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Ruthenium-Catalyzed Sequential Enyne Cross-Metathesis/ATRA Reactions

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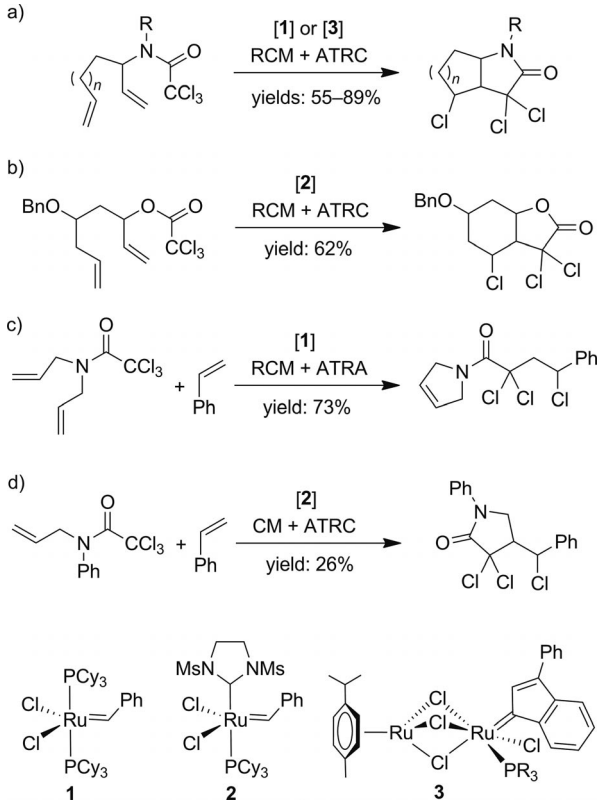
Sequential enyne cross-metathesis reactions of arylalkynes with ethylene followed by atom transfer radical addition (ATRA) with ethyl dichloroacetate or dichloroacetonitrile provide 1,5-dichloropent-2-ene derivatives. The second-generation Grubbs alkylidene complex [$RuCl_2$(=CHPh)(PCy_3)(NHC)] [NHC = 1,3-bis(2,4,6-trimethylphenyl)-2-imidazolidinylidene] is used as the catalyst precursor for both reactions. Preliminary results show that the reaction products can be converted into vinylcyclopropanes by dechlorination with magnesium or manganese.

Introduction

In 1999, the groups of Snapper and Demonceau reported that the first-generation Grubbs catalyst **1** can mediate atom transfer radical addition (ATRA) reactions of halogenated compounds to olefins.[1] Subsequent studies have shown that several other (alkylidene)ruthenium complexes are also able to promote ATRA reactions.[2,3] These findings triggered attempts to perform metathesis and ATRA reactions in a sequential fashion with the same ruthenium catalyst, and the first examples were described in 2005.[4] It was demonstrated that **1** is able to catalyze ring-closing metathesis (RCM)/atom transfer radical cyclization (ATRC) cascades to give bicyclic lactams (Scheme 1a).[4a] Recent studies have shown that this tandem reaction can be combined with palladium-mediated rearrangements,[5] and that the dimetallic complex **3** is also a suitable catalyst precursor.[6] In a related fashion, bicyclic lactones can be obtained from RCM/ATRC reactions (Scheme 1b).[4b] In this case, utilization of the second-generation Grubbs metathesis catalyst **2** was advantageous. Sequential metathesis/radical additions are not restricted to intramolecular reactions. An RCM followed by an intermolecular ATRA (Scheme 1c)[4a] and an intermolecular cross-metathesis (CM) combined with an ATRC reaction have been reported.[7] However, in both cases the products were obtained in moderate yields.

Here, we describe a new reaction cascade and show that it is possible to combine enyne cross-metathesis reactions with ATRA reactions in one pot to give 1,5-dichloropent-2-ene derivatives, which are interesting starting materials for the synthesis of vinylcyclopropanes.



Scheme 1. Examples of sequential metathesis/ATRA reactions.

Results and Discussion

Ruthenium-catalyzed enyne metathesis reactions have emerged as versatile C–C coupling reactions in synthetic chemistry.[8] The enyne cross-metathesis of alkynes with ethylene gives buta-1,3-dienes.[9] This reaction is best performed in the presence of the second-generation Grubbs

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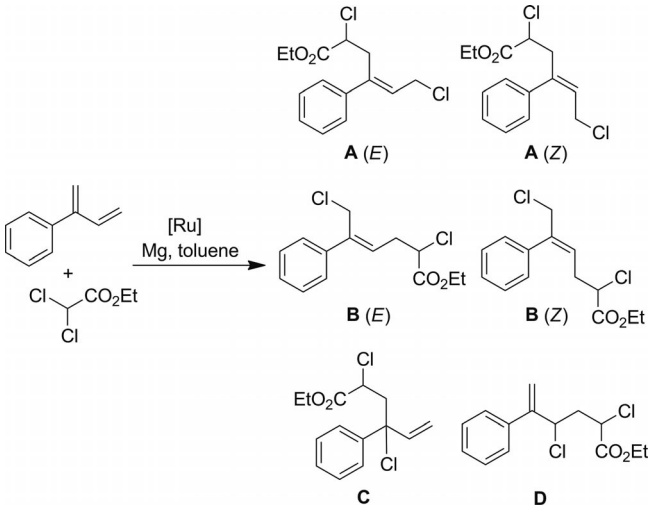
catalyst **2**.[10] To examine the feasibility of sequential enyne cross-metathesis/ATRA reactions, we initially focused on the second step as ATRA reactions of 1,3-dienes have hardly been investigated.[11] As test reactions, we used the ATRA of ethyl dichloroacetate to 2-phenylbuta-1,3-diene. Ethyl dichloroacetate displays a low intrinsic activity compared to commonly used ATRA substrates such as CCl_4. However, it is more interesting from a synthetic point of view (see below).

Initially, reactions were performed with the half-sandwich complex [Cp*$RuCl_2(PPh_3)$] in conjunction with magnesium. This combination is one of the best catalyst systems for ATRA reactions known to date.[12] The role of magnesium is in the generation and regeneration of the catalytically active Ru^{II} complex.[12,13] In ATRA reactions with terminal olefins, the new C–C bond is generated with high selectivity at the terminal carbon atom of the olefin.[3a] Still, there are several possible isomers for addition products of ethyl dichloroacetate and 2-phenylbuta-1,3-diene. If the addition proceeds in a 1,4 fashion, isomers **A** and **B** are formed, which are each a mixture of two stereoisomers (Scheme 2). 1,2-Addition, on the other hand, gives the isomer(s) **C** and/or **D** as a mixture of diastereoisomers.



Scheme 2. Possible reaction products of the ATRA reaction of 2-phenylbuta-1,3-diene and ethyl dichloroacetate.

The reaction of 2-phenylbuta-1,3-diene (100 mM) with ethyl dichloroacetate (130 mM) was carried out in toluene at 80 °C by using 5 mol-% of the catalyst precursor [Cp*$RuCl_2(PPh_3)$] and magnesium powder as the additive. After 16 h, the ATRA adducts **A** and **B** were formed in 68 and 2% yield, respectively (Table 1). The 1,2-addition products **C** and **D** were not observed. This result demonstrated that an ATRA reaction of ethyl dichloroacetate with an enyne metathesis product is feasible if forcing conditions are employed (high catalyst loading and elevated temperature).

Next, we investigated whether **2**, which is a good enyne cross-metathesis catalyst,[10] was also able to promote the reaction between 2-phenylbuta-1,3-diene and ethyl dichloroacetate. Under similar conditions as before, the same total yield of 70% was obtained. However, the regioselectivity was slightly lower with an increased yield of 5% for **B** {2% for reactions with [Cp*$RuCl_2(PPh_3)$]}. The conversion of 2-phenylbuta-1,3-diene was complete at the end of the reaction, which is likely to be because of competing polymerization processes. When magnesium was omitted, the yield of the ATRA dropped substantially. This result is in line with previous reports about the beneficial effects of Mg for transition-metal-catalyzed ATRA reactions.[12,14] We also tested the ATRA activity of Hoveyda's alkylidene complex [$RuCl_2$L(NHC)] [L = (*o*-isopropoxyphenyl)methylene],[15] which is a competent enyne cross-metathesis catalyst.[8a] The complex was also able to catalyze the ATRA reaction, but its activity was lower than that of **2**.

Table 1. Ru-catalyzed ATRA reactions between ethyl dichloroacetate and 2-phenylbuta-1,3-diene.[a] The yields were determined by GC–MS with mesitylene as the internal standard.

Catalyst	Additive	Yield **A** [%]	Yield **B** [%]
[Cp*$RuCl_2(PPh_3)$]	Mg	68	2
2	Mg	65	5
2	none	42	3
[$RuCl_2$L(NHC)][b]	Mg	44	4

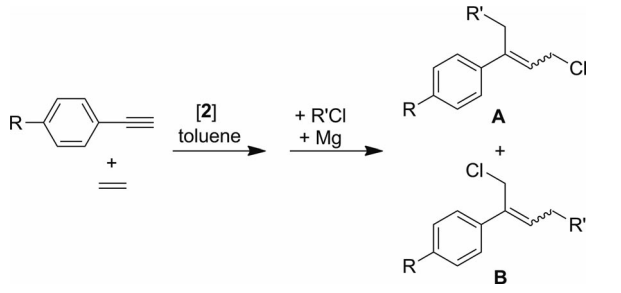
[a] Reaction conditions: [2-phenylbuta-1,3-diene] = 100 mM, [ethyl dichloroacetate] = 130 mM, [Ru] = 5 mM, 80 °C, 16 h, 20 equiv. Mg with respect to the diene. [b] L = (*o*-isopropoxyphenyl)methylene.

Having established that **2** is able to catalyze an ATRA reaction with the enyne metathesis product 2-phenylbuta-1,3-diene, we explored the possibility of performing sequential enyne cross-metathesis/ATRA reactions in one pot with different aromatic alkynes. As outlined above, **2** is a suitable catalyst precursor for enyne cross-metathesis and ATRA reactions. However, these results do not imply that **2** is necessarily a suitable catalyst precursor for *sequential* enyne cross-metathesis/ATRA reactions. During the enyne cross-metathesis reaction, the complex might be converted into a species that is inactive (or less active) as a catalyst in ATRA reactions. As halogenated substrates, we used dichloroacetonitrile and ethyl trichloroacetate in addition to ethyl dichloroacetate. The results are summarized in Table 2.

The enyne cross-metathesis of different aromatic alkynes with ethylene followed by an ATRA reaction with ethyl dichloroacetate gave the corresponding 1,4-addition products in isolated yields of 28–57%. Isomer **A** was the dominant product in all cases with a slight preference for the (*Z*) configuration. Reactions with dichloroacetonitrile were less efficient and required the addition of more catalyst during the ATRA step (another 2 mol-%). Still, the yields were lower than those obtained with ethyl dichloroacetate. Isomer **A** was again the dominant product, but this time the preferred configuration was (*E*). Not unexpectedly, a reaction with ethyl trichloroacetate, which is a substrate of high intrinsic activity,[12a] gave a good yield of 74% (isolated yield 58%).

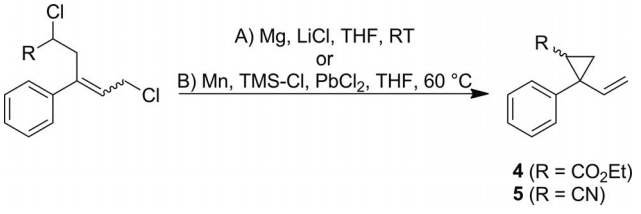
We have previously shown that the ATRA products derived from simple olefins can be dehalogenated with activated magnesium[16] or manganese[17] to give cyclopropanes by an intramolecular C–C coupling reaction. These results

Table 2. Sequential enyne cross-metathesis/ATRA reactions in the presence of catalyst **2**.[a]



R	R′	Yield **A** [%]	Yield **B** [%]	Isolated yield **A** + **B** [%]	(*E*)/(*Z*) **A**
H	$CHClCO_2Et$	65	5	56	42:58
H	CHClCN	39	8	38	81:19
Me	$CHClCO_2Et$	62	4	52	37:63
Me	CHClCN	48	8	40	69:31
F	$CHClCO_2Et$	49	9	57	33:67
F	CHClCN	35	12	45	73:27
CF_3	$CHClCO_2Et$	55	13	47	43:57
CF_3	CHClCN	41[b]	15[b]	40	80:20
Ph	$CHClCO_2Et$	–[c]	–[c]	28	40:60[d]
H	CCl_2CO_2Et	71	3	58	40:60

[a] Reaction conditions: Enyne metathesis: [alkyne] = 100 mM, [**2**] = 5 mM, 1 atm ethylene, toluene, 30 °C, 90 min; ATRA: 1.3 equiv. R′Cl and 20 equiv. Mg with respect to the alkyne, 80 °C, 16 h. When R′ = CN, an additional amount of 2 mol-% catalyst and 1.3 equiv. of chlorinated compound dissolved in a small amount of dichloroethane was added after 16 h and the mixture stirred for another 16 h. The crude yields of **A** and **B** and the (*E*)/(*Z*) ratio of **A** were determined by GC–MS with mesitylene as the internal standard. [b] Additional stirring time of 34 h. [c] The determination of the yield by GC–MS was not possible because of decomposition in the instrument. [d] Determined by ^{1}H NMR spectroscopy.



Scheme 3. Reductive dechlorination of 1,5-dichloropent-2-ene derivatives to vinylcyclopropane derivatives.

prompted us to investigate dechlorination reactions with the 1,4-addition products described above. We examined the reactivity of ethyl 2,6-dichloro-4-phenylhex-4-enoate and 2,6-dichloro-4-phenylhex-4-enenitrile. As a reducing agent, we employed magnesium in the presence of LiCl[18] or manganese, which was preactivated with $PbCl_2$ and chlorotrimethylsilane.[19] Analysis of the reaction mixtures showed that a dechlorination reaction had taken place in both cases. However, instead of cyclopentenes, we observed the formation of vinlycyclopropanes **4** and **5** as a mixture of isomers (Scheme 3). To the best of our knowledge, the reductive coupling of 1,5-dichloropent-2-enes to give vinylcyclopropanes has not been described before. The mechanism might involve the formation of a Grignard reagent followed by an intramolecular nucleophilic attack of the olefin and liberation of chloride (S_N2'-type reaction), but further investigations are needed to substantiate this hypothesis. Cyclopropane **4** has previously been prepared in moderate yield (56%) by Rh-catalyzed cyclopropanation of 2-phenylbuta-1,3-diene with ethyl diazoacetate[20] and by an Ru-catalyzed enyne cross-metathesis/cyclopropanation reaction cascade (30%).[21] To the best of our knowledge, the synthesis of cyclopropane **5** has not been reported before.

A comparison of the two dechlorination procedures is given in Table 3. For the reaction with ethyl 2,6-dichloro-4-phenylhex-4-enoate, both procedures provided cyclopropane **4**, but the utilization of magnesium gave a lower yield than that obtained with manganese (42 vs. 64%). For reactions with 2,6-dichloro-4-phenylhex-4-enenitrile, only dehalogenation with manganese was successful.

Table 3. Reductive dechlorination of 1,5-dichloropent-2-ene derivatives.

R	Conditions[a]	Time [min]	Yield [%][b]	Isolated yield [%]	(*E*)/(*Z*)
CO_2Et	A	20	45[c]	42	50:50
CO_2Et	B	180	66	64	50:50
CN	A	10	0[c]	–	–
CN	B	90	70	37	45:55

[a] Reaction conditions: A: 10 equiv. Mg, [LiCl] = 100 mM, THF, room temp.; B: 10 equiv. Mn, 1 equiv. trimethylsilyl chloride, 0.05 equiv. $PbCl_2$, THF, 60 °C. [b] Determined by ^{1}H NMR spectroscopy with 1,3,5-triisopropylbenzene as the internal standard. [c] Longer reaction times did not improve the yield.

The isolation of **4** and **5** was difficult as they decompose during column chromatography on silica gel, neutral alumina, and deactivated silica gel (NEt_3). In the case of **4**, the crude products were acceptably clean (>90%, NMR). Cyclopropane **5** was purified by trap-to-trap distillation, which resulted in a substantial loss of material.

Conclusions

The second-generation Grubbs metathesis catalyst **2** was used to perform enyne cross-metathesis/ATRA reactions in a sequential fashion. The new procedure provides 1,5-dichloropent-2-ene derivatives with good regioselectivity. The products are potentially interesting intermediates for subsequent transformations as demonstrated by the synthesis of the vinylcyclopropanes **4** and **5** by dechlorination with manganese.

Experimental Section

General: [Cp*$RuCl_2(PPh_3)$] was prepared as described in the literature.[22] [$RuCl_2$(=CHPh)(PCy_3)(NHC)] (**2**) and [$RuCl_2$L(NHC)] were purchased from Sigma Aldrich. The substrates were all commercially available. Mg powder (>99%) was purchased from Sigma Aldrich. To activate its surface, it was stirred magnetically under dry dinitrogen for 5 d before use. Mn powder (–140+325 mesh, 99.6%) was purchased from AlfaAesar. ^{1}H and ^{13}C NMR spectra were recorded with a Bruker Avance DPX 400

spectrometer with the residual solvents as internal standards. All spectra were recorded at room temperature. The isolated yields refer to isomer A plus isomer B (see Table 2), whereas the NMR data are given for the main isomer A. Unless otherwise stated, all reactions were performed under dry nitrogen. The solvents were obtained from a solvent purification system from innovative technologies (IT).

General Procedure for the Sequential Enyne Cross-Metathesis/ATRA Reactions: The arylacetylene (1.0 mmol), **2** (42 mg, 50 μmol), and mesitylene (internal standard, 42 μL, 0.30 mmol) were dissolved in toluene (10 mL). The solution was degassed under vacuum, purged with ethylene gas (1 atm), and stirred at 30 °C. After 90 min, ethylene was removed by cycling with vacuum/N_2. Ethyl dichloroacetate (160 μL, 1.3 mmol) and activated Mg (486 mg, 20 mmol) were added, and the reaction mixture was stirred vigorously at 80 °C for 16 h. The mixture was cooled to room temperature, Mg was removed by filtration, and the solution was concentrated under vacuum. The residue was purified by flash chromatography on silica gel (cyclohexane/dichloromethane, 7:3 or 8:2; Table 2, Entry 10). The products were obtained as colorless or pale yellow oils. The (*E*)/(*Z*) configuration was assigned by a ROESY experiment. For ethyl 2,6-dichloro-4-phenylhex-4-enoate (Table 2, Entry 1), the isomer for which NOE coupling of the olefinic proton with the phenyl protons was observed was assigned as the (*E*) isomer. The stereochemistry of the other products was assigned by comparison of the GC and NMR spectroscopic data with those of ethyl 2,6-dichloro-4-phenylhex-4-enoate.

Ethyl 2,6-Dichloro-4-phenylhex-4-enoate: Table 2, Entry 1. Isolated yield: 161 mg, 56%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.42–7.30 (m, 4 H), 7.21–7.19 (m, 1 H), 6.00 (t, *J* = 8.0 Hz, 1 H), 4.30 (d, *J* = 8.0 Hz, 2 H), 4.22–4.11 (m, 3 H), 3.32 (dd, *J* = 14.4, 6.8 Hz, 1 H), 3.19 (dd, *J* = 14.8, 8.4 Hz, 1 H), 1.28 (t, *J* = 7.2 Hz, 3 H) ppm; (*Z*) olefin: δ = 7.42–7.30 (m, 4 H), 7.21–7.19 (m, 1 H), 5.84 (t, *J* = 8.0 Hz, 1 H), 4.22–4.11 (m, 2 H), 4.09 (dd, *J* = 8.4, 6.8 Hz, 1 H), 3.94 (d, *J* = 8.0 Hz, 2 H), 3.16 (dd, *J* = 14.4, 6.9 Hz, 1 H), 2.94 (dd, *J* = 14.4, 8.0 Hz, 1 H), 1.25 (t, *J* = 7.2 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) olefins (C_{Ar}): δ = 128.7. 128.3, 128.20, 128.17, 128.0 ppm; (*E*) olefin: δ = 160.1, 139.7, 139.3, 126.8, 62.2, 54.8, 40.4, 35.2, 14.0 ppm; (*Z*) olefin: δ = 169.0, 140.4, 136.8, 127.1, 62.1, 54.6, 44.1, 41.3, 13.9 ppm. HRMS (EI): calcd. for $C_{14}H_{16}Cl_2O_2$ $[M]^+$ 286.0527; found 286.0534.

2,6-Dichloro-4-phenylhex-4-enenitrile: Table 2, Entry 2. Isolated yield: 91 mg, 38%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.45–7.31 (m, 4 H), 7.22–7.20 (m, 1 H), 6.13 (t, *J* = 8.0 Hz, 1 H), 4.30 (d, *J* = 8.0 Hz, 2 H), 4.29 (dd, *J* = 8.0, 7.4 Hz, 1 H), 3.32 (dd, *J* = 14.4, 7.4 Hz, 1 H), 3.19 (dd, *J* = 14.4, 8.0 Hz, 1 H) ppm; (*Z*) olefin: δ = 7.45–7.31 (m, 4 H), 7.22–7.20 (m, 1 H), 5.96 (t, *J* = 8.0 Hz, 1 H), 4.18 (dd, *J* = 8.4, 7.2 Hz, 1 H), 3.98 (d, *J* = 8.0 Hz, 2 H), 3.17 (dd, *J* = 14.0, 7.2 Hz, 1 H), 3.08 (dd, *J* = 14.0, 8.4 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) olefin: δ = 138.6, 137.7, 129.4, 129.0, 128.9, 128.1, 126.7, 116.4, 45.6, 40.4, 39.8, 36.9 ppm. HRMS (EI): calcd. for $C_{12}H_{11}Cl_2N$ $[M]^+$ 239.0281; found 239.0281.

Ethyl 2,6-Dichloro-4-(*p*-tolyl)hex-4-enoate: Table 2, Entry 3. Isolated yield: 157 mg, 52%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.23–7.16 (m, 2 H), 7.11–7.08 (m, 2 H), 5.98 (t, *J* = 8.0 Hz, 1 H), 4.29 (d, *J* = 8.0 Hz, 2 H), 4.21–4.12 (m, 3 H), 3.30 (dd, *J* = 14.8, 6.8 Hz, 1 H), 3.19 (dd, *J* = 14.8, 8.0 Hz, 1 H), 2.36 (s, 1 H) 1.26 (t, *J* = 7.2 Hz, 3 H) ppm; (*Z*) olefin: δ = 7.23–7.16 (m, 4 H), 5.84 (t, *J* = 8.0 Hz, 1 H), 4.20–4.12 (m, 2 H), 4.08 (dd, *J* = 8.0, 6.8 Hz, 1 H), 3.95 (d, *J* = 8.0 Hz, 2 H), 3.16 (dd, *J* = 14.4, 6.8 Hz, 1 H), 2.91 (dd, *J* = 14.4, 8.0 Hz, 1 H), 2.37 (s, 3 H), 1.28 (t, *J* = 7.2 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) olefin: δ = 169.1, 140.5, 139.3, 138.2, 138.0, 133.8, 129.4, 128.1, 127.2, 126.8, 126.6, 62.2, 62.1, 54.9, 54.7, 44.2, 41.4, 40.5, 35.2, 21.2, 21.1, 14.0 ppm. HRMS (EI): calcd. for $C_{15}H_{18}Cl_2O_2$ $[M]^+$ 300.0684; found 300.0672.

2,6-Dichloro-4-(*p*-tolyl)hex-4-enenitrile: Table 2, Entry 4. Isolated yield: 102 mg, 40%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.24–7.19 (m, 4 H), 6.11 (t, *J* = 8.0 Hz, 1 H), 4.33–4.25 (m, 3 H), 3.37 (dd, *J* = 14.4, 7.2 Hz, 1 H), 3.28 (dd, *J* = 14.4, 8.0 Hz, 1 H), 2.37 (s, 3 H) ppm; (*Z*) olefin: δ = 7.22–7.20 (m, 2 H), 7.11–7.09 (m, 2 H), 5.93 (t, *J* = 7.8 Hz, 1 H), 4.18 (dd, *J* = 8.2, 7.4 Hz, 1 H), 3.99 (d, *J* = 7.8 Hz, 2 H), 3.28 (dd, *J* = 14.4, 6.9 Hz, 1 H), 3.05 (dd, *J* = 14.4, 8.2 Hz, 1 H), 2.39 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) olefin: δ = 138.9, 138.7, 138.3, 137.6, 135.6, 132.5, 129.7, 129.4, 128.6, 128.0, 126.5, 116.47, 116.46, 45.6, 40.9, 40.44, 40.40, 29.9, 36.8, 21.2, 21.1 ppm. HRMS (EI): calcd. for $C_{13}H_{13}Cl_2N$ $[M]^+$ 253.0425; found 253.0435.

Ethyl 2,6-Dichloro-4-(4-fluorophenyl)hex-4-enoate: Table 2, Entry 5. Isolated yield: 174 mg, 57%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.32–7.27 (m, 2 H), 7.05–7.02 (m, 2 H), 5.96 (t, *J* = 8.0 Hz, 1 H), 4.28 (d, *J* = 8.0 Hz, 2 H), 4.22–4.10 (m, 3 H), 3.28 (dd, *J* = 14.8, 6.4 Hz, 1 H), 3.30 (dd, *J* = 14.8, 8.4 Hz, 1 H), 1.25 (t, *J* = 7.2 Hz, 3 H) ppm; (*Z*) olefin: δ = 7.12–7.06 (m, 2 H), 7.22–7.17 (m, 2 H), 5.85 (t, *J* = 8.0 Hz, 1 H), 4.22–4.10 (m, 2 H), 4.07 (dd, *J* = 8.4, 6.8 Hz, 1 H), 3.90 (m, 2 H), 3.13 (dd, *J* = 14.0, 6.8 Hz, 1 H), 2.94 (dd, *J* = 14.0, 8.4 Hz, 1 H), 1.25 (t, *J* = 7.2 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) olefin: δ = 168.96, 168.93, 162.7 (d, *J* = 246 Hz), 162.5 (d, *J* = 246 Hz), 139.5, 138.4, 135.8 (d, *J* = 3 Hz), 132.7 (d, *J* = 4 Hz), 130.0 (d, *J* = 8 Hz), 128.5 (d, *J* = 8 Hz), 128.1, 127.5, 115.8 (d, *J* = 21 Hz), 115.6 (d, *J* = 22 Hz), 62.3, 62.2, 54.7, 54.5, 44.1, 41.0, 40.2, 35.3, 14.0, 13.9 ppm. HRMS (EI): calcd. for $C_{14}H_{15}Cl_2FO_2$ $[M]^+$ 304.0433; found 304.0449.

2,6-Dichloro-4-(4-fluorophenyl)hex-4-enenitrile: Table 2, Entry 6. Isolated yield: 116 mg, 45%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.36–7.31 (m, 2 H), 7.14–7.08 (m, 2 H), 6.11 (t, *J* = 8.0 Hz, 1 H), 4.30 (d, *J* = 8.0 Hz, 2 H), 4.30 (dd, *J* = 8.0, 7.4 Hz, 1 H), 3.37 (dd, *J* = 14.8, 7.6 Hz, 1 H), 3.30 (dd, *J* = 14.8, 8.0 Hz, 1 H) ppm; (*Z*) olefin: δ = 7.25–7.18 (m, 2 H), 7.17–7.08 (m, 2 H), 6.00 (t, *J* = 8.0 Hz, 1 H), 4.21 (dd, *J* = 8.0, 7.2 Hz, 1 H), 3.97 (d, *J* = 8.0 Hz, 2 H), 3.18 (dd, *J* = 14.0, 7.2 Hz, 1 H), 3.08 (dd, *J* = 14.4, 8.0 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) olefin: δ = 163.0 (d, *J* = 249 Hz), 137.4, 136.8, 134.7 (d, *J* = 8 Hz), 130.0 (d, *J* = 8 Hz), 129.6, 129.0, 128.5 (d, *J* = 8 Hz), 125.3, 116.1 (d, *J* = 21 Hz), 45.5, 40.5, 40.3, 39.6, 37.0 ppm. HRMS (EI): calcd. for $C_{12}H_{10}Cl_2FN$ $[M]^+$ 257.0174; found 257.0175.

Ethyl 2,6-Dichloro-4-[4-(trifluoromethyl)phenyl]hex-4-enoate: Table 2, Entry 7. Isolated yield: 167 mg, 47%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.63 (dd, *J* = 8.8, 0.8 Hz, 2 H), 7.44 (dd, *J* = 8.8, 0.8 Hz, 2 H), 6.05 (t, *J* = 8.0 Hz, 1 H), 4.29 (d, *J* = 8.0 Hz, 2 H), 4.20–4.04 (m, 3 H), 3.32 (dd, *J* = 14.8, 6.8 Hz, 1 H), 3.20 (dd, *J* = 14.8, 8.0 Hz, 1 H), 1.25 (t, *J* = 7.2 Hz, 3 H) ppm; (*Z*) olefin: δ = 7.67 (dd, *J* = 8.4, 0.8 Hz, 2 H), 7.36 (dd, *J* = 8.4, 0.8 Hz, 2 H), 5.91 (t, *J* = 8.0 Hz, 1 H), 4.20–4.04 (m, 2 H), 4.09 (dd, *J* = 8.4, 6.8 Hz, 1 H), 3.89–3.86 (m, 2 H), 3.17 (dd, *J* = 14.4, 6.4 Hz, 1 H), 3.08 (dd, *J* = 14.4, 8.0 Hz, 1 H), 1.27 (t, *J* = 7.2 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) olefin: δ = 168.77, 168.75, 143.4, 140.7, 139.2, 138.2, 130.4 (q, *J* = 32 Hz), 130.3 (q, *J* = 32 Hz), 129.8, 128.7, 128.2, 127.2, 125.71 (q, *J* = 4 Hz), 125.67 (q, *J* = 4 Hz), 123.93 (q, *J* = 270 Hz), 123.87 (q, *J* = 270 Hz), 62.4, 62.3, 54.6, 54.4, 43.8, 40.7, 39.9, 35.1, 14.0, 13.9 ppm. HRMS (EI): calcd. for $C_{15}H_{15}Cl_2F_3O_2$ $[M]^+$ 354.0401; found 354.0388.

2,6-Dichloro-4-[4-(trifluoromethyl)phenyl]hex-4-enenitrile: Table 2, Entry 8. Isolated yield: 123 mg, 40%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.66 (dd, *J* = 8.8, 0.4 Hz, 2 H), 7.46 (dd, *J* = 8.8, 0.4 Hz, 2 H), 6.19 (t, *J* = 8.0 Hz, 1 H), 4.30 (d, *J* = 8.0 Hz, 2 H), 4.30 (dd, *J* = 8.0, 7.2 Hz, 1 H), 3.40 (dd, *J* = 14.4, 7.2 Hz, 1 H), 3.33 (dd, *J* = 14.4, 8.0 Hz, 1 H) ppm; (*Z*) olefin: δ = 7.71 (dd, *J* = 8.6, 0.6 Hz, 2 H), 7.37 (dd, *J* = 8.6, 0.6 Hz, 2 H), 6.05 (t, *J* = 8.0 Hz, 1 H), 4.19 (dd, *J* = 8.4, 7.2 Hz, 1 H), 3.92 (d, *J* = 8.0 Hz, 2 H), 3.20 (dd, *J* = 14.4, 7.2 Hz, 1 H), 3.08 (dd, *J* = 14.4, 8.4 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) olefin only: δ = 142.4, 136.5, 131.3, 130.9 (q, *J* = 32 Hz), 127.1, 126.0 (q, *J* = 4 Hz), 122.4 (q, *J* = 270 Hz), 116.1, 40.1, 39.3, 36.7 ppm. HRMS (EI): calcd. for $C_{13}H_{10}Cl_2F_3N$ $[M]^+$ 307.0142; found 307.0145.

Ethyl 4-(1,1′-Biphenyl-4-yl)-2,6-dichlorohex-4-enoate: Table 2, Entry 9. Isolated yield: 102 mg, 28%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.64–7.59 (m, 4 H), 7.49–7.35 (m, 4 H), 7.27 (d, *J* = 10.4 Hz, 1 H), 6.08 (t, *J* = 8.0 Hz, 1 H), 4.33 (d, *J* = 8.0 Hz, 2 H), 4.23–4.13 (m, 3 H), 3.37 (dd, *J* = 14.8, 6.4 Hz, 1 H), 3.23 (dd, *J* = 14.8, 8.4 Hz, 1 H), 1.27 (t, *J* = 7.2 Hz, 3 H) ppm; (*Z*) olefin: δ = 7.64–7.59 (m, 4 H), 7.49–7.35 (m, 4 H), 7.27 (d, *J* = 10.4 Hz, 1 H), 5.88 (t, *J* = 8.0 Hz, 1 H), 4.23–4.13 (m, 3 H), 4.00 (d, *J* = 8.0 Hz, 2 H), 3.16 (dd, *J* = 14.4, 6.8 Hz, 1 H), 2.98 (dd, *J* = 14.4, 8.0 Hz, 1 H), 1.29 (t, *J* = 7.2 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) olefin: δ = 169.1, 169.0, 141.2, 141.1, 140.34, 140.31, 140.1, 138.9, 138.5, 135.7, 128.9, 128.8, 128.7, 127.9, 127.6, 127.5, 127.4, 127.3, 127.2, 127.02, 126.98, 62.3, 62.1, 54.9, 54.7, 44.1, 41.4, 40.5, 35.1, 14.01, 13.95 ppm. HRMS (EI): calcd. for $C_{20}H_{20}Cl_2O_2$ $[M]^+$ 362.0840; found 362.0847.

Ethyl 2,2,6-Trichloro-4-phenylhex-4-enoate: Table 2, Entry 10. Isolated yield: 187 mg, 58%. ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) olefin: δ = 7.36–7.25 (m, 5 H), 5.99 (t, *J* = 8.0 Hz, 1 H), 4.34 (d, *J* = 8.0 Hz, 2 H), 3.77 (s, 2 H), 3.72 (q, *J* = 7.2 Hz, 2 H), 1.14 (t, *J* = 7.2 Hz, 3 H) ppm; (*Z*) olefin: δ = 7.36–7.25 (m, 5 H), 5.94 (t, *J* = 7.6 Hz, 1 H), 3.93 (d, *J* = 8.0 Hz, 2 H), 3.82 (q, *J* = 7.2 Hz, 2 H), 3.61 (s, 2 H), 1.16 (t, *J* = 7.2 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) olefin: δ = 165.2, 165.1, 140.8, 138.6, 137.5, 136.9, 131.8, 130.6, 128.7, 128.3, 128.2, 128.09, 128.05, 127.5, 83.5, 83.1, 63.9, 63.8, 53.6, 45.2, 41.1, 41.0, 13.63, 13.58 ppm. HRMS (EI): calcd. for $C_{14}H_{15}Cl_3O_2$ $[M]^+$ 320.0684; found 320.0672.

Ethyl 2-Phenyl-2-vinylcyclopropanecarboxylate (4). Method A: Activated Mg powder (487 mg, 20.0 mmol, 10 equiv.) was added to an LiCl (100 mM) solution in tetrahydrofuran (THF, 20 mL). Ethyl 2,2-dichloro-4-phenylhex-4-enoate (574 mg, 2.00 mmol, 1 equiv.) was added, and the suspension was stirred at room temperature for 30 min, Mg was removed by filtration, and the solvent was removed under reduced pressure. Dichloromethane (20 mL) was added, and the suspension was filtered again. The solution was washed with water, and the organic phase was dried with magnesium sulfate. Evaporation of the solvent gave the crude product as a pale yellow oil in 42% yield (91 mg) as a mixture of two diastereoisomers [(*E*)/(*Z*) = 50:50, determined by NMR spectroscopy]. **Method B:** A mixture of Mn powder (549 mg, 10.0 mmol, 10 equiv.), $PbCl_2$ (14 mg, 50 μmol, 0.05 equiv.), and Me_3SiCl (127 μL, 109 mg, 1.00 mmol, 1 equiv.) in THF (5 mL) was stirred at room temperature for 2 min. A solution of 2,6-dichloro-4-phenylhex-4-enenitrile (287 mg, 1.00 mmol) in THF (5 mL) was added. The reaction mixture was stirred at 60 °C for 90 min, and the conversion was monitored by GC–MS. After cooling to room temperature, the reaction mixture was quenched with water (15 mL), and the Mn powder was removed by filtration. Dichloromethane (20 mL) was added, and the organic phase was washed with water and dried with magnesium sulfate. Evaporation of the solvent gave the crude product as a colorless oil in 64% yield (138 mg) as a mixture of two diastereoisomers [(*E*)/(*Z*) = 50:50, determined by NMR spectroscopy]. The NMR spectroscopic data of **4** are in agreement with that reported previously, and the isomers were assigned accordingly.[21] ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) isomer: δ = 7.36–7.25 (m, 5 H), 6.10 (dd, *J* = 17.2, 10.4 Hz, 1 H), 5.08 (dd, *J* = 10.4, 1.2 Hz, 1 H), 4.62 (dd, *J* = 17.2, 1.2 Hz, 1 H), 4.25–4.16 (m, 2 H), 2.26 (dd, *J* = 8.0, 6.0 Hz, 1 H), 1.77 (dd, *J* = 6.0, 4.8 Hz, 1 H), 1.57 (dd, *J* = 8.2, 4.8 Hz, 1 H), 1.31 (t, *J* = 6.8 Hz, 3 H) ppm; (*Z*) isomer: δ = 7.36–7.25 (m, 5 H), 5.68 (dd, *J* = 17.2, 10.4 Hz, 1 H), 5.01 (dd, *J* = 10.4, 0.8 Hz, 1 H), 4.65 (dd, *J* = 17.2, 0.8 Hz, 1 H), 3.95–3.81 (m, 2 H), 2.17 (dd, *J* = 8.0, 6.0 Hz, 1 H), 2.00 (dd, *J* = 6.0, 4.8 Hz, 1 H), 1.42 (dd, *J* = 8.0, 4.8 Hz, 1 H), 0.99 (t, *J* = 6.8 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) isomer: δ = 171.4, 141.7, 138.8, 130.0, 128.4, 127.1, 116.6, 60.7, 38.1, 28.7, 20.5, 14.4 ppm; (*Z*) isomer: δ = 170.3, 143.6, 137.8, 130.3, 128.1, 127.1, 114.3, 60.3, 38.2, 29.2, 18.8, 14.0 ppm. The assignment of the signals in the ^{13}C NMR spectrum was possible due to separation of the diastereoisomers by column chromatography (silica gel, dichloromethane; partial decomposition). HRMS (EI): calcd. for $C_{14}H_{16}O_2$ $[M]^+$ 216.1150; found 216.1157.

2-Phenyl-2-vinylcyclopropanenitrile (5). Method A: This method is analogous to that described for **4**; however, no product was formed in this case. **Method B:** A mixture of Mn powder (495 mg, 9.00 mmol, 10.0 equiv.), $PbCl_2$ (12.5 mg, 45 μmol, 0.05 equiv.), and Me_3SiCl (115 μL, 98 mg, 0.90 mmol, 1 equiv.) in THF (5 mL) was stirred at room temperature for 2 min. A solution of 2,6-dichloro-4-phenylhex-4-enenitrile (220 mg, 0.90 mmol) in THF (5 mL) was added. The reaction mixture was stirred at 60 °C for 90 min (monitored by GC–MS). After cooling to room temperature, the reaction mixture was quenched with water (15 mL), and the Mn powder was removed by filtration. Dichloromethane (20 mL) was added, and the organic phase was washed with water and dried with magnesium sulfate. Evaporation of the solvent followed by trap-to-trap distillation under vacuum gave **5** as a colorless oil in 37% yield (56 mg) as a mixture of two diastereoisomers [(*E*)/(*Z*) = 45:55]. The assignment was made based on the ^{1}H NMR data in analogy to that reported for **4**.[20] ^{1}H NMR (400 MHz, $CDCl_3$): (*E*) isomer: δ = 7.46–7.31 (m, 5 H), 5.98 (dd, *J* = 16.8, 10.4 Hz, 1 H), 5.31 (d, *J* = 10.4 Hz, 1 H), 4.88 (d, *J* = 16.8 Hz, 1 H), 1.97 (dd, *J* = 8.4, 6.0 Hz, 1 H), 1.72 (dd, *J* = 8.8, 5.2 Hz, 1 H), 1.66 (pt, *J* = *J*′ = 5.2 Hz, 1 H) ppm; (*Z*) isomer: δ = 7.46–7.31 (m, 5 H), 5.66 (dd, *J* = 16.8, 10.2 Hz, 1 H), 5.01 (d, *J* = 10.2 Hz, 1 H), 4.82 (d, *J* = 16.8 Hz, 1 H), 1.89 (dd, *J* = 8.4, 6.0 Hz, 1 H), 1.82 (pt, *J* = *J*′ = 5.2 Hz, 1 H), 1.60 (dd, *J* = 8.4, 5.2 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): (*E*) and (*Z*) isomer: δ = 140.7, 139.0, 136.2, 130.1, 129.4, 128.6, 128.0, 127.7, 119.5, 119.0, 118.2, 116.0, 36.3, 35.7, 20.2, 19.8, 11.89, 11.89 (signals overlap) ppm. HRMS (EI): calcd. for $C_{12}H_{11}N$ $[M]^+$ 169.0891; found 169.0883.

Supporting Information (see footnote on the first page of this article): ^{1}H and ^{13}C NMR spectra, gas chromatograms, and mass spectra for the main isomers.

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