), 5.14 (dd, J_1=17.4 Hz, J_2=1.8 Hz, 1H), 5.13 (dd, J_1=10.5 Hz, J_2=1.5 Hz, 1H), 5.06 (dd, J_1=11.1 Hz, J_2=0.9 Hz, 1H), 3.02 (d, J=6.6 Hz, 2H), 1.51 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 170.39, 142.41, 130.69, 118.15, 112.72, 80.97, 40.21, 26.41. HRMS (EI): m/z calcd for $C_9H_{14}O_2$ [M^+]: 154.0994; found: 154.0987.

3.2.6. 1-Phenylallyl but-3-enoate (2f). Yield: 80%; colorless oil. IR (neat, ν/cm^{-1}): 3087, 1740, 1644, 1165, 987, 924, 700. ^1H NMR (300 MHz, $CDCl_3$): δ 7.39–7.33 (m, 5H), 6.32 (d, J=6.3 Hz, 1H), 6.09–6.00 (m, 1H), 5.99–5.90 (m, 1H), 5.33 (dd, J_1=17.1 Hz, J_2=1.2 Hz, 1H), 5.28 (dd, J_1=11.4 Hz, J_2=1.2 Hz, 1H), 5.20 (dd, J_1=16.8 Hz, J_2=1.8 Hz, 1H), 5.19 (dd, J_1=10.2 Hz, J_2=1.5 Hz, 1H), 3.19 (d, J=6.9 Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 170.45, 138.82, 136.20, 130.12, 128.59, 128.22, 127.15, 118.75, 117.05, 76.37, 39.56. HRMS (EI): m/z calcd for $C_{13}H_{14}O_2$ [M^+]: 202.0994; found: 202.0991.

3.2.7. Cinnamyl but-3-enoate (2g).[14] Yield: 87%; colorless oil. IR (neat, ν/cm^{-1}): 3028, 1739, 1644, 1256, 1170, 968, 924. ^1H NMR (400 MHz, $CDCl_3$): δ 7.37–7.21 (m, 5H),

6.63 (d, J=15.6 Hz, 1H), 6.26 (dt, J_1=15.6 Hz, J_2=6.4 Hz, 1H), 6.01–5.90 (m, 1H), 5.17 (dd, J_1=15.6 Hz, J_2=1.6 Hz, 1H), 5.16 (dd, J_1=11.0 Hz, J_2=1.6 Hz, 1H), 4.74 (d, J=6.9 Hz, 2H), 3.12 (d, J=6.9 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 171.41, 136.26, 134.44, 130.28, 128.72, 128.21, 126.74, 123.12, 118.81, 65.40, 39.25.

3.2.8. (*E*)-3,7-Dimethylocta-2,6-dienyl but-3-enoate (2h).[14] Yield: 87%; colorless oil. IR (neat, ν/cm^{-1}): 3023, 2919, 1739, 1452, 1251, 1169, 989, 919. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.99–5.88 (m, 1H), 5.34 (t, J=6.9 Hz, 1H), 5.17 (dd, J_1=15.6 Hz, J_2=1.8 Hz, 1H), 5.16 (dd, J_1=11.4 Hz, J_2=1.8 Hz, 1H), 5.07 (t, J=6.9 Hz, 1H), 4.61 (d, J=6.9 Hz, 2H), 3.09 (d, J=6.9 Hz, 2H), 2.09–2.04 (m, 4H), 1.70 (s, 3H), 1.68 (s, 3H), 1.60 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 171.63, 142.45, 131.89, 130.48, 123.80, 118.51, 118.25, 61.69, 39.59, 39.25, 26.34, 25.74, 17.75, 16.54.

3.2.9. 2-Methylbut-3-yn-2-yl but-3-enoate (7). Yield: 80%; colorless oil. IR (neat, ν/cm^{-1}): 3297, 2990, 2943, 1749, 1644, 1182, 1132, 973, 849, 669. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.96–5.83 (m, 1H), 5.14 (dd, J_1=15.6 Hz, J_2=1.5 Hz, 1H), 5.13 (dd, J_1=11.4 Hz, J_2=1.5 Hz, 1H), 3.04 (d, J=7.2 Hz, 2H), 2.52 (s, 1H), 1.66 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 169.74, 130.21, 118.44, 84.57, 72.41, 71.92, 39.73, 28.85. HRMS (EI): m/z calcd for $C_9H_{12}O_2$ [M$^+$]: 152.0837; found: 152.0835.

3.2.10. (*E*)-Allyl hexa-3,5-dienoate (10a).[6b] Yield: 89%; colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.34 (ddd, J_1=16.9 Hz, J_2=10.5 Hz, J_3=10.5 Hz, 1H), 6.16 (dd, J_1=15.1 Hz, J_2=10.5 Hz, 1H), 5.97–5.87 (m, 1H), 5.80 (dt, J_1=15.1 Hz, J_2=10.2 Hz, 1H), 5.32 (dd, J_1=17.4 Hz, J_2=1.4 Hz, 1H), 5.24 (dd, J_1=10.5 Hz, J_2=1.4 Hz, 1H), 5.17 (d, J=16.9 Hz, 1H), 5.07 (d, J=10.1 Hz, 1H), 4.60 (d, J=5.9 Hz, 2H), 3.16 (d, J=6.9 Hz, 2H).

3.2.11. (*E*)-((*E*)-Hex-2-enyl)hexa-3,5-dienoate (10b). Yield: 87%; colorless oil. IR (neat, ν/cm^{-1}): 3033, 2960, 1738, 1336, 1241, 1174, 1004, 972, 904. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.33 (ddd, J_1=16.9 Hz, J_2=10.6 Hz, J_3=10.2 Hz, 1H), 6.14 (dd, J_1=15.1 Hz, J_2=10.1 Hz, 1H), 5.79 (dt, J_1=15.1 Hz, J_2=7.3 Hz, 1H), 5.77 (dt, J_1=16.5 Hz, J_2=6.9 Hz, 1H), 5.58 (dt, J_1=15.1 Hz, J_2=10.2 Hz, 1H), 5.16 (d, J=16.0 Hz, 1H), 5.05 (d, J=10.1 Hz, 1H), 4.53 (d, J=6.4 Hz, 2H), 3.13 (d, J=7.3 Hz, 2H), 2.03 (dt, J_1=6.9 Hz, J_2=6.9 Hz, 2H), 1.45–1.36 (m, 2H), 0.90 (t, J=7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 171.29, 136.63, 136.43, 134.40, 125.69, 123.85, 116.94, 65.63, 38.01, 34.35, 22.07, 13.68. HRMS (EI): m/z calcd for $C_{12}H_{18}O_2$ [M$^+$]: 194.1307; found: 194.1307.

3.2.12. (*E*)-((2*E*,6*Z*)-Nona-2,6-dienyl)hexa-3,5-dienoate (10c). Yield: 84%; colorless oil. IR (neat, ν/cm^{-1}): 3007, 2964, 1740, 1265, 1173, 970, 903. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.34 (ddd, J_1=16.9 Hz, J_2=11.1 Hz, J_3=10.1 Hz, 1H), 6.14 (dd, J_1=15.1 Hz, J_2=10.6 Hz, 1H), 5.79 (dt, J_1=15.1 Hz, J_2=6.9 Hz, 1H), 5.77 (dt, J_1=14.2 Hz, J_2=6.9 Hz, 1H), 5.59 (dt, J_1=15.1 Hz, J_2=10.2 Hz, 1H), 5.39 (dt, J_1=10.5 Hz, J_2=6.9 Hz, 1H), 5.30 (dt, J_1=10.5 Hz, J_2=6.8 Hz, 1H), 5.16 (d, J=16.9 Hz, 1H), 5.06 (d, J=10.1 Hz, 1H), 4.53 (d, J=6.4 Hz, 2H), 3.13 (d, J=7.4 Hz, 2H), 2.15–2.12 (m, 4H), 2.03 (dq, J_1=7.3 Hz, J_2=7.3 Hz, 2H), 0.95 (t, J=7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 171.27, 136.45, 136.08, 134.44, 132.39, 127.94, 125.69, 124.08, 116.98, 65.53, 38.03, 32.39, 26.55, 20.62, 14.37. HRMS (EI): m/z calcd for $C_{15}H_{22}O_2$ [M$^+$]: 234.1620; found: 234.1626.

3.2.13. (*E*)-2-Methyleneheptyl hexa-3,5-dienoate (10d). Yield: 80%; colorless oil. IR (neat, ν/cm^{-1}): 3023, 2932, 2861, 1740, 1652, 1238, 1173, 1003, 903. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.32 (ddd, J_1=17.1 Hz, J_2=10.2 Hz, J_3=10.2 Hz, 1H), 6.14 (dd, J_1=15.9 Hz, J_2=10.8 Hz, 1H), 5.78 (dt, J_1=15.1 Hz, J_2=10.2 Hz, 1H), 5.14 (d, J=17.1 Hz, 1H), 5.04 (dd, J_1=10.5 Hz, J_2=1.2 Hz, 1H), 4.99 (s, 1H), 4.92 (s, 1H), 4.53 (s, 2H), 3.14 (d, J=6.9 Hz, 1H), 2.03 (t, J=7.8 Hz, 2H), 1.48–1.39 (m, 2H), 1.32–1.23 (m, 4H), 0.88 (t, J=6.6 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 171.01, 143.96, 136.33, 134.45, 125.45, 116.89, 112.09, 67.03, 37.92, 33.19, 31.48, 27.19, 22.46, 13.98. HRMS (EI): m/z calcd for $C_{14}H_{22}O_2$ [M$^+$]: 222.1620; found: 222.1616.

3.2.14. (*E*)-2-Methylbut-3-en-2-yl hexa-3,5-dienoate (10e). Yield: 79%; colorless oil. IR (neat, ν/cm^{-1}): 3090, 2981, 2936, 1736, 1647, 1188, 1129, 1004, 921, 847. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.32 (ddd, J_1=17.1 Hz, J_2=10.0 Hz, J_3=9.9 Hz, 1H), 6.13 (dd, J_1=15.6 Hz, J_2=10.5 Hz, 1H), 6.06 (dd, J_1=16.8, J_2=11.1 Hz, 1H), 5.76 (dt, J_1=15.1 Hz, J_2=10.2 Hz, 1H), 5.16 (d, J=18.0 Hz, 1H), 5.14 (d, J=16.5 Hz, 1H), 5.06 (d, J=11.1 Hz, 1H), 5.03 (d, J=9.6 Hz, 1H), 3.05 (d, J=7.2 Hz, 2H), 1.51 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 170.31, 142.37, 136.50, 134.10, 126.08, 116.65, 112.77, 81.10, 38.98, 26.41. HRMS (EI): m/z calcd for $C_{11}H_{16}O_2$ [M$^+$]: 180.1150; found: 180.1154.

3.2.15. (*E*)-1-Vinylcyclohexyl hexa-3,5-dienoate (10f). Yield: 65%; colorless oil. IR (neat, ν/cm^{-1}): 3087, 2936, 2862, 1734, 1651, 1449, 1415, 1182, 1130, 1004, 908. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.34 (ddd, J_1=16.9 Hz, J_2=10.9 Hz, J_3=10.1 Hz, 1H), 6.16 (dd, J_1=16.0 Hz, J_2=10.6 Hz, 1H), 6.09 (dd, J_1=17.8 Hz, J_2=11.0 Hz, 1H), 5.79 (dt, J_1=15.1 Hz, J_2=10.1 Hz, 1H), 5.16 (d, J=16.5 Hz, 2H), 5.12 (d, J=10.6 Hz, 1H), 5.05 (d, J=10.1 Hz, 1H), 3.09 (d, J=7.3 Hz, 2H), 2.21–2.18 (m, 2H), 1.61–1.46 (m, 7H), 1.35–1.25 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 170.15, 141.82, 136.56, 134.22, 126.25, 116.73, 113.81, 82.30, 39.09, 34.88, 25.40, 21.89. HRMS (EI): m/z calcd for $C_{14}H_{20}O_2$ [M$^+$]: 220.1463; found: 220.1466.

3.3. General procedure for Ireland–Claisen rearrangement of 2/3

To a solution of allyl but-3-enoate **2** (containing minor amount of the respective allylic crotonate **3**) (8 mmol) in acetonitrile (10 mL/g of **2/3**) were added DBU (2.44 g, 16 mmol) and TMSCl (2.61 g, 24 mmol). The mixture was heated under reflux and stirred for 4.5–8.5 h (as specified in Table 1), and then concentrated under reduced pressure. The residue was dissolved in ether (30 mL) and washed with 3 M hydrogen chloride (15 mL) and brine, and dried

with anhydrous $MgSO_4$. Concentration under reduced pressure and kügelrohr distillation or silica gel column chromatography (hexane/acetone=10:1) afforded **5a–e** as colorless oils and **5f**, **6**, and **9** as colorless solids.

3.3.1. (*E*)-2-Ethylidenepent-4-enoic acid (5a).[15] Yield: 90%; colorless oil; *E*/*Z*>97:3. IR (neat, ν/cm^{-1}): ~3000, 2983, 1690, 1640, 1421, 1290, 1224, 1154, 915, 685. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.12 (q, J=7.2 Hz, 1H), 5.88–5.77 (m, 1H), 5.03 (dd, J_1=16.9 Hz, J_2=1.5 Hz, 1H), 5.02 (dd, J_1=10.5 Hz, J_2=1.5 Hz, 1H), 3.09 (d, J=6.0 Hz, 1H), 1.85 (d, J=6.9 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 172.68 (s), 141.57 (d), 134.85 (d), 130.14 (t), 115.14 (s), 30.09 (t), 14.51 (q). HRMS: *m*/*z* calcd for $C_7H_{10}O_2$ [M$^+$]: 126.0681; found: 126.0679.

3.3.2. 2-Ethylidene-3-vinylcaproic acid (5b). Yield: 82%; colorless oil; *E*/*Z*=78:22. IR (neat, ν/cm^{-1}): ~3000, 2962, 1694, 1634, 1417, 1276, 914. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.04 (q, J=7.5 Hz, 1H, *E*-isomer), 6.11 (q, J=6.6 Hz, 1H, *Z*-isomer), 6.09 (ddd, J_1=17.3 Hz, J_2=10.2 Hz, J_3=7.5 Hz, 1H, *E*-isomer), 5.81 (ddd, J_1=17.3 Hz, J_2=10.2 Hz, J_3=7.5 Hz, 1H, *Z*-isomer), 5.01 (d, J=17.3 Hz, 1H), 4.99 (d, J=10.2 Hz, 1H), 3.36 (dt, J_1=7.5 Hz, J_2=7.5 Hz, 1H, *E*-isomer), 3.14 (dt, J_1=7.5 Hz, J_2=7.5 Hz, 1H, *Z*-isomer), 2.04 (d, J=7.2 Hz, 3H, *Z*-isomer), 1.88 (d, J=7.2 Hz, 3H, *E*-isomer), 1.70 (dt, J_1=7.5 Hz, J_2=7.5 Hz, 2H), 1.58–1.48 (m, 2H, *Z*-isomer), 1.37–1.22 (m, 2H, *E*-isomer), 0.91 (t, J=7.5 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 173.04 (s), 140.59 (d), 140.54 (d), 134.64 (s), 114.28 (t), 42.02 (d), 35.11 (t), 20.97 (t), 14.48 (q), 13.99 (q) (*E*-isomer); 173.91 (s), 140.93 (d), 138.13 (d), 135.14 (s), 114.72 (t), 46.60 (d), 35.99 (t), 20.59 (t), 16.06 (q), 14.03 (q) (*Z*-isomer). HRMS: *m*/*z* calcd for $C_{10}H_{16}O_2$ [M$^+$]: 168.1150; found: 168.1143.

3.3.3. 2-Ethylidene-3-vinylnon-6-enoic acid (5c). Yield: 84%; colorless oil; *E*/*Z*=83:17. IR (neat, ν/cm^{-1}): ~3000, 2966, 1680, 1634, 1417, 1269, 914. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.05 (q, J=7.2 Hz, 1H, *E*-isomer), 6.13 (q, J=7.5 Hz, 1H, *Z*-isomer), 6.09 (ddd, J_1=16.5 Hz, J_2=10.2 Hz, J_3=7.5 Hz, 1H, *E*-isomer), 5.82 (ddd, J_1=16.5 Hz, J_2=10.2 Hz, J_3=7.5 Hz, 1H, *Z*-isomer), 5.38 (dt, J_1=10.8 Hz, J_2=5.4 Hz, 1H), 5.32 (dt, J_1=10.5 Hz, J_2=5.1 Hz, 1H), 5.01 (dd, J_1=17.4 Hz, J_2=1.5 Hz, 1H), 4.99 (dd, J_1=10.2 Hz, J_2=0.9 Hz, 1H), 3.37 (dt, J_1=7.5 Hz, J_2=7.5 Hz, 1H, *E*-isomer), 3.15 (dt, J_1=7.5 Hz, J_2=7.5 Hz, 1H, *Z*-isomer), 2.07–1.95 (m, 4H), 1.88 (d, J=7.2 Hz, 3H), 1.80–1.72 (m, 2H), 0.96 (d, J=7.5 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 173.12 (s), 140.82 (d), 140.22 (d), 134.48 (s), 132.12 (d), 128.63 (d), 114.61 (t), 41.74 (d), 32.99 (t), 25.27 (t), 20.58 (t), 14.45 (q), 14.33 (q) (*E*-isomer); 173.96 (s), 140.61 (d), 138.44 (d), 134.89 (s), 132.20 (d), 128.51 (d), 115.05 (t), 46.57 (d), 33.77 (t), 25.04 (t), 20.60 (t), 16.09 (q), 14.37 (q) (*Z*-isomer). HRMS: *m*/*z* calcd for $C_{13}H_{20}O_2$ [M$^+$]: 208.1463; found: 208.1454.

3.3.4. (*E*)-2-Ethylidene-4-methylenenonanoic acid (5d). Yield: 78%; colorless oil; *E*/*Z*>97:3. IR (neat, ν/cm^{-1}): ~3000, 2932, 1686, 1644, 1420, 1290, 1225. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.16 (q, J=7.2 Hz, 1H), 4.74 (d, J=1.8 Hz, 1H), 4.61 (d, J=1.8 Hz, 1H), 3.02 (s, 2H), 2.04 (t, J=7.5 Hz, 2H), 1.82 (d, J=7.2 Hz, 3H), 1.54–1.44 (m, 2H), 1.35–1.27 (m, 4H), 0.91 (t, J=6.3 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 172.79 (s), 146.53 (s), 141.85 (d), 130.41 (s), 108.86 (t), 36.76 (t), 32.11 (t), 31.60 (t), 27.43 (t), 22.58 (t), 14.70 (q), 14.09 (q). HRMS: *m*/*z* calcd for $C_{12}H_{20}O_2$ [M$^+$]: 196.1463; found: 196.1461.

3.3.5. (*E*)-2-Ethylidene-5-methylhex-4-enoic acid (5e).[15] Yield: 80%; colorless oil; *E*/*Z*>96:4. IR (neat, ν/cm^{-1}): ~3000, 2932, 1695, 1418, 1276, 1235, 935. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.01 (q, J=7.2 Hz, 1H), 5.05 (t, J=5.7 Hz, 1H), 3.02 (d, J=7.2 Hz, 2H), 1.86 (d, J=7.5 Hz, 3H), 1.70 (s, 3H), 1.69 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 173.28 (s), 140.02 (d), 132.36 (s), 132.07 (s), 121.32 (d), 25.72 (q), 25.22 (t), 17.87 (q), 14.54 (q). HRMS: *m*/*z* calcd for $C_9H_{14}O_2$ [M$^+$]: 154.0994; found: 154.0994.

3.3.6. (2*E*,4*E*)-2-Ethylidene-5-phenylpent-4-enoic acid (5f).[15] Yield: 78%; colorless solid; 2*E*,4*E*/2*Z*,4*E*>97:3; mp 78–80 °C. IR (KBr, ν/cm^{-1}): ~3000, 1676, 1420, 1287, 1203, 961, 742. ^{1}H NMR (400 MHz, $CDCl_3$): δ 12.15 (br, 1H), 7.34–7.16 (m, 5H), 7.14 (q, J=6.9 Hz, 1H), 6.39 (d, J=16.0 Hz, 1H), 6.20 (dt, J_1=16.0 Hz, J_2=6.0 Hz, 1H), 3.23 (d, J=6.4 Hz, 2H), 1.90 (d, J=7.2 Hz, 3H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 172.68 (s), 141.58 (d), 137.45 (s), 130.53 (d), 130.51 (s), 128.44 (d), 127.04 (d), 126.82 (d), 126.08 (d), 29.39 (t), 14.59 (q). HRMS: *m*/*z* calcd for $C_{13}H_{14}O_2$ [M$^+$]: 202.0994; found: 202.0994.

3.3.7. (2*E*,3*Z*)-2-Ethylidene-3-phenylpent-3-enoic acid (6). Yield: 78%; colorless solid; 2*E*,3*Z*/2*Z*,3*Z*>93:7; mp 106–109 °C. IR (KBr, ν/cm^{-1}): ~3000, 1689, 1427, 1288, 959, 765, 700. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.36 (q, J=7.2 Hz, 1H), 7.31–7.20 (m, 5H), 6.28 (q, J=6.6 Hz, 1H), 1.78 (d, J=6.9 Hz, 3H), 1.71 (d, J=6.9 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 170.68 (s), 143.90 (d), 140.01 (s), 134.73 (s), 131.33 (s), 128.43 (d), 127.01 (d), 126.60 (d), 125.57 (d), 15.52 (t), 15.40 (t). HRMS: *m*/*z* calcd for $C_{13}H_{14}O_2$ [M$^+$]: 202.0994; found: 202.0997.

3.3.8. 3,7-Dimethyl-2,3-divinyloct-6-enoic acid (4h). Yield: 79%; colorless oil; de 50%. IR (neat, ν/cm^{-1}): ~3000, 2972, 1701, 1414, 1377, 1259, 918. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.90 (dd, J_1=17.4 Hz, J_2=11.5 Hz, 1H), 5.88–5.78 (m, 1H), 5.21 (dd, J_1=10.1 Hz, J_2=1.8 Hz, 1H), 5.15 (dd, J_1=16.5 Hz, J_2=1.8 Hz, 1H), 5.11 (dd, J_1=10.5 Hz, J_2=1.4 Hz, 1H), 5.06 (t, J=7.3 Hz, 1H), 4.97 (dd, J_1=17.4 Hz, J_2=1.4 Hz, 1H), 2.92 (d, J=9.6 Hz, 1H), 1.95–1.82 (m, 2H), 1.67 (s, 3H), 1.57 (s, 3H), 1.53–1.44 (m, 1H), 1.38–1.25 (m, 1H), 1.07 (s, 3H). Major isomer: ^{13}C NMR (100 MHz, $CDCl_3$): δ 179.19 (s), 143.18 (d), 133.08 (d), 131.57 (s), 124.45 (d), 119.65 (t), 114.18 (t), 60.11 (d), 42.33 (s), 39.18 (t), 25.77 (q), 22.71 (t), 19.03 (q), 17.66 (q). HRMS: *m*/*z* calcd for $C_{14}H_{22}O_2$ [M$^+$]: 222.1620; found: 222.1625.

3.3.9. (*E*)-5-Methyl-2-vinylhexa-2,4-dienoic acid (9). Yield: 47%; colorless solid; mp 102–104 °C. IR (KBr, ν/cm^{-1}) ~3000, 2972, 1675, 1433, 1280, 920, 706. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.62 (d, J=12.0 Hz, 1H), 6.59 (dd, J_1=17.7 Hz, J_2=11.7 Hz, 1H), 6.40 (d, J=12.0 Hz, 1H), 5.69 (dd, J_1=17.7 Hz, J_2=1.8 Hz, 1H), 5.44 (d, J=11.7 Hz, 1H), 1.95 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 172.82 (s), 148.25 (s), 137.77 (d), 129.00 (d), 124.79 (s),

121.39 (d), 120.23 (t), 27.15 (q), 19.12 (q). HRMS: *m/z* calcd for $C_9H_{12}O_2$ [M^+]: 152.0837; found: 152.0840.

3.4. General procedure for Ireland–Claisen rearrangement of 10

To a solution of allyl hexa-3,5-dienoate **10** (containing minor amount of the respective allyl hexa-2,4-dienoate **11**) (8 mmol) in acetonitrile (10 mL/g of **10**) were added DBU (2.44 g, 16 mmol) and TMSCl (2.61 g, 24 mmol). The mixture was heated under reflux and stirred for 4.5–8.5 h, and then concentrated under reduced pressure. The residue was dissolved in ether (30 mL) and washed with 3 M hydrogen chloride (15 mL) and brine, and dried with anhydrous $MgSO_4$. Concentration under reduced pressure and silica gel column chromatography (hexane/acetone=10:1) afforded **13b–c** as colorless oils and **13a**, **13d–f** as colorless solids.

3.4.1. 2-Allylhexa-2,4-dienoic acid (13a). Yield: 91%; colorless solid; 2*E*,4*E*/2*E*,4*Z*>90:10; mp 58–60 °C. IR (neat, ν/cm^{-1}): ~3000, 2937, 1687, 1425, 1258, 975, 912. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.75 (d, J=11.4 Hz, 1H, 2*E*,4*Z*-isomer), 7.36 (d, J=11.4 Hz, 1H, 2*E*,4*E*-isomer), 6.35 (dd, J_1=14.9 Hz, J_2=11.4 Hz, 1H), 6.20 (dq, J_1=15.1 Hz, J_2=6.9 Hz, 1H), 6.03–5.88 (m, 1H, 2*E*,4*E*-isomer), 5.90–5.80 (m, 1H, 2*E*,4*Z*-isomer), 5.05 (dd, J_1=18.8 Hz, J_2=1.4 Hz, 1H), 5.01 (dd, J_1=9.6 Hz, J_2=1.4 Hz, 1H), 3.17 (d, J=8.0 Hz, 2H), 1.90 (d, J=6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 173.98 (s), 142.30 (d), 140.52 (d), 135.43 (d), 127.18 (d), 125.87 (s), 115.38 (t), 30.38 (t), 19.14 (q) (2*E*,4*E*-isomer); 173.96 (s), 143.50 (d), 139.32 (d), 136.06 (d), 128.20 (d), 124.53 (s), 115.48 (t), 30.48 (t), 14.15 (q) (2*E*,4*Z*-isomer). HRMS: *m/z* calcd for $C_9H_{12}O_2$ [M^+]: 152.0837; found: 152.0841.

3.4.2. 2-(Hex-1-en-3-yl)hexa-2,4-dienoic acid (13b). Yield: 81%; colorless oil; 2*E*,4*E*/2*E*,4*Z*=72:28. IR (neat, ν/cm^{-1}): ~3000, 1654, 1413, 1299, 1177, 908, 767, 682. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.71 (d, J=11.1 Hz, 1H, 2*E*,4*Z*-isomer), 7.34 (d, J=11.1 Hz, 1H, 2*E*,4*E*-isomer), 6.49 (dd, J_1=14.8 Hz, J_2=11.4 Hz, 1H), 6.19 (dq, J_1=14.8 Hz, J_2=6.6 Hz, 1H), 6.14–6.04 (m, 1H), 5.03 (dd, J_1=20.1 Hz, J_2=1.2 Hz, 1H), 5.00 (dd, J_1=10.2 Hz, J_2=1.2 Hz, 1H), 3.46 (dt, J_1=7.2 Hz, J_2=7.2 Hz, 1H, 2*E*,4*E*-isomer), 3.23 (dt, J_1=7.2 Hz, J_2=7.2 Hz, 1H, 2*E*,4*Z*-isomer), 1.91 (d, J=6.6 Hz, 3H), 1.72 (dt, J_1=7.8 Hz, J_2=7.8 Hz, 2H), 1.60–1.47 (m, 2H, 2*E*,4*Z*-isomer), 1.35–1.25 (m, 2H, 2*E*,4*E*-isomer), 0.91 (t, J=7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 173.79 (s), 141.90 (d), 140.73 (d), 140.21 (d), 130.26 (s), 126.95 (d), 114.43 (t), 42.43 (d), 35.53 (t), 21.02 (t), 19.02 (q), 14.02 (q) (2*E*,4*E*-isomer); 173.71 (s), 141.35 (d), 138.38 (d), 136.20 (d), 132.27 (s), 124.27 (d), 114.69 (t), 46.07 (d), 36.23 (t), 20.61 (t), 18.62 (q), 13.99 (q) (2*E*,4*Z*-isomer). HRMS: *m/z* calcd for $C_{12}H_{18}O_2$ [M^+]: 194.1307; found: 194.1310.

3.4.3. (2*E*,6*Z*)-2-((*E*)-But-2-enylidene)- and (2*E*,6*Z*)-2-((*Z*)-but-2-enylidene)-3-vinylnon-6-enoic acid (13c). Yield: 79%; colorless oil; 2*E*,4*E*/2*E*,4*Z*=88:12. IR (neat, ν/cm^{-1}): ~3000, 2964, 1681, 1637, 1416, 1251, 971, 915, 730. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.71 (d, J=11.7 Hz, 1H, 2*E*,4*Z*-isomer), 7.34 (d, J=11.4 Hz, 1H, 2*E*,4*E*-isomer), 6.50 (dd, J_1=15.9 Hz, J_2=6.6 Hz, 1H), 6.18 (dq, J_1=15.0 Hz, J_2=7.2 Hz, 1H), 6.14–6.04 (m, 1H), 5.38 (dt, J_1=10.5 Hz, J_2=6.6 Hz, 1H), 5.33 (dt, J_1=10.8 Hz, J_2=6.9 Hz, 1H), 5.03 (dd, J_1=19.2 Hz, J_2=1.5 Hz, 1H), 5.02 (dd, J_1=10.2 Hz, J_2=1.5 Hz, 1H), 3.46 (dt, J_1=7.2 Hz, J_2=7.2 Hz, 1H, 2*E*,4*E*-isomer), 3.23 (dt, J_1=7.2 Hz, J_2=7.2 Hz, 1H, 2*E*,4*Z*-isomer), 2.08–1.97 (m, 4H), 1.90 (d, J=6.6 Hz, 3H), 1.81 (dq, J_1=7.8 Hz, J_2=7.8 Hz, 2H), 0.95 (t, J=7.5 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 173.56 (s), 142.09 (d), 140.44 (d), 140.33 (d), 132.21 (d), 129.91 (s), 128.55 (d), 126.92 (d), 114.63 (t), 42.17 (d), 33.37 (t), 25.08 (t), 20.50 (t), 19.04 (q), 14.37 (q) (2*E*,4*E*-isomer); 173.64 (s), 141.50 (d), 138.54 (d), 136.68 (d), 132.17 (d), 132.16 (s), 129.22 (d), 124.21 (d), 115.03 (t), 46.08 (d), 33.98 (t), 25.35 (t), 20.59 (t), 18.64 (q), 13.97 (q) (2*E*,4*Z*-isomer). HRMS: *m/z* calcd for $C_{15}H_{22}O_2$ [M^+]: 234.1620; found: 234.1629.

3.4.4. (2*E*,4*E*)-2-((*E*)-But-2-enylidene)-4-methylenenonanoic acid (13d). Yield: 80%; colorless solid; 2*E*,4*E*/2*E*,4*Z*>97:3; mp 56–58 °C. IR (KBr, ν/cm^{-1}): ~3000, 1697, 1442, 1264, 883, 637. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.42 (d, J=11.1 Hz, 1H), 6.29 (dd, J_1=16.1 Hz, J_2=11.1 Hz, 1H), 6.22 (dq, J_1=15.0 Hz, J_2=6.6 Hz, 1H), 4.76 (s, 1H), 4.62 (s, 1H), 3.09 (s, 2H), 2.06 (t, J=7.8 Hz, 2H), 1.89 (d, J=6.9 Hz, 3H), 1.55–1.45 (m, 2H), 1.34–1.28 (m, 4H), 0.91 (t, J=6.6 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 173.90 (s), 147.16 (s), 142.57 (d), 140.06 (d), 127.41 (d), 126.11 (s), 109.38 (t), 36.74 (t), 32.46 (t), 31.60 (t), 27.42 (t), 22.59 (t), 19.02 (q), 14.09 (q). HRMS: *m/z* calcd for $C_{14}H_{22}O_2$ [M^+]: 222.1620; found: 222.1620.

3.4.5. (2*E*,4*E*)-2-(3-Methylbut-2-enyl)hexa-2,4-dienoic acid (13e).[16] Yield: 85%; white solid; 2*E*,4*E*/2*E*,4*Z*>97:3; mp 76–77 °C. IR (KBr, ν/cm^{-1}): ~3000, 2967, 1674, 1426, 1307, 1258, 972. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.28 (d, J=11.1 Hz, 1H), 6.41 (dd, J_1=15.3 Hz, J_2=11.1 Hz, 1H), 6.17 (dq, J_1=15.0, J_2=6.9 Hz, 1H), 5.06 (t, J=6.9 Hz, 1H), 3.09 (d, J=6.6 Hz, 2H), 1.90 (d, J=6.9 Hz, 3H), 1.73 (s, 3H), 1.69 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 173.85 (s), 140.86 (d), 139.67 (d), 132.40 (s), 127.89 (s), 127.29 (d), 121.83 (d), 25.73 (t), 25.65 (q), 19.08 (q), 17.92 (q). HRMS: *m/z* calcd for $C_{11}H_{16}O_2$ [M^+]: 180.1150; found: 180.1144.

3.4.6. (2*E*,4*E*)-2-(2-Cyclohexylideneethyl)hexa-2,4-dienoic acid (13f). Yield: 87%; colorless solid; 2*E*,4*E*/2*E*,4*Z*>98:2; mp 99–101 °C. IR (KBr, ν/cm^{-1}): 2915, 1676, 1635, 1424, 1313, 1256, 975. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25 (d, J=11.4 Hz, 1H), 6.40 (dd, J_1=16.5 Hz, J_2=11.4 Hz, 1H), 6.15 (dq, J_1=14.7 Hz, J_2=6.9 Hz, 1H), 4.99 (t, J=7.4 Hz, 1H), 3.10 (d, J=6.9 Hz, 2H), 2.25 (t, J=5.0 Hz, 2H), 2.04 (t, J=6.0 Hz, 2H), 1.89 (d, J=6.8 Hz, 3H), 1.55–1.51 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 173.83 (s), 140.89 (d), 140.31 (s), 139.65 (d), 128.09 (s), 127.38 (d), 118.40 (d), 37.19 (t), 28.96 (t), 28.60 (t), 27.77 (t), 26.98 (t), 24.84 (t), 19.16 (q). HRMS: *m/z* calcd for $C_{14}H_{20}O_2$ [M^+]: 220.1463; found: 220.1470.

Acknowledgements

Y.L., R.W., and Q.W. are grateful to the Givaudan Schweiz AG for financial support under the Discovery-Project (No.

04174). The diligent assistance of Mr. Yongjun Wang (Spring 2006) as undergraduate research participant is much appreciated.

References and notes

1. For some reviews on Claisen rearrangement, see: (a) Lutz, R. P. *Chem. Rev.* **1984**, *84*, 205; (b) Ziegler, F. E. *Chem. Rev.* **1988**, *88*, 1423; (c) Blechert, S. *Synthesis* **1989**, 71; (d) Enders, D.; Knopp, M.; Schiffers, R. *Tetrahedron: Asymmetry* **1996**, *7*, 1847; (e) Ito, H.; Taguchi, T. *Chem. Soc. Rev.* **1999**, *28*, 43; (f) Nubbemeyer, U. *Synthesis* **2003**, 961.
2. (a) Ireland, R. E.; Mueller, R. H. *J. Am. Chem. Soc.* **1972**, *94*, 5897; (b) Ireland, R. E.; Mueller, R. H.; Willard, A. K. *J. Am. Chem. Soc.* **1976**, *98*, 2868; (c) Ireland, R. E.; Wipf, P.; Armstrong, J. D. *J. Org. Chem.* **1991**, *56*, 650; (d) Ireland, R. E.; Wipf, P.; Xiang, J. N. *J. Org. Chem.* **1991**, *56*, 3572.
3. For excellent recent reviews, see: (a) Castro, A. M. M. *Chem. Rev.* **2004**, *104*, 2939; (b) Chai, Y.-H.; Hong, S.-p.; Lindsay, H. A.; McFarland, C.; McIntosh, M. C. *Tetrahedron* **2002**, *58*, 2905.
4. Li, Y.; Wang, Q.; Goeke, A.; Fráter, G. *Synlett* **2007**, 288.
5. Silyltriflate and Lewis acid promoted Claisen rearrangements: Schreiber, S. L.; Smith, D. B. *J. Org. Chem.* **1989**, *54*, 9; Kobayashi, M.; Masumoto, K.; Nakai, E.; Nakai, T. *Tetrahedron Lett.* **1996**, *37*, 3005; Koch, G.; Janser, P.; Kottirsch, G.; Romero-Giron, E. *Tetrahedron Lett.* **2002**, *43*, 4837.
6. (a) Hoye, T. R.; Magee, A. S.; Trumper, W. S. *Synth. Commun.* **1982**, *12*, 183; (b) Lombardo, L. *Tetrahedron Lett.* **1985**, *26*, 381.
7. (a) Fráter, G. *Helv. Chim. Acta* **1975**, *58*, 442; (b) Wilson, R. S.; Myers, R. S. *J. Org. Chem.* **1975**, *40*, 3309; (c) Amaike, M.; Mori, K. *Liebigs Ann. Chem.* **1995**, 1451.
8. Harcken, C.; Brückner, R.; Rank, E. *Chem.—Eur. J.* **1998**, *4*, 2342.
9. Oediger, H.; Kabbe, H.-J.; Möller, F.; Eiter, K. *Chem. Ber.* **1966**, *99*, 2012.
10. For a review of the chemistry and other pyrimidoazepines, see: Oediger, H.; Möller, F.; Eiter, K. *Synthesis* **1972**, 591.
11. Ghosh, N. *Synlett* **2004**, 574.
12. Under the standard conditions, no reaction occurred with saturated allyl carboxylates.
13. Fuson, R. C. *Chem. Rev.* **1935**, *16*, 1.
14. Kiji, J.; Okano, T.; Nishiumi, W.; Nonishi, H. *Chem. Lett.* **1988**, 957.
15. Domingo, L. R.; Gil, S.; Parra, M.; Sáez, J. A.; Torres, M. *Tetrahedron* **2003**, *59*, 6233.
16. Miller, J. A.; Zweifel, G. *J. Am. Chem. Soc.* **1981**, *103*, 6217.