Efficient preparation of β-trifluoromethyl acrylates and derivatives *via* palladium cross-coupling reactions

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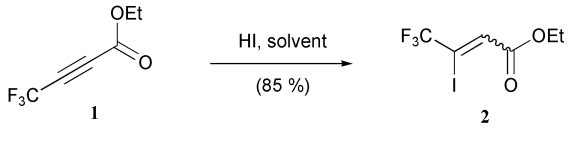
Stereoselective construction of 3-trifluoromethyl conjugated dienoates, trienoates or dienynoates was achieved from ethyl (*Z*)-4,4,4-trifluoro-3-iodobutenoate and alkenyltin or alkynyltin reagents through the Stille reaction or under Heck–Sonogashira coupling conditions. Reduction of ethyl 3-trifluoromethyldienoates using DIBAL-H selectively yielded allylic alcohols and hydrolysis with lithium hydroxide yielded the corresponding acids.

Functionalised molecules bearing fluorine atoms, which modify their bioactivity by enhancement of both nucleophilicity and electronic properties, are often required in medicinal chemistry.[1,2] Among these molecules, trifluoromethyl substituted α,β-unsaturated esters are important.[3] Trifluoromethyl substituted polyenes have previously been obtained by Wittig–Horner olefination of trifluoromethyl ketones or phosphonates,[4] or through sulfone-based cross-coupling.[5] These major routes have been successfully applied to the synthesis of a trifluoromethyl substituted juvenile hormone,[6] and retinal or retinoic acid.[7] Nevertheless, the weak *E*/*Z* selectivity of the trisubstituted double bond created, which contains a trifluoromethyl group, constitutes the major drawback of such approaches. Following our previous study describing the synthesis of (*Z*)- or (*E*)-3-methylalk-2-enoic or 3-substituted but-3-enoic acids,[8] we decided to examine the possibility of extending this methodology to the direct synthesis of dienoic, trienoic or enynoic esters bearing a trifluoromethyl group[9] from ethyl (*Z*)-4,4,4-trifluoro-3-iodobutenoate **2**.

Results and discussion

Synthesis of ethyl (*Z*)-4,4,4-trifluoro-3-iodobutenoate (2)

Hydroiodation of ethyl 4,4,4-trifluorobut-2-ynoate, **1**, initially prepared from α-acylmethylenephosphorane by the methodology described by Hamper[10] with hydroiodic acid, yielded mainly the *Z* isomer **2**, as shown in Scheme 1.[11] As shown in Table 1, it should be noted that temperature and reaction time are important parameters in obtaining a pure *Z* stereoisomer.



1 2

Scheme 1

Table 1 Addition of hydroiodic acid to **1**

Entry	HI/equiv.	*T*/°C	Time/h	Solvent	*E*/*Z*[a]	Yield (%)[b]
1	1.2	−5	5	Et_2O	0/100	85
2	1.2	5	5	Et_2O	5/95	80
3	2	100	1	None	8/92	68
4	2	100	24	Toluene	20/80	64
5	2	100	144	–	40/60	62

[a] The *E*/*Z* ratio was determined by ^{1}H NMR. [b] Overall yield for both isomers.

The *Z* configuration of **2** was determined from the coupling constant $^3J_{C2-F} = 5.3$ Hz for carbon 2 [for (*E*)-**2** the value of the coupling constant is 3.3 Hz] and ^{19}F NMR spectroscopy (using C_6F_6 as external standard upfield positive) in which the $\delta(CF_3)$ of the *Z* isomer (−69.2 ppm) is always upfield compared with the $\delta(CF_3)$ of the *E* isomer (−61.7 ppm).[12]

In conclusion, because of the high volatility of **1** and the exothermicity of the reaction, the use of a hydroiodic solution at −5 °C instead of the sodium iodide–acetic acid system is an appealing procedure.[9a,13] It should be noted that the isomerisation reaction conducted on pure (*Z*)-**2** in the presence of a catalytic amount of iodine or hydroiodic acid failed to give pure (*E*)-**2**. All attempts yielded a 40:60 mixture of *E*/*Z* isomers.

Reactivity of ethyl (*Z*)-4,4,4-trifluoro-3-iodobut-2-enoate (2)

Attention was next directed to the synthesis of ethyl 3-trifluoromethyldienoates by palladium complex-mediated cross-coupling between **2** and organotin reagents as described in Scheme 2.[14] Vinyltin compounds were used with 3% of dichlorobis(acetonitrile)palladium(II) in DMF as solvent. The mild experimental conditions of the Stille cross-coupling reaction resulted in good yields of dienes **3a–j** and no polymerisation or isomerisation products were detected. The results are shown in Table 2. NMR studies on **3a** confirmed retention of the stereochemistry of the α double bond.[12] Finally, extending this methodology to other tin reagents demonstrated that alkynyltin reagents gave functional enynes in good yields

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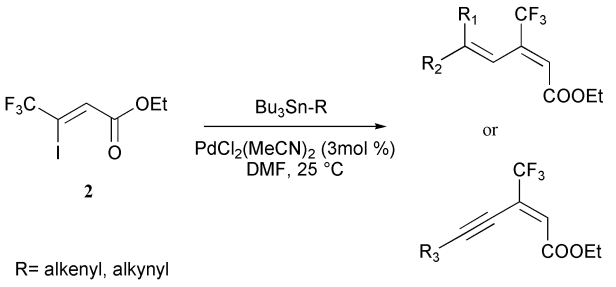
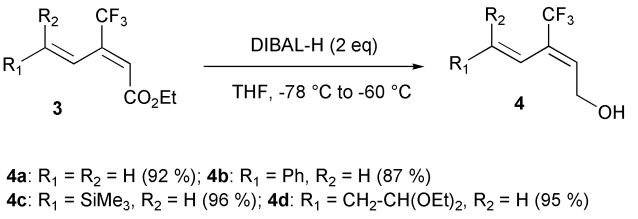


Scheme 2



4a: $R_1 = R_2 = H$ (92 %); **4b**: R_1 = Ph, R_2 = H (87 %)
4c: $R_1 = SiMe_3$, R_2 = H (96 %); **4d**: $R_1 = CH_2\text{-}CH(OEt)_2$, R_2 = H (95 %)

Scheme 3

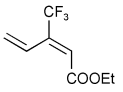
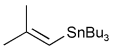
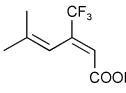
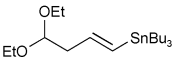
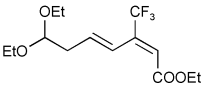
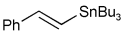
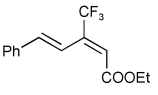
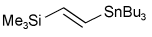
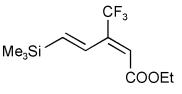
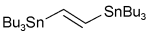
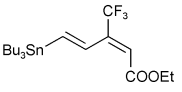
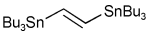
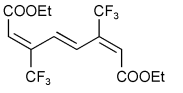
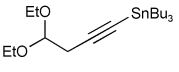
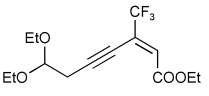
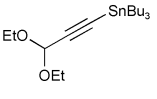
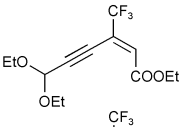
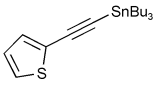
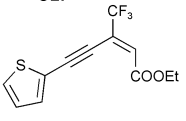
(entries 8–10) with complete retention of the α double bond configuration.

While most examples in Table 2 are straightforward, the reaction of **2** with (*E*)-1,2-bis(tributylstannyl)ethylene merits further discussion. The reaction of **2** with 1.6 equiv. of (*E*)-1,2-bis(tributylstannyl)ethylene (entry 6) provided an 80% yield of a separable mixture of dienylstannane **3f** and the bis-coupling product **3g** (20%). Using 1 equiv. of (*E*)-1,2-bis(tributylstannyl)ethylene yielded a mixture of **3f**/**3g** = 40/60, while the reaction of **2** with 0.5 equiv. of (*E*)-1,2-bis(tributylstannyl)-ethylene yielded only the bis-coupling product **3g** (entry 7). In non-fluorinated series, starting from ethyl iodovinylic propenoate or but-2-enoate, the bis-coupling products were always obtained as the major products (80%) while the expected dienylstannanes was obtained as the minor product (20%)[15] when coupled with 1.4 equiv. of (*E*)-1,2-bis(tributylstannyl)ethylene. Nevertheless, identical results to that in entry 6 were observed when the carboxylic function was protected as its tributylstannyl ester.[16] This slight difference of reactivity between **3f** and its non-fluorinated analogue **3f′** (*i.e.*, CH_3 instead of CF_3) could be explained by the lower kinetic reactivity of **3f**. The partial charge on the tin substituted vinylic carbon atom using PM3 semi-empirical calculations were found lower for **3f** than **3f′**; this could explain why **3f** is less reactive during the transmetallation step of the palladium cycle.[17]

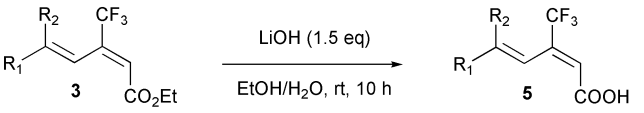
Synthesis of 3-trifluoromethyldienols (4)

The synthetic potential of compounds **3a–j** has not been fully studied to date. However, selective reduction of the ester function into the primary alcohol was investigated in order to preserve the trifluoromethyl diene moiety. So, treatment of dienes **3** with DIBAL-H (2 equiv.) at −78 °C afforded dienyl alcohols **4** quantitatively (Scheme 3).

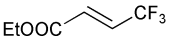
Table 2 Cross-coupling of **2** with alkenyl or alkynyltin reagents

Entry	Tin reagent	Product	Compound	Yield (%)
1			**3a**	77
2			**3b**	47
3			**3c**	41
4			**3d**	78
5			**3e**	88
6			**3f**	84[a]
7			**3g**	55
8			**3h**	74
9			**3i**	78
10			**3j**	68

[a] Obtained as a separable 80:20 mixture of **3f** and **3g**.



5a: $R_1 = R_2$ = Me (69 %); **5b**: $R_1 = CH_2\text{-}CH(OEt)_2$, R_2 = H (73 %)

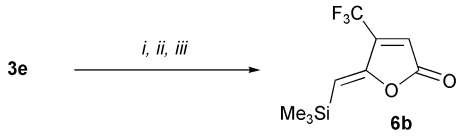
5c: $R_1 = SiMe_3$, R_2 = H (83 %); **5d**: R_1=  , R_2= H (76 %)

Scheme 4

Synthesis of 3-trifluoromethyldienoic acids (5)

The saponification reaction with lithium hydroxide in a 1:1 water–ethanol mixture at 20 °C gave fair yields of the corresponding acids **5**. Using the same methodology the starting ester **2** was also transformed to the corresponding acid **5** (Scheme 4). A good yield of (2*E*,4*E*)-3-trifluoromethyl-5-trimethylsilylpenta-2,4-dienoic acid, **5c**, was obtained.

Synthesis of the corresponding trifluoromethylbutenolide was investigated by a previously described method[18] as shown in Scheme 5. Iodolactonisation promoted by ICl followed by DBU induced deshydroiodation afforded trimethylsilylmethylenebutenolide **6b** in 12% yield as a single isomer. The low yield obtained over two steps can be explained by the volatility of the above mentioned compound **6b**.



i: ICl, CH_2Cl_2, 0 °C, 25 %, **6a**; ii: DBU, CH_2Cl_2, - 78 °C, *E*/*Z*= 94/6;
iii: rt, isomerisation *E*/*Z*= 0/100, 47 %, **6b**.

Scheme 5

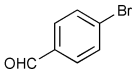
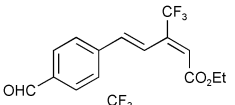
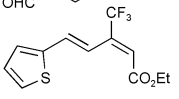
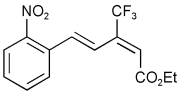
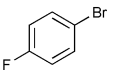
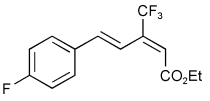
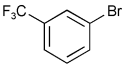
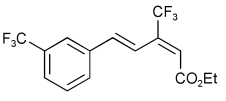
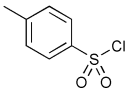
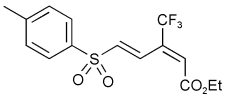
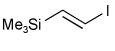
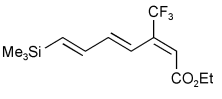
Cross-coupling reactions of 3f with organic halides: synthesis of ethyl (2*E*,4*E*)-3-trifluoromethyl-5-substituted-penta-2,4-dienoates 7a–g.

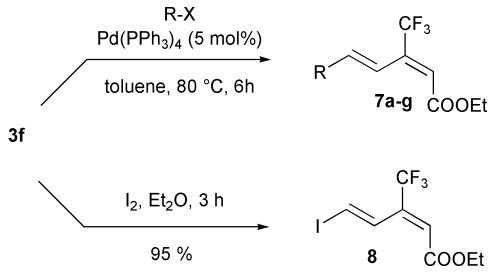
The reactivity of **3f** was then examined in the situation of cross-coupling with organic halides. The results are reported in Table 3. The substitution reaction appears to have a general character with complete control of the configuration, leading to ethyl (2*E*,4*E*)-3-trifluoromethyl-5-substituted-penta-2,4-dienoates **7a**–**e**. As for the synthesis of compounds **3**, the $^3J_{C-F}$ coupling constant for carbon **2** strongly suggests *Z* stereochemistry (*i.e.*, CF_3/H) (Scheme 6, Table 3).

Reactivity of ethyl (2*E*,4*E*)-3-trifluoromethyl-5-iodopenta-2,4-dienoate (8)

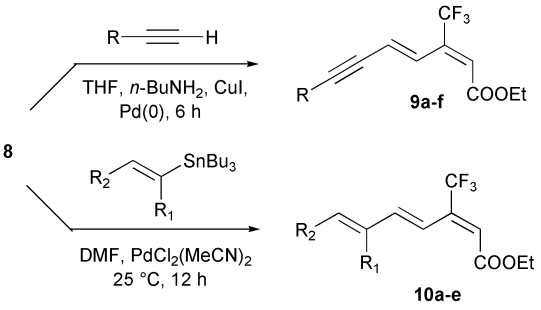
Iododestannylation of **3f** was performed using standard experimental conditions and yielded ethyl (2*E*,4*E*)-3-trifluoromethyl-5-iodopenta-2,4-dienoate **8** (95%) (Scheme 6). The reactivity of **8** was first studied under Heck–Sonogashira cross-coupling conditions[19] with diverse alkynes. Numerous experimental conditions recommended for such cross-couplings have been tested (base: triethylamine, isopropylamine, *n*-butylamine; solvent: benzene, toluene, THF). The best results were obtained using *n*-butylamine as the base and THF for the solvent and the products resulting from the duplication reaction of terminal alkyne were detected in each

Table 3 Cross-coupling reaction of **3f** with organic halides

Entry	R–X	Product	Compound	Yield (%)
1			**7a**	82
2			**7b**	72
3			**7c**	64
4			**7d**	77
5			**7e**	86
6			**7f**	82
7			**7g**	70



Scheme 6



Scheme 7

case, necessitating to the use of a slight excess of alkyne (the percentage of dimerisation of the alkynes is minimal, $< 3\%$); the corresponding trifluoromethylated dienynoates **9a**–**f** were obtained (Scheme 7, Table 4).

Similarly, coupling of **8** under Stille cross-coupling conditions with vinyltin reagents yielded stereodefined trifluoromethylated trienoates **10a**–**e** with fair yields (Scheme 7, Table 5).

Conclusion

In summary, we have shown that starting from ethyl (*Z*)-4,4,4-trifluoro-3-iodobutenoate, an α-trifluoromethyl propenoate synthon was transferred using either Stille or Heck–Sonogashira cross-coupling conditions with tin reagents or alkynes and this constitutes an easy method for selective synthesis of functional dienes, trienes and enynes bearing a trifluoromethyl group.

Experimental

General

All reactions were carried out under inert atmosphere (Ar or N_2). THF and ether were dried and freshly distilled from sodium/benzophenone. DMF was dried by distillation over calcium hydride. Flash chromatography was carried out with Merck silica gel (230–400 mesh). ^{1}H NMR spectra were recorded at 200 MHz (Bruker AC 200) or at 400 MHz (Bruker ARX 400) using $CDCl_3$ as the solvent. Data, reported using the residual solvent proton resonance of $CDCl_3$ ($\delta_H = 7.25$) as the internal reference, are as follows in the order of chemical shift (δ relative to Me_4Si), multiplicity (s, d, t, q, m, b for singlet, doublet, triplet, quartet, multiplet, broad) and coupling constants (J in Hz). ^{13}C NMR were recorded at 50.5 MHz on the same instruments, using the $CDCl_3$ solvent peak at $\delta_C = 77.0$ as the reference. Mass spectra were obtained on a Hewlett Packard (engine 5989A) in direct introduction mode (70 eV) or in the GC/MS (70 eV) mode. IR spectra were recorded on a Nicolet 250FT-IR spectrophotometer. Melting points are uncorrected. Ethyl 4,4,4-trifluorobut-2-ynoate (**1**) was prepared by the method described by Hamper.[10] Vinyltributyltin and isobutenyltributyltin were prepared from vinylmagnesium bromide or isobutenylmagnesium bromide and bistributyltin oxide, respectively.[20] (*E*)-1,2-Bis(tributyltin)ethylene was prepared by hydrostannation of tributyltinacetylene. (*E*)-1-Trimethylsilyl-2-*n*-tributylstannylethylene was prepared by hydrostannation of trimethylsilylacetylene.[21] Other vinyltin reagents were prepared by hydrostannation of the corresponding terminal alkynes under radical conditions (AIBN) and used as thermodynamic mixtures of *E* and *Z* isomers.[22] 3,3-Diethoxyprop-1-ynyltributyltin, 4,4-diethoxybut-1-ynyltributyltin, and 2-thiophenylethynyltributyltin were prepared by exchange between the corresponding alkynes and diethylaminotributyltin. 2-Ethynylthiophene was prepared by the methodology described by Vaitiekunas and Nord.[23]

Table 4 Cross-coupling of **8** with alkynes

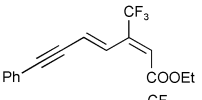
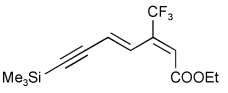
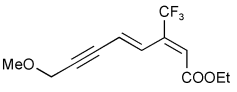
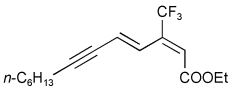
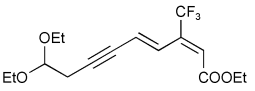
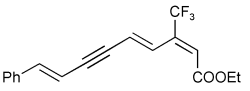
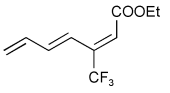
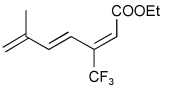
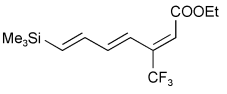
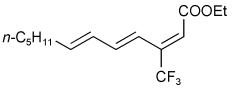
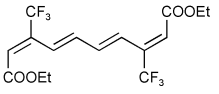
Entry	R	Product	Compound	Yield (%)
1	Ph		**9a**	75
2	Me_3Si		**9b**	48
3	$MeOCH_2$		**9c**	78
4	n-C_6H_{13}		**9d**	63
5	$(EtO)_2$–CH_2		**9e**	67
6	Ph		**9f**	71

Table 5 Cross-coupling of **8** with vinyltins

Entry	R_1	R_2	Product	Compound	Yield (%)
1	H	H		**10a**	68
2	Me	H		**10b**	83
3	H	Me_3Si		**10c (7g)**	67
4	H	n-C_5H_{11}		**10d**	75
5	H			**10e**	80

Ethyl (*Z*)-4,4,4-trifluoro-3-iodobut-2-enoate (2)

In a 100 mL flask, 14.6 mL (60 mmol) of an aqueous solution of hydroiodic acid (57%) were added dropwise to 8.3 g (50 mmol) of **1** in diethyl ether (50 mL). After stirring for 5 h at −5 °C, a 5% solution of $Na_2S_2O_3$ was added and the reaction mixture was then washed with brine and extracted with diethyl ether. The organic phases were dried over magnesium sulfate and concentrated, yielding (12.5 g, 40 mmol, 85%) of **2**, which was sufficiently pure to be used without purification. IR: 2991, 1735, 1638, 1267 cm^{-1}. ^1H NMR δ: 1.37 (3H, t, $J = 7.2$ Hz), 4.34 (2H, q, $J = 7.2$ Hz), 7.18 (1H, q, $J_{H-F} = 1.2$ Hz). ^{13}C NMR δ: 14, 61.7, 98.4 (q, $J_{C-F} = 37$ Hz), 120.7 (q, $J_{C-F} = 273$ Hz), 132 (q, $J_{C-F} = 5.3$ Hz), 163. MS (70 eV) m/z: 294 (M^+, 75), 266 (68), 249 (100), 221 (48), 127 (26), 103 (11), 94 (10), 75 (54), 69 (19), 53 (25), 45 (30), 43 (14). ^{19}F NMR δ: −69.2. Anal. Calcd for $C_6H_9F_3IO_2$: C, 30.02; H, 3.78; I, 52.87; found: C, 30.12; H, 3.79, I, 52.72.

General procedure to obtain ethyl dienoates

2 (2.94 g, 10 mmol) diluted in DMF (5 mL) is added dropwise to a DMF solution of vinyltin reagent (12 mmol). At the end of the addition, dichlorobis(acetonitrile)palladium(II) (78 mg, 0.3 mmol) is added. The mixture is stirred for 3 h at 25 °C then hydrolysed with a saturated solution of ammonium chloride. The aqueous layer is extracted with diethyl ether. After usual treatments, the crude products are purified using column chromatography on silica gel (petroleum ether–diethyl ether 70:30 as an eluent).

Ethyl (*E*)-3-trifluoromethylpenta-2,4-dienoate (3a). IR: 2964, 1726, 1648, 1260 cm^{-1}. ^1H NMR δ: 1.34 (3H, t, $J = 7.1$ Hz), 4.27 (2H, q, $J = 7.1$ Hz), 5.65 (1H, d, $J = 12$ Hz), 5.83 (1H, dq, $J = 18.3$ Hz, $J_{H-F} = 2.5$ Hz), 6.31 (1H, s), 7.50 (1H, dd, $J = 18.3$ Hz, $J = 12$ Hz). ^{13}C NMR δ: 14, 61, 121 (q, $J_{C-F} = 6$ Hz), 122.3 (q, $J_{C-F} = 276$ Hz), 124, 126, 140 (q, $J_{C-F} = 29$ Hz), 164.3. MS (70 eV) m/z: 194 (M^+, 19), 166 (100), 165 (35), 149 (51), 121 (64), 101 (70), 90 (37), 45 (11), 43 (16). ^{19}F NMR δ: −66.9. Anal. Calcd for $C_8H_9F_3O_2$: C, 49.49; H, 4.67; found: C, 49.42; H, 4.71.

Ethyl (*E*)-3-trifluoromethyl-5-methylhexa-2,4-dienoate (3b). IR: 2981, 1726, 1651, 1258 cm^{-1}. ^1H NMR δ: 1.26 (3H, t, $J = 6.8$ Hz), 1.61 (3H, s), 1.86 (3H, q, $J_{H-F} = 1.3$ Hz), 4.18 (3H, q, $J = 7.1$ Hz), 5.69 (1H, s), 6.37 (1H, s). ^{13}C NMR δ: 13.7, 19.4, 25.5, 60.6, 113.4, 122.5 (q, $J_{C-F} = 275$ Hz), 122.8 (q, $J_{C-F} = 5$ Hz), 139.7 (q, $J_{C-F} = 30$ Hz), 144.2, 164.2. MS (70 eV) m/z: 222 (M^+, 13), 207 (17), 179 (90), 177 (27), 149 (25), 130 (88), 129 (93), 127 (44), 85 (14), 83 (17), 80 (15), 79 (100), 78 (12), 75 (10), 65 (29), 59 (13), 43 (39). ^{19}F NMR δ: −71.7. Anal. Calcd for $C_{10}H_{13}F_3O_2$: C, 54.05; H, 5.90; found: C, 54.12; H, 5.88.

Ethyl (2*E*,4*E*)-7,7-diethoxy-3-trifluoromethylhepta-2,4-dienoate (3c). IR: 2977, 1725, 1647, 1200 cm^{-1}. ^1H NMR δ: 1.23 (6H, t, $J = 7.1$ Hz), 1.34 (3H, t, $J = 7.1$ Hz), 2.59 (2H, ddd, $J = 7.2$ Hz, $J = 5.9$ Hz, $J = 1.3$ Hz), 3.55 (2H, dq, $J = 7.0$ Hz, $J = 9.4$ Hz), 3.70 (2H, dq, $J = 7.0$ Hz, $J = 9.4$ Hz), 4.26 (2H, q, $J = 7.1$ Hz), 4.59 (1H, t, $J = 5.8$ Hz), 6.22 (1H, s), 6.25–6.43 (1H, dtq, $J = 16.5$ Hz, $J = 7.1$ Hz, $J_{H-F} = 2$ Hz), 7.35 (1H, bd, $J = 16.5$ Hz). ^{13}C NMR δ: 13.9, 15.1, 38.7, 60.8, 61.5, 101.8, 119.0 (q, $J_{C-F} = 6$ Hz), 122, 122.4 (q, $J_{C-F} = 276$ Hz), 136.9 (q, $J_{C-F} = 1.8$ Hz), 140.1 (q, $J_{C-F} = 29$ Hz), 164.6. MS (70 eV) m/z: 265 ($M^+ - OEt$, 3), 191 (10), 103 (97), 75 (78), 47 (100). ^{19}F NMR δ: −67.2. Anal. Calcd for $C_{14}H_{21}F_3O_4$: C, 54.19; H, 6.82; found: C, 54.15; H, 6.85.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-5-phenylpenta-2,4-dienoate (3d). IR: 3088, 2986, 1720, 1628, 1200 cm^{-1}. ^1H NMR δ: 1.39 (3H, t, $J = 7.1$ Hz), 4.33 (2H, q, $J = 7.1$ Hz), 6.34 (1H, s), 7.16 (1H, d, $J = 17.1$ Hz), 7.32–7.46 ($3H_{Ar}$, m), 7.56–7.61 ($2H_{Ar}$, m), 8.17 (1H, d, $J = 17.1$ Hz). ^{13}C NMR δ: 13.8, 61, 118.0, 119.5 (q, $J_{C-F} = 6$ Hz), 122.5 (q, $J_{C-F} = 277$ Hz), 127.5 (2C), 128.7 (2C) 129.4, 135.9, 138.2 (q, $J_{C-F} = 2$ Hz), 140.6 (q, $J_{C-F} = 29$ Hz), 164.8. MS (70 eV) m/z: 270 (M^+, 24), 225 (14), 197 (22), 196 (18), 177 (100), 77 (11), 51 (13). ^{19}F NMR δ: −66.7. Anal. Calcd for $C_{14}H_{13}F_3O_2$: C, 62.22; H, 4.85; found: C, 62.28; H, 4.87.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-5-trimethylsilylpenta-2,4-dienoate (3e). IR: 2963, 1725, 1637, 1251 cm^{-1}. ^1H NMR δ: 0.19 (9H, s), 1.37 (3H, t, $J = 7.1$ Hz), 4.29 (2H, q, $J = 7.1$ Hz), 6.31 (1H, s), 6.62 (1H, dq, $J = 20.1$ Hz, $J_{H-F} = 2$ Hz), 7.65 (1H, bd, $J = 20.1$ Hz). ^{13}C NMR δ: −1.2 (3C), 14.7, 61.7, 121.2 (q, $J_{C-F} = 6$ Hz), 123.1 (q, $J_{C-F} = 277$ Hz), 132.7, 141.3 (q, $J_{C-F} = 28$ Hz), 143.5, 165.2. MS (70 eV) m/z: 251 ($M^+ - Me$, 1), 237 (15), 174 (23), 146 (38), 79 (15), 75 (78), 73 (100), 45 (19), 43 (13). ^{19}F NMR δ: −66.8. Anal. Calcd for $C_{11}H_{17}F_3O_2Si$: C, 49.61; H, 6.43; found: C, 49.69; H, 6.41.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-5-tributylstannylpenta-2,4-dienoate (3f). IR: 2960, 1730, 1630, 1290 cm^{-1}. ^1H NMR δ: 0.83–1.72 (27H, m), 1.29 (3H, t, $J = 7.1$ Hz), 4.22 (2H, q, $J = 7.1$ Hz), 6.18 (1H, bs), 7.04 (1H, dq, $J = 20.4$ Hz,

J_{H-F} = 2.1 Hz, J_{Sn-H} = 60 Hz), 7.64 (1H, bd, J = 20.4 Hz, J_{Sn-H} = 64 Hz). ^{13}C NMR δ: 9.5 (J_{Sn-C} = 348–339 Hz, 3C), 13.5 (3C), 13.9, 27.1 (J_{Sn-C} = 54 Hz, 3C), 28.8 (J_{Sn-C} = 21 Hz, 3C), 60.8, 119.0 (q, J_{C-F} = 6.Hz), 122.4 (q, J_{C-F} = 277 Hz), 134.5 (J_{Sn-C} = 16 Hz), 140.2 (q, J_{C-F} = 27.Hz), 145.6 (J_{Sn-C} = 336–321 Hz), 164.5. MS (70 eV) m/z: 427 (M^+ – Bu, 100), 291 (9), 371 (26), 193 (19), 165 (59), 57 (51), 41 (90). ^{19}F NMR δ: −66.6.

Ethyl (2*E*,4*E*,6*E*)-3,6-bis(trifluoromethyl)octa-2,4,6-triene-1,8-dioate (3g). Mp: 88–90 °C. IR: 3050, 2980, 1740, 1655 cm^{-1}. ^{1}H NMR δ: 1.31 (6H, t, J = 7.1 Hz), 4.26 (4H, q, J = 7.1 Hz), 6.42 (2H, bq, J_{H-F} = 1 Hz), 7.96 (2H, bq, J_{H-F} = 1.5 Hz). ^{13}C NMR δ: 14.0, 61.6, 121.9 (q, J_{C-F} = 277 Hz), 124.3 (q, J_{C-F} = 6 Hz), 126.5 (q, J_{C-F} = 2.6 Hz), 139.2 (q, J_{C-F} = 29 Hz), 164.1. MS (70 eV) m/z: 360 (M^+, 14), 315 (16), 303 (19), 287 (27), 286 (53), 285 (83), 269 (50), 259 (32), 258 (100), 229 (29), 195 (42), 189 (22), 163 (48), 145 (69), 95 (26), 75 (35), 69 (43), 45 (34). ^{19}F NMR δ: −67.0. Anal. Calcd for $C_{14}H_{14}F_6O_4$: C, 46.68; H, 3.92; found: C, 46.59; H, 3.85.

Ethyl (2*E*)-7,7-diethoxy-3-trifluoromethylhept-2-en-4-ynoate (3h). IR: 2981, 2254, 1734, 1193 cm^{-1}. ^{1}H NMR δ: 1.17 (6H, t, J = 7.1 Hz), 1.27 (3H, t, J = 7.1 Hz), 2.77 (2H, d, J = 5.7 Hz), 3.53 (2H, dq, J = 9.3 Hz, J = 7.1 Hz), 3.70 (2H, dq, J = 9.3 Hz, J = 7.1 Hz), 4.21 (2H, q, J = 7.1 Hz), 4.70 (1H, t, J = 5.7 Hz), 6.53 (1H, bs). ^{13}C NMR δ: 14.0, 15.0, 26.4, 61.2, 62.1 (2C), 73.3, 100.2, 101.4, 120.8 (q, J_{C-F} = 275 Hz), 126 (q, J_{C-F} = 35 Hz), 127.8 (q, J_{C-F} = 4.3 Hz), 163.2. MS (70 eV) m/z: 263 (M^+ – OEt, 2), 103 (75), 75 (62), 47 (100). ^{19}F NMR δ: −70.9. Anal. Calcd for $C_{14}H_{19}F_3O_4$: C, 54.54; H, 6.21; found: C, 54.58; H, 6.18.

Ethyl (2*E*)-6,6-diethoxy-3-trifluoromethylhex-2-en-4-ynoate (3i). IR: 2980, 2930, 2220, 1735, 1635 cm^{-1}. ^{1}H NMR δ: 1.17 (6H, t, J = 7.1 Hz), 1.25 (3H, t, J = 7.1 Hz), 3.58 (2H, dq, J = 7.1 Hz, J = 9.5 Hz), 3.72 (2H, dq, J = 7.1 Hz, J = 9.5 Hz), 4.20 (2H, q, J = 7.1 Hz), 5.40 (1H, s), 6.58 (1H, bq, J_{H-F} = 1 Hz). ^{13}C NMR δ: 13.9, 14.9 (2C), 61.2 (2C), 61.5 (2C), 75.4, 91.3, 98.3, 120.7 (q, J_{C-F} = 275 Hz), 124.6 (q, J_{C-F} = 35 Hz), 130.1 (q, J_{C-F} = 4 Hz), 162.7. MS (70 eV) m/z: 249 (M^+ – OEt, 3), 103 (63), 75 (58), 47 (100). ^{19}F NMR δ: −71.3. Anal. Calcd for $C_{13}H_{17}F_3O_4$: C, 53.06; H, 5.82; found: C, 53.08; H, 5.79.

Ethyl (2*E*)-3-trifluoromethyl-6-(2′-thiophenyl)pent-2-en-4-ynoate (3j). IR: 3080, 2980, 2195, 1720, 1630 cm^{-1}. ^{1}H NMR δ: 1.33 (3H, t, J = 7.1 Hz), 4.28 (2H, q, J = 7.1 Hz), 6.57 (1H, q, J_{H-F} = 1.0 Hz), 7.02 (1H, bt, J = 4.1 Hz), 7.38–7.43 (2H, m). ^{13}C NMR δ: 14.1, 61.4, 85.0, 96.9, 120.8 (q, J_{C-F} = 276 Hz), 121.0, 125.6 (q, J_{C-F} = 35 Hz), 127.1 (q, J_{C-F} = 4.5 Hz), 127.5, 130.3, 134.7, 163.3. ^{19}F NMR δ: −66.8. Anal. Calcd for $C_{12}H_9F_3O_2S$: C, 52.55; H, 3.31; found: C, 52.59; H, 3.33.

Synthesis of γ-trifluoromethyldienoic alcohols 4

Di-isobutylaluminium hydride (DIBAL-H; 6.9 mL, 2.3 equiv., 1 M in hexane) was added dropwise to a 25 mL freezing (−78 °C) solution of THF containing 3 mmol of ester **3** in a 50 mL flask under argon. After being stirred 4 h at −60 °C, the mixture was hydrolysed with a saturated solution of ammonium chloride, then a 10% solution of HCl was added. The mixture was extracted with diethyl ether and methylene chloride. After usual treatments, the crude products **4** were purified using column chromatography on silica gel (diethyl ether–ethyl acetate 80:20 as an eluent).

(2*E*)-3-Trifluoromethylpenta-2,4-dienol (4a). IR: 3355, 2950, 1613, 1140, 1045 cm^{-1}. ^{1}H NMR δ: 3.17 (1H, bs), 4.41 (2H, dq, J = 6.0 Hz, J_{H-F} = 2 Hz), 5.43–5.54 (2H, m), 6.28–6.42 (1H + 1H, m). ^{13}C NMR δ: 58.1, 120.9, 122.8 (q, J_{C-F} = 274 Hz), 125.5, 128.8 (q, J_{C-F} = 29 Hz), 134.1 (q, J_{C-F} = 6 Hz). MS (70 eV) m/z: 152 (M^+, 1), 132 (28), 104 (100), 103 (48), 83 (42), 77 (33), 57 (20), 55 (59), 53 (38), 40 (36), 39 (55). ^{19}F NMR δ: −68.7. Anal. Calcd for $C_6H_7F_3O$: C, 47.38; H, 4.64; found: C, 47.29; H, 4.68.

(2*E*,4*E*)-3-Trifluoromethyl-5-phenylpenta-2,4-dienol (4b). IR: 3340, 3060, 3020, 1500, 1170, 1120 cm^{-1}. ^{1}H NMR δ: 3.00 (1H, bs), 4.48 (2H, bd, J = 4.4 Hz), 6.34 (1H, J = 6.1 Hz, J_{H-F} = 1.1 Hz), 6.70 (1H, d, J = 16.6 Hz), 6.82 (1H, d, J = 16.6 Hz), 7.30–7.46 (5H$_{Ar}$, m). ^{13}C NMR δ: 58.5, 117.1, 123.1 (q, J_{C-F} = 274 Hz), 126.7 (2C), 128.7 (3C), 128.8 (q, J_{C-F} = 29 Hz), 133.7 (q, J_{C-F} = 6 Hz), 134.8, 136.1. MS (70 eV) m/z: 228 (M^+, 33), 210 (13), 178 (14), 177 (20), 159 (56), 141 (23), 128 (33), 115 (30), 104 (100), 91 (90), 77 (29), 51 (35), 39 (18). ^{19}F NMR δ: −68.0. Anal. Calcd for $C_{12}H_{11}F_3O$: C, 63.16; H, 4.86; found: C, 63.19; H, 4.89.

(2*E*,4*E*)-3-Trifluoromethyl-5-trimethylsilylpenta-2,4-dienol (4c). IR: 3320, 2960, 1170, 1120 cm^{-1}. ^{1}H NMR δ: 0.10 (9H, s), 2.29 (1H, bs), 4.41 (2H, bd), 6.11 (1H, dq, J = 19.5 Hz, J_{H-F} = 1.5 Hz), 6.26 (1H, bt, J = 6 Hz), 6.42 (1H, bd, J = 19.5 Hz). ^{13}C NMR δ: −1.2 (3C), 58.5, 123 (q, J_{C-F} = 275 Hz), 130.1 (q, J_{C-F} = 28.Hz), 131.5, 133.9 (q, J_{C-F} = 6 Hz), 139.0. MS (70 eV) m/z: 209 (M^+ – Me, 2), 115 (22), 104 (23), 85 (16), 77 (31), 73 (100), 45 (28). ^{19}F NMR δ: −68.5. Anal. Calcd for $C_9H_{15}F_3OSi$: C, 48.19; H, 6.74; found: C, 48.25; H, 6.71.

(2*E*,4*E*)-7,7-Diethoxy-3-trifluoromethylhepta-2,4-dienol (4d). IR: 3400, 2990, 1660, 1170, 1120, 1050 cm^{-1}. ^{1}H NMR δ: 1.14 (6H, t, J = 7.0 Hz), 2.42 (2H, dd, J = 6.2 Hz), 3.02 (1H, bs), 3.45 (2H, dq, J = 6.9 Hz, J = 9.4 Hz), 3.61 (2H, dq, J = 6.9 Hz, J = 9.4 Hz), 4.31 (2H, bd, J = 4.0 Hz), 4.47 (1H, t, J = 5.8 Hz), 5.81 (1H, dt, J = 16.3 Hz, J = 6.7 Hz), 6.01 (1H, d, J = 16.3 Hz), 6.18 (1H, bt, J = 5.7 Hz). ^{13}C NMR δ: 15.0 (2C), 38.1, 58.1, 61.6 (2C), 102.0, 121.4, 123.0 (q, J_{C-F} = 274 Hz), 128.2 (q, J_{C-F} = 29 Hz), 132.3, 133.2 (q, J_{C-F} = 6 Hz). MS (70 eV) m/z 223 (M^+ – OEt, 4), 103 (61), 75 (58), 47 (100). ^{19}F NMR δ: −68.7. Anal. Calcd for $C_{12}H_{19}F_3O_3$: C, 53.72; H, 7.14; found: C, 53.68; H, 7.16.

Synthesis of β-trifluoromethyldienoic acids 5

Ester **3** (2 mmol) was added to a 50:50 solution of ethanol and water (10 mL) containing 7.2 mg (3 mmol) of lithium hydroxide in a 50 mL flask. The mixture was stirred overnight at room temperature After evaporation of ethanol, acidification of the aqueous phase, extraction with diethyl ether, washing with brine, drying ($MgSO_4$) and evaporation of the solvent, the crude acids **5** obtained were purified by crystallisation (hexane–diethyl ether 95:5).

(*E*)-3-Trifluoromethyl-5-methylhexa-2,4-dienoic acid (5a). Mp: 58–60 °C. IR: 3141, 3095, 2991, 2954, 2926, 1700, 1657, 1290 cm^{-1}. ^{1}H NMR δ: 1.69 (3H, s), 1.93 (3H, q, J_{H-F} = 1.1 Hz), 5.77 (1H, s), 6.44 (1H, s), 9.67 (1H, bs). ^{13}C NMR δ: 19.9, 26.0, 113.2, 121.6 (q, J_{C-F} = 5 Hz), 122.3 (q, J_{C-F} = 276 Hz), 141.7 (q, J_{C-F} = 30 Hz), 145.6, 169.8. MS (70 eV) m/z: 194 (M^+, 26), 179 (100), 146 (45), 129 (89), 127 (43), 109 (38), 103 (31), 83 (17), 69 (19), 45 (18), 43 (21), 41 (28). ^{19}F NMR δ: −71.7. Anal. Calcd for $C_8H_9F_3O_2$: C, 49.49; H, 4.67; found: C, 49.55; H, 4.68.

(2*E*,4*E*)-7,7-Diethoxy-3-trifluoromethylhepta-2,4-dienoic acid (5b). Mp: 96–98 °C. IR: 2983, 1707, 1648, 1177 cm^{-1}. ^{1}H NMR δ: 1.24 (6H, t, J = 7.0 Hz), 2.62 (2H, t, J = 6.4 Hz), 3.55 (2H, dq, J = 9.2 Hz, J = 7.2 Hz), 3.72 (2H, dq, J = 9.2

Hz, $J = 7.1$ Hz), 4.63 (1H, t, $J = 5.7$ Hz), 6.26 (1H, s), 6.27–6.48 (1H, m), 7.41 (1H, bd, $J = 16.5$ Hz), 7.50 (1H, bs). ^{13}C NMR δ: 15.0, 38.6, 61.6, 101.6, 118.3, 121.0, 122.2 (q, $J_{C-F} = 277$ Hz), 137.8, 141.7 (q, $J_{C-F} = 29$ Hz), 169. MS (70 eV) m/z: 237 ($M^+ - OEt$, 15), 191 (30), 115 (25), 103 (96), 75 (74), 47 (100), 45 (21), 43 (24), 41 (11). ^{19}F NMR δ: −67.1. Anal. Calcd for $C_{12}H_{17}F_3O_4$: C, 51.06; H, 6.07; found: C, 51.11; H, 6.05.

(2*E*,4*E*)-3-Trifluoromethyl-5-trimethylsilylpenta-2,4-dienoic acid (5c). Mp: 62–64 °C. IR: 2965, 1709, 1634, 1233 cm^{-1}. ^{1}H NMR δ: 0.19 (9H, s), 6.35 (1H, s), 6.70 (1H, dq, $J = 20.0$ Hz, $J_{H-F} = 2$ Hz), 7.64 (1H, bd, $J = 20$ Hz), 8.83 (1H, bs). ^{13}C NMR δ: −1.3 (3C), 120.0 (q, $J_{C-F} = 6$ Hz), 122.9 (q, $J_{C-F} = 277$ Hz), 132.4, 143.6 (q, $J_{C-F} = 28$ Hz), 145.3, 170.5. MS (70 eV) m/z: 223 ($M^+ - Me$, 4), 146 (75), 75 (100), 73 (54), 45 (23), 43 (18). ^{19}F NMR δ:−66.9. Anal. Calcd for $C_9H_{13}F_3O_2Si$: C, 45.37; H, 5.50; found: C, 45.32; H, 5.58.

(2*E*,4*E*,6*E*)-3,6-Ditrifluoromethylocta-2,4,6-trienedioic acid (5d). Mp: 114–116 °C. IR: 3155, 3083, 2984, 1713, 1648 cm^{-1}. ^{1}H NMR δ: 4.20 (2H, bs), 6.64 (2H, s), 7.78 (2H, s). ^{13}C NMR δ: 122.7 (q, $J_{C-F} = 276$ Hz), 125.3 (q, $J_{C-F} = 2.3$ Hz), 128.0 (q, $J_{C-F} = 6$ Hz), 135.7 (q, $J_{C-F} = 29$ Hz), 165.5. MS (70 eV) m/z: 304 (M^+, 13), 286 (32), 259 (16), 258 (100), 189 (42), 165 (29), 163 (33), 150 (36), 75 (46), 69 (49), 45 (46). Anal. Calcd for $C_{10}H_6F_6O_4$: C, 39.49; H, 1.99; found: C, 39.53; H, 2.04.

Halolactonisation[18b]

4-Trifluoromethyl-5-iodotrimethylsilylmethyl-5*H*-furan-2-one (6a). Mp: 74–76 °C. IR: 3098, 2961, 2856, 1797, 1770, 1634, 1351, 1245 cm^{-1}. ^{1}H NMR δ: 0.17 (9H, s), 3.53 (1H, d, $J = 3$ Hz), 5.59–5.63 (1H, m), 6.62 (1H, bs). ^{13}C NMR δ: 0.4, 13.5, 86.5, 120.5 (q, $J_{C-F} = 271$ Hz), 125.8 (q, $J_{C-F} = 4$ Hz), 154.9 (q, $J_{C-F} = 36$ Hz), 167.8. MS (70 eV) m/z: 236 ($M^+ - HI$, 2), 221 (27), 193 (16), 97 (60), 84 (30), 77 (100), 75 (80), 69 (26), 47 (16), 45 (22), 43 (26). ^{19}F NMR δ: −67.2. Anal. Calcd for $C_9H_{12}F_3IO_2Si$: C, 29.68; H, 3.32; found: C, 29.74; H, 3.37.

(*Z*)-4-Trifluoromethyl-5-trimethylsilylmethylidene-5*H*-furan-2-one (6b). IR: 2962, 1792, 1762, 1628 cm^{-1}. ^{1}H NMR δ: 0.24 (9H, s), 5.69 (1H, bs), 6.56 (1H, bs); ^{13}C NMR δ: −0.4 (3C), 118.1, 120.5 (q, $J_{C-F} = 258$ Hz), 122.1 (q, $J_{C-F} = 3$ Hz), 144.2 (q, $J_{C-F} = 37$ Hz), 152.9, 166.6. MS (70 eV) m/z: 236 (M^+, 7), 221 (100), 208 (37), 193 (30), 97 (43), 84 (19), 77 (62), 75 (50), 69 (11). ^{19}F NMR δ: −68.8. Anal. Calcd for $C_9H_{11}F_3O_2Si$: C, 45.75; H, 4.69; found: C, 45.78; H, 4.64.

Cross-coupling of 3f with organic halides

Toluene (10 mL) , 2.5 g (5.2 mmol) of **3f**, 5 mmol of organic halide and 23 mg (5% mol) of tetrakis(triphenylphosphine)palladium(0) are introduced into a 50 mL flask. The mixture is degassed under vacuum and stirred at 80 °C for 6 h. After cooling, the mixture is hydrolysed with 10 mL of a 1 M solution of potassium fluoride and 10 mL of acetone to precipitate the tributyltin halide formed. After vigorous stirring for 2 h, the reaction mixture is filtered and extracted with diethyl ether. After removal of the solvents under reduced pressure, the crude products **7** are purified using column chromatography on silica gel (petroleum ether–diethyl ether 95:5 as an eluent).

Ethyl (2*E*,4*E*)-3-trifluoromethyl-5-(4′-formylphenyl)penta-2,4-dienoate (7a). IR: 3052, 2834, 1692, 1680 cm^{-1}. ^{1}H NMR δ: 1.32 (3H, t, $J = 7.1$ Hz), 4.26 (2H, q, $J = 7.1$ Hz), 6.34 (1H, q, $J_{H-F} = 0.7$ Hz), 7.10 (1H, dq, $J = 17.0$ Hz, $J_{H-F} = 1.5$ Hz), 7.65 (2H$_{Ar}$, d, $J = 8.4$ Hz), 7.85 (2H$_{Ar}$, d, $J = 8.4$ Hz), 8.22 (1H, dq, $J = 17.0$ Hz, $J_{H-F} = 1$ Hz), 10 (1H, s). ^{13}C NMR δ: 14.5, 61.7, 121.4, 121.8 (q, $J_{C-F} = 6$ Hz), 122.8 (q, $J_{C-F} = 277$ Hz), 128.4 (2C), 130.6 (2C), 137.0, 140.5 (q, $J_{C-F} = 29$ Hz), 142.2, 143.1, 165.1, 191.9. MS (70 eV) m/z: 298 (M^+, 66), 253 (22), 225 (24), 205 (80), 197 (36), 178 (14), 177 (100), 128 (43), 126 (16), 77 (18). ^{19}F NMR δ: −66.9. Anal. Calcd for $C_{15}H_{13}F_3O_3$: C, 60.40; H, 4.39; found: C, 60.45; H, 4.35.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-5-(2′-thiophenyl)penta-2,4-dienoate (7b). IR: 3092, 2993, 1715, 1622, 1598 cm^{-1}. ^{1}H NMR δ: 1.32 (3H, t, $J = 7.1$ Hz), 4.25 (2H, q, $J = 7.1$ Hz), 6.22 (1H, s), 7.01 (1H, bt, $J = 4.5$ Hz), 7.16 (1H, bd, $J = 4.5$ Hz), 7.21 (1H, bd, $J = 16.5$ Hz), 7.31 (1H, d, $J = 4.5$ Hz), 7.92 (1H, d, $J = 16.5$ Hz). ^{13}C NMR δ:14.6, 61.5, 117.9, 119.4 (q, $J_{C-F} = 6$ Hz), 123.0 (q, $J_{C-F} = 277$ Hz), 128.0, 128.5, 129.0, 131.7, 140.7 (q, $J_{C-F} = 29$ Hz), 142.2, 165.4. MS (70 eV) m/z: 276 (M^+, 45), 231 (19), 203 (47), 183 (100), 135 (14), 134 (30), 69 (11), 45 (18). ^{19}F NMR δ: −66.7. Anal. Calcd for $C_{12}H_{11}F_3O_2S$: C, 52.17; H, 4.01; found: C, 52.19; H, 3.98.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-5-(2′-nitrophenyl)penta-2,4-dienoate (7c). IR: 3091, 2987, 1714, 1633, 1525 cm^{-1}. ^{1}H NMR δ: 1.31 (3H, t, $J = 7.1$ Hz), 4.25 (2H, q, $J = 7.1$ Hz), 6.38 (1H, q, $J_{H-F} = 0.6$ Hz), 7.46 (1H, bdt, $J = 7.7$ Hz, $J = 1.6$ Hz), 7.57 (1H, bt, $J = 17.6$ Hz), 7.62 (1H, bdt, $J = 7.6$ Hz, $J = 1.3$ Hz), 7.72 (1H, dd, $J = 7.8$ Hz, $J = 1.5$ Hz), 7.98 (1H, bd, $J = 17.6$ Hz), 8.00 (1H, dd, $J = 8.2$ Hz, $J = 1.2$ Hz). ^{13}C NMR δ: 14.5, 61.7, 122.3 (q, $J_{C-F} = 6$ Hz), 122.7 (q, $J_{C-F} = 277$ Hz), 122.7, 125.3, 129.3, 130.0, 132.6, 134.0, 134.2, 140.5 (q, $J_{C-F} = 30$ Hz), 148.6, 165.1. MS (70 eV) m/z: 315 (M^+, 1), 270 (26), 252 (23), 152 (27), 134 (43), 120 (100), 119 (26), 104 (36), 102 (15), 92 (87), 91 (19), 77 (33), 65 (28), 63 (20). ^{19}F NMR δ: −67.2. Anal. Calcd for $C_{14}H_{12}F_3NO_4$: C, 53.34; H, 3.84; found: C, 53.36; H, 3.87.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-5-(4′-fluorophenyl)penta-2,4-dienoate (7d). IR: 3080, 2960, 1725, 1630, 1600 cm^{-1}. ^{1}H NMR δ: 1.32 (3H, t, $J = 7.1$Hz), 4.25 (2H, q, $J = 7.1$ Hz), 6.27 (1H, s), 7.00 (2H, t, $J = 8.6$ Hz), 7.05 (1H, bd, $J = 17.1$ Hz), 7.50 (2H, dd, $J = 8.6$ Hz, $J_{H-F} = 5.7$ Hz), 8.04 (1H, d, $J = 17.1$ Hz). ^{13}C NMR δ: 14.1, 61.1, 115.9 (2C, d, $J_{C-F} = 22$ Hz), 117.8 (d, $J_{C-F} = 3$ Hz), 119.6 (q, $J_{C-F} = 6$ Hz), 122.5 (q, $J_{C-F} = 277$ Hz), 129.3 (2C, d, $J_{C-F} = 8$ Hz), 132.2, 137.0, 140.6 (q, $J_{C-F} = 29$ Hz), 163.4 (d, $J_{C-F} = 250$ Hz), 164.9 (q, $J_{C-F} = 0.8$ Hz). MS (70 eV) m/z: 288 (M^+, 36), 243 (16), 215 (23), 195 (100), 146 (34), 120 (10). ^{19}F NMR δ: −114.6, −66.9. Anal. Calcd for $C_{14}H_{12}F_4O_2$: C, 58.34; H, 4.20; found: C, 58.41; H, 4.25.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-5-(3′-trifluoromethylphenyl)-penta-2,4-dienoate (7e). IR: 3100, 3000, 1740, 1650 cm^{-1}. ^{1}H NMR δ: 1.33 (3H, t, $J = 7.1$ Hz), 4.27 (2H, q, $J = 7.1$ Hz), 6.33 (1H, s), 7.10 (1H, dq, $J = 17.1$ Hz, $J_{H-F} = 1.5$ Hz), 7.42–7.72 (4H, m), 8.14 (1H, d, $J = 17.1$ Hz). ^{13}C NMR δ: 14.1, 61.3, 119.7, 120.9 (q, $J_{C-F} = 6$ Hz), 122.5 (q, $J_{C-F} = 276$ Hz), 123.9 (q, $J_{C-F} = 272$ Hz), 124.4 (q, $J_{C-F} = 4$ Hz), 125.8 (q, $J_{C-F} = 4$ Hz), 129.3, 130.2 (q, $J_{C-F} = 1.5$ Hz), 131.3 (q, $J_{C-F} = 32$ Hz), 136.5 (q, $J_{C-F} = 2$ Hz), 136.8 (q, $J_{C-F} = 0.8$ Hz), 140.1 (q, $J_{C-F} = 29$ Hz), 164.7 (q, $J_{C-F} = 1$ Hz). MS (70 eV) m/z: 338 (M^+, 39), 293 (18), 265 (23), 246 (17), 245 (100), 196 (17), 177 (26), 146 (11). ^{19}F NMR δ: −67.0, −66.1. Anal. Calcd for $C_{15}H_{12}F_6O_2$: C, 53.26; H, 3.58; found: C, 53.29; H, 3.57.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-5-tosylpenta-2,4-dienoate (7f). IR: 2960, 1730, 1630, 1290 cm^{-1}. ^{1}H NMR δ: 1.31 (3H, t, $J = 7.1$ Hz), 2.40 (3H, s), 4.27 (2H, q, $J = 7.1$ Hz), 6.54 (1H, s), 6.78 (1H, dq, $J = 16.2$ Hz, $J_{H-F} = 1.3$ Hz), 7.32 (2H$_{Ar}$, d, $J = 8.1$ Hz), 7.76 (2H$_{Ar}$, d, $J = 8.1$ Hz), 8.29 (1H, bd, $J = 16.2$ Hz). ^{13}C NMR δ:14.6, 22.2, 62.7, 122.2 (q,

J_{C-F} = 276 Hz), 128.7 (2C), 128.8 (q, J_{C-F} = 6 Hz), 129.6, 130.7 (2C), 136.4 (q, J_{C-F} = 31 Hz), 136.8, 137.0, 145.8, 163.8. MS (70 eV) *m/z*: 193 (41), 165 (100), 139 (21), 91 (40), 77 (13), 65 (40), 51 (17), 39 (25). ^{19}F NMR δ: −68.2. Anal. Calcd for $C_{15}H_{15}F_3O_4S$: C, 51.72; H, 4.34; found: C, 51.76; H, 4.28.

Ethyl (2*E*,4*E*,6*E*)-3-trifluoromethyl-7-trimethylsilylhepta-2,4,6-trienoate (7g). IR: 2950, 1710, 1620 cm^{-1}. ^{1}H NMR δ: 0.08 (9H, s), 1.30 (3H, t, J = 7.1 Hz), 4.22 (2H, t, J = 7.1 Hz), 6.20 (1H, s), 6.22 (1H, d, J = 17.6 Hz), 6.62 (1H, dd, J = 17.6 Hz, J = 10 Hz), 6.72 (1H, ddq, J = 15.4 Hz, J = 10 Hz, J_{H-F} = 2 Hz), 7.46 (1H, d, J = 15.4 Hz). ^{13}C NMR δ: − 1.6 (3C), 14.1, 61, 119.6 (q, J_{C-F} = 6 Hz), 121.8, 122.4 (q, J_{C-F} = 277 Hz), 140.8 (q, J_{C-F} = 29 Hz), 141 (q, J_{C-F} = 2 Hz), 142.6, 143.7 (q, J_{C-F} = 0.7 Hz), 164.8. MS (70 eV) *m/z*: 292 (M^+, 10), 127 (29), 103 (21), 81 (30), 79 (11), 77 (100), 59 (21), 45 (15), 43 (14). ^{19}F NMR δ: −67. Anal. Calcd for $C_{13}H_{19}F_3O_2Si$: C, 53.40; H, 6.55; found: C, 53.43; H, 6.56.

Synthesis of ethyl (2*E*,4*E*)-3-trifluoromethyl-5-iodopenta-2,4-dienoate, 8

Iodine (2.54 g, 10 mmol) was dissolved in 50 mL of diethyl ether, then a 30 mL solution of diethyl ether containing 9 mmol of **3f** was added dropwise in a 200 mL flask at 0 °C. After 2 h, the mixture was hydrolysed with 30 mL of a 1 M solution of potassium fluoride and 25 mL of ethyl acetate to precipitate the tributyltin iodide formed. The mixture was filtered through a celite pad and extracted with diethyl ether. The organic phases were washed with a 5% solution of sodium thiosulfate and dried over magnesium sulfate. Removal of the solvents under reduced pressure yielded **8**, purified by column chromatography (hexane–diethyl ether 95:5). IR: 2963, 1723, 1633, 1220 cm^{-1}. ^{1}H NMR δ: 1.30 (3H, t, J = 7.1 Hz), 4.22 (2H, q, J = 7.1 Hz), 6.20 (1H, m), 7.26 (1H, ddq, J = 15.6 Hz, J = 0.6 Hz, J_{H-F} = 2 Hz), 8.32 (1H, ddq, J = 15.6 Hz, J = 1 Hz, J_{H-F} = 1 Hz). ^{13}C NMR δ: 13.9, 61.4, 90.8, 120.2 (q, J_{C-F} = 6 Hz), 121.8 (q, J_{C-F} = 276 Hz), 134.0, 139.1 (q, J_{C-F} = 30 Hz), 164.0. MS (70 eV) *m/z*: 275 (M^+ − OEt, 10), 193 (30), 165 (100), 120 (22), 89 (13), 69 (12), 51 (21), 50 (13). ^{19}F NMR δ: −67.2. Anal. Calcd for $C_8H_8F_3IO_2$: C, 30.02; H, 2.52; found: C, 29.86; H, 2.42.

Heck–Sonogashira cross-coupling of 8 with alkynes

n-Butylamine (1 mL, 10 mmol) under argon atmosphere was added to a solution of 6.3 mmol of alcyne in THF (120 mL). The solution was stirred for 15 min at room temperature, followed by addition of 4.2 mmol of **8**, 217 mg (0.31 mmol) of dichlorobis(triphenylphosphine)palladium(II) and 59 mg (0.31 mmol) of copper(I) iodide. The resulting mixture was stirred at room temperature for 6 h and then poured into water, extracted with diethyl ether, washed with a saturated solution of ammonium chloride and dried over magnesium sulfate. The residue **9** was purified by column chromatography on silica gel (hexane–diethyl ether 30:70 as eluant).

Ethyl (2*E*,4*E*)-3-trifluoromethyl-7-phenylhepta-2,4-dien-6-ynoate (9a). IR: 3090, 2990, 2200, 1725, 1625, 1490, 1320, 1200, 1130 cm^{-1}. ^{1}H NMR δ: 1.31 (3H, t, J = 7.1 Hz), 4.25 (2H, q, J = 7.1 Hz), 6.26 (1H q, J_{H-F} = 1 Hz), 6.43 (1H, ddq, J = 16.9 Hz, J_{H-F} = 1.8 Hz, J = 0.7 Hz), 7.29–7.35 (3H, m), 7.44–7.50 (2H, m), 7.92 (1H, ddq, J = 16.9 Hz, J = 1.3 Hz, J_{H-F} = 1 Hz). ^{13}C NMR δ: 13.9, 61.1, 88.3, 97.2, 118.7 (q, J_{C-F} = 2.5 Hz), 120.8 (q, J_{C-F} = 6 Hz), 122.2 (q, J_{C-F} = 276 Hz), 122.5, 128.3 (2C), 128.9, 129.7, 131.7 (2C), 139.3 (q, J_{C-F} = 30 Hz), 164.2. MS (70 eV) *m/z*: 294 (M^+, 9), 266 (11), 201 (14), 152 (15), 105 (100), 77 (13). ^{19}F NMR δ: −66.9. Anal. Calcd for $C_{16}H_{13}F_3O_2$: C, 58.34; H, 4.20; found: C, 58.41; H, 4.25.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-7-trimethylsilylhepta-2,4-dien-6-ynoate (9b). IR: 3080, 2130, 1725, 1628, 1585 cm^{-1}. ^{1}H NMR δ: 0.24 (9H, s), 1.36 (3H, t, J = 7.1 Hz), 4.29 (2H, q, J = 7.1 Hz), 6.22 (1H, d, J = 17.1 Hz), 6.29 (1H, s), 7.84 (1H, d, J = 17.1 Hz). ^{13}C NMR δ: −0.5 (3C), 13.9, 61.1, 103.1, 103.2, 118.5 (q, J_{C-F} = 2.5 Hz), 121.2 (q, J_{C-F} = 6 Hz), 122.0 (q, J_{C-F} = 276 Hz), 130.5, 139.2 (q, J_{C-F} = 30 Hz), 161.1. MS (70 eV) *m/z*: 290 (M^+, 32), 262 (32), 245 (16), 229 (28), 203 (28), 198 (23), 193 (21), 115 (19), 103 (18), 101 (30), 91 (22), 81 (30), 75 (75), 73 (27), 47 (13), 45 (14), 43 (25). ^{19}F NMR δ: −67.0. Anal. Calcd for $C_{13}H_{17}F_3O_2Si$: C, 53.78; H, 5.90; found: C, 53.41; H, 5.85.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-8-methoxyocta-2,4-dien-6-ynoate (9c). IR: 3090, 2985, 2235, 1730, 1627 cm^{-1}. ^{1}H NMR δ: 1.28 (3H, t, J = 7.1 Hz), 3.37 (3H, s), 4.22 (2H, q, J = 7.1 Hz), 4.23 (2H, s), 6.17 (1H, dq, J = 16.8 Hz, J_{H-F} = 2 Hz), 6.23 (1H, q, J_{H-F} = 1 Hz), 7.74 (1H, dq, J = 16.8 Hz, J_{H-F} = 1.5 Hz). ^{13}C NMR δ: 14.5, 58.2, 60.7, 61.7, 85.4, 93.1, 118.4, 121.9 (q, J_{C-F} = 6 Hz), 122.6 (q, J_{C-F} = 276 Hz), 130.8, 139.5 (q, J_{C-F} = 30 Hz), 164.6. MS (70 eV) *m/z*: 262 (M^+, 42), 217 (29), 203 (22), 190 (13), 189 (100), 175 (10), 174 (14), 152 (17), 145 (24), 141 (22), 127 (32), 109 (18), 91 (17), 85 (20), 75 (12), 63 (28), 59 (15), 45 (32). ^{19}F NMR δ: −67.9. Anal. Calcd for $C_{12}H_{13}F_3O_3$: C, 54.96; H, 5.00; found: C, 53.81; H, 4.95.

Ethyl (2*E*,4*E*)-3-trifluoromethyltrideca-2,4-dien-6-ynoate (9d). IR: 3081, 2932, 2210, 1718, 1625 cm^{-1}. ^{1}H NMR δ: 0.87 (3H, t, J = 6.6 Hz), 1.22–1.58 (8H, m), 1.29 (3H, *t*, J = 7.1 Hz), 2.34 (2H, dt, J = 6.9 Hz, J = 2.2 Hz), 4.22 (2H, q, J = 7.1 Hz), 6.14 (1H, dq, J = 16.5 Hz, J_{H-F} = 2 Hz), 6.19 (1H, s), 7.67 (1H, d, J = 16.5 Hz). ^{13}C NMR δ: 14.6, 14.7, 20.4, 23.1, 29.0, 29.2, 31.9, 61.8, 80.4, 100.1, 120.4 (q, J_{C-F} = 2 Hz), 120.7 (q, J_{C-F} = 6 Hz), 122.9 (q, J_{C-F} = 276 Hz), 129.5, 140.2 (q, J_{C-F} = 59 Hz), 165.0. MS (70 eV) *m/z*: 302 (M^+, 5), 165 (11), 159 (19), 109 (11), 91 (18), 69 (20), 67 (21), 57 (15), 55 (43), 43 (88), 41 (100), 39 (33). ^{19}F NMR δ: −66.9. Anal. Calcd for $C_{16}H_{21}F_3O_2$: C, 63.56; H, 7.00; found: C, 63.41; H, 6.88.

Ethyl (2*E*,4*E*)-9,9-diethoxy-3-trifluoromethylnona-2,4-dien-6-ynoate (9e). IR: 2990, 2225, 1730, 1595 cm^{-1}. ^{1}H NMR δ: 1.20 (6H, t, J = 7.1 Hz), 1.28 (3H, t, J = 7.1 Hz), 2.69 (2H, dd, J = 5.5 Hz, J = 2.2 Hz), 3.53 (2H, dq, J = 7.1 Hz, J = 9.4 Hz), 3.66 (2H, dq, J = 7.1 Hz, J = 9.4 Hz), 4.21 (2H, q, J = 7.1 Hz), 4.64 (1H, t, J = 5.5 Hz), 6.14 (1H, bdq, J = 17.1 Hz, J_{H-F} = 2 Hz), 6.19 (1H, s), 7.67 (1H, dq, J = 17.1 Hz, J_{H-F} = 0.6 Hz). ^{13}C NMR δ: 14.7, 15.8, 26.7, 61.8, 62.6, 81.6, 94.5, 101.2, 119.9 (q, J_{C-F} = 2.5 Hz), 121.2 (q, J_{C-F} = 6 Hz), 122.8 (q, J_{C-F} = 276 Hz), 130.1, 140.0 (q, J_{C-F} = 29 Hz), 164.9. MS (70 eV) *m/z*: 289 (12), 103 (62), 75 (57), 47 (100). ^{19}F NMR δ: −67.0. Anal. Calcd for $C_{16}H_{21}F_3O_4$: C, 57.48; H, 6.33; found: C, 57.41; H, 6.45.

Ethyl (2*E*,4*E*,8*E*)-3-trifluoromethyl-9-phenylnona-2,4,8-trien-6-ynoate (9f). IR: 3074, 2992, 2240, 1725, 1620 cm^{-1}. ^{1}H NMR δ: 1.39 (3H, t, J = 7.1 Hz), 4.32 (2H, q, J = 7.1 Hz), 6.32 (1H, s), 6.39 (1H, dd, J = 16.3 Hz, J = 1.8 Hz), 6.44 (1H, bd, J = 16.8 Hz), 7.10 (1H, d, J = 16.3 Hz), 7.27–7.50 ($5H_{Ar}$, m), 7.91 (1H, d, J = 16.8 Hz). ^{13}C NMR δ: 14.6, 61.7, 91.5, 97.6, 108.1, 119.4 (q, J_{C-F} = 2 Hz), 121.1 (q, J_{C-F} = 6 Hz), 122.7 (q, J_{C-F} = 277 Hz), 127.0 (2C), 129.2 (2C), 129.5, 130.1, 136.4, 139.9 (q, J_{C-F} = 30 Hz), 143.6, 164.8. MS (70 eV) *m/z*: 320 (M^+, 38), 272 (10), 247 (58), 246 (50), 228 (31), 227 (72), 179 (28), 178 (100), 177 (21), 152 (21), 139 (22), 131 (50), 115 (48), 103 (14), 77 (13), 51 (14). ^{19}F NMR δ: −66.8. Anal. Calcd for $C_{18}H_{15}F_3O_2$: C, 67.50; H, 4.72; found: C, 67.41; H, 4.81.

Stille coupling of 8 with vinyltin reagents

8 (1.60 g, 5 mmol), (*E*)-1-trimethylsilyl-2-*n*-tributylstannylethylene (2.14 g, 5.5 mmol) and 65 mg (0.25 mmol) of dichlorobis(acetonitrile)palladium(II) diluted in DMF (15 mL) were mixed in a 50 mL flask. The mixture was stirred for 6 h at 25 °C, then hydrolysed with 25 mL of a 1 M solution of potassium fluoride and 25 mL of acetone to precipitate the tributyltin iodide formed. After vigorous stirring for 2 h, the reaction mixture was filtered, and extracted with diethyl ether. After the usual work-up, the crude **10** were purified by column chromatography on silica gel (petroleum ether–diethyl ether 95:5 as eluant).

Ethyl (2*E*,4*E*)-3-trifluoromethylhepta-2,4,6-trienoate (10a). IR: 3085, 2976, 1726, 1632 cm^{-1}. ^1H NMR δ: 1.28 (3H, t, $J = 7.1$ Hz), 4.21 (2H, q, $J = 7.1$ Hz), 5.37 (1H, d, $J = 10.1$ Hz), 5.46 (1H, d, $J = 16.5$ Hz), 6.20 (1H, s), 6.44 (1H, dt, $J = 16.5$ Hz, $J = 10.1$ Hz), 6.72 (1H, ddq, $J = 16.2$ Hz, $J = 10.1$ Hz, $J_{H-F} = 2.3$ Hz), 7.45 (1H, d, $J = 16.2$ Hz). ^{13}C NMR δ: 14.1, 61.0, 119.7 (q, $J_{C-F} = 6$ Hz), 122.1, 122.5 (q, $J_{C-F} = 277$ Hz), 123.2, 137.1 (q, $J_{C-F} = 0.8$ Hz), 139.2 (q, $J_{C-F} = 2$ Hz), 140.4 (q, $J_{C-F} = 29$ Hz), 164.7 (q, $J_{C-F} = 0.8$ Hz). MS (70 eV) m/z: 220 (M^+, 16), 175 (12), 147 (22), 127 (100), 79 (13), 78 (13), 51 (20), 39 (13). ^{19}F NMR δ: −67.1. Anal. Calcd for $C_{10}H_{11}F_3O_2$: C, 54.55; H, 5.04; found: C, 54.41; H, 5.05.

Ethyl (2*E*,4*E*)-3-trifluoromethyl-6-methylhepta-2,4,6-trienoate (10b). IR: 3070, 2970, 1720, 1625 cm^{-1}. ^1H NMR δ: 1.30 (3H, t, $J = 7.1$ Hz), 1.93 (3H, dd, $J = 1.2$ Hz, $J = 0.8$ Hz), 4.22 (2H, q, $J = 7.1$ Hz), 5.24 (1H, q, $J = 0.8$ Hz), 5.26 (1H, q, $J = 1.2$ Hz), 6.21 (1H, s), 6.82 (1H, dq, $J = 16.9$ Hz, $J_{H-F} = 2.3$ Hz), 7.47 (1H, dq, $J = 16.9$ Hz, $J_{H-F} = 0.7$ Hz). ^{13}C NMR δ: 14.1, 17.9, 61.0, 118.5, 119.5 (q, $J_{C-F} = 6$ Hz), 122.5 (q, $J_{C-F} = 277$ Hz), 122.7, 140.9 (q, $J_{C-F} = 29$ Hz), 141.1 (q, $J_{C-F} = 2$ Hz), 142.0 (q, $J_{C-F} = 0.8$ Hz), 164.9 (q, $J_{C-F} = 1$ Hz). MS (70 eV) m/z: 234 (M^+, 15), 189 (11), 165 (13), 161 (36), 141 (100), 109 (10), 51 (13), 41 (15), 39 (24). ^{19}F NMR δ: −66.9. Anal. Calcd for $C_{11}H_{13}F_3O_2$: C, 56.41; H, 5.59; found: C, 56.21; H, 5.47.

Ethyl (2*E*,4*E*,6*E*)-3-trifluoromethyldodeca-2,4,6-trienoate (10d). IR: 3060, 2950, 2920, 2840, 1720, 1615 cm^{-1}. ^1H NMR δ: 0.87 (3H, t, $J = 6.1$ Hz), 1.22–1.65 (6H, m), 1.29 (3H, t, $J = 7.1$ Hz), 2.14 (2H, dt, $J = 6.9$ Hz), 4.21 (2H, q, $J = 7.1$ Hz), 5.99 (1H, dt, $J = 6.9$ Hz, $J = 15.1$ Hz), 6.13 (1H, s), 6.18 (1H, dd, $J = 15.1$ Hz, $J = 9.8$ Hz), 6.72 (1H, ddq, $J = 16.1$ Hz, $J = 9.8$ Hz, $J_{H-F} = 2$ Hz), 7.35 (1H, dq, $J = 16.1$ Hz, $J_{H-F} = 0.7$ Hz). ^{13}C NMR δ: 14.0, 14.1, 22.5, 28.5, 31.4, 33.0, 60.8, 118.1 (q, $J_{C-F} = 6$ Hz), 119.5, 122.6 (q, $J_{C-F} = 277$ Hz), 130.8 (q, $J_{C-F} = 1$ Hz), 139.6 (q, $J_{C-F} = 2$ Hz), 141.0 (q, $J_{C-F} = 29$ Hz), 142.6, 165.0 (q, $J_{C-F} = 0.8$ Hz). ^{19}F NMR δ: −66.9. MS (70 eV) m/z: 290 (M^+, 10), 267 (20), 265 (32), 262 (28), 246 (100), 233 (42), 221 (12), 219 (18), 45 (15), 43 (40). Anal. Calcd for $C_{15}H_{21}F_3O_2$: C, 62.06; H, 7.29; found: C, 62.21; H, 7.11.

Ethyl (2*E*,4*E*,6*E*,8*E*)-3,8-bis(trifluoromethyl)deca-2,4,6,8-tetraene-1,10-dioate (10e). IR: 3072, 2965, 2856, 1724, 1629 cm^{-1}. ^1H NMR δ: 1.31 (6H, t, $J = 7.1$ Hz), 4.21 (4H, q, $J = 7.1$ Hz), 6.29 (2H, s), 6.84 (2H, d, $J = 14.3$ Hz), 7.68 (2H, d, $J = 14.3$ Hz). ^{13}C NMR δ: 14.1 (2C), 61.3 (2C), 121.2 (2C, q, $J_{C-F} = 6.0$ Hz), 122.3 (2C, q, $J_{C-F} = 277$ Hz), 126.4 (2C), 138.3 (2C), 139.9 (2C, q, J_{C-F} 29 Hz), 164.6 (2C, q, $J_{C-F} = 0.7$ Hz). MS (70 eV) m/z: 386 (M^+, 13), 285 (18), 313 (22), 293 (23), 267 (38), 265 (48), 248 (27), 239 (17), 217 (18), 199 (16), 171 (17), 169 (16), 152 (34), 151 (100), 150 (15), 45 (12). ^{19}F NMR δ: −67.0. Anal. Calcd for $C_{16}H_{16}F_6O_4$: C, 49.75; H, 4.17; found: C, 49.71; H, 4.05.

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