Radical-polar crossover domino reaction involving alkynes: A stereoselective zinc atom radical transfer

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I. General information

Experiments involving organometallic compounds were carried out in dried glassware under a positive pressure of dry Ar. Anhydrous solvents were distilled to remove stabilizers and dried with a Mbraun Solvent Purification System SPS-800. Bu₂Zn (Fluka) and Et₂Zn (Aldrich) and all other reagents were of commercial quality and were used without purification. ¹H NMR, ²H-NMR and ¹³C NMR spectra were recorded with Brucker AVANCE 400 spectrometer fitted with BBFO probe with Z gradient. Chemical shifts are reported in δ relative to an internal standard of residual chloroform (δ = 7.27 for ¹H NMR and 77.16 for ¹³C NMR). IR spectra were recorded with an ATR diamant spectrophotometer. High resolution mass spectra (HRMS) were obtained on a Finnigan MAT 95.

II. Experimental Procedures

II.1 General procedure 1 – Preparation of enoates 1a-1e: Enoates 1a-e were prepared from the corresponding propargyl alcohols by the following general procedure: To a stirred solution of bromomethyl acrylic acid methyl ester (4.1 mmol) in CH₂Cl₂ (12 mL) at 0°C was added successively Et₃N (0.7 mL, 5 mmol), alcohol (4 mmol), and NaI (0.150 g, 1 mmol). The mixture was heated in a sealed tube at 80°C for 12 to 24 h. The mixture was cooled to room temperature and diluted with CH₂Cl₂ (30 mL). HCl (1 M, 15 mL) was added and the layers separated, the aqueous one being extracted once with CH₂Cl₂ (15 mL). The combined organics were washed with brine, dried over MgSO₄ and the crude material "solid loaded" on a silica gel column.

methyl 2-((prop-2-ynyloxy)methyl)acrylate (1a): Prepared according to general procedure 1 from propargyl alcohol (0.25 mL, 4 mmol). Purification by chromatography using
ether/pentane (gradient) as eluent gave the title compound (364 mg, 59%). IR (neat) : 3284 broad, 1717, 1637, 1438, 1090 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz) : δ 2.48 (1H, t, J = 2.3 Hz), 3.80 (3H, s), 4.24 (2H, d, J = 2.3 Hz), 4.32 (2H, dd, J = 1.8, 1.3 Hz), 5.93 (1H, m), 6.36 (1H, m); ¹³C NMR (CDCl₃, 100 MHz) : δ 51.8, 57.7, 67.7, 74.8, 79.3, 126.5, 136.4, 166.0 ; HRMS calcd for C₈H₁₀O₃Na [M-Na]^+ : 177.05222. Found: 177.05195.

**methyl 2-((3-(trimethylsilyl)prop-2-ynyloxy)methyl)acrylate (1b)** : Prepared according to general procedure 1 from 3-(trimethylsilyl)prop-2-yn-1-ol (500 mg, 4 mmol). Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (647 mg, 73%). IR (neat) : 2955, 1720, 1637, 1438, 1094 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz) : δ 0.20 (9H, s), 3.80 (3H, s), 4.23 (2H, s), 4.30 (2H, m), 5.93 (1H, m), 6.36 (1H, m); ¹³C NMR (CDCl₃, 100 MHz) : δ 0.1, 52.0, 58.7, 68.0, 91.9, 101.2, 126.7, 136.7, 166.3 ; HRMS calcd for C₁₁H₁₈O₃NaSi [M-Na]^+ : 249.09174. Found: 249.09194.

**methyl 2-((3-phenylprop-2-ynyloxy)methyl)acrylate (1c)** : Prepared according to general procedure 1 from 3-phenylprop-2-yn-1-ol (500 mg, 3.8 mmol). Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (745 mg, 85 %). IR (neat) : 2950, 1718, 1439, 1090 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz) : δ 2.96 (3H, s), 4.37 (2H, m), 4.45 (2H, s), 5.95 (1H, m), 6.36 (1H, m), 7.30 (3H, m), 7.45 (2H, m); ¹³C NMR (CDCl₃, 100 MHz) : δ 52.2, 59.0, 68.3, 85.1, 86.9, 122.9, 126.9, 128.6, 128.8, 132.1, 137.0, 166.6 ; HRMS calcd for C₁₄H₁₄O₃Na [M-Na]^+ : 253.08352. Found: 253.08323.

**methyl 2-((3-cyclohexenylprop-2-ynyloxy)methyl)acrylate (1d)** : Prepared according to general procedure 1 from 3-cyclohexenylprop-2-yn-1-ol (200 mg, 0.85 mmol). Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (89 mg, 45 %). IR (neat) : 2929, 1719, 1636, 1437, 1090 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz) : δ 1.60 (4H, m), 2.12 (4H, m), 3.78 (3H, s), 4.29 (2H, m), 4.33 (2H, s), 5.91 (1H, m), 6.13 (1H, m), 6.33 (1H, m); ¹³C NMR (CDCl₃, 100 MHz) : δ 21.4, 22.2, 25.6, 29.1, 51.9, 58.7, 67.7, 81.9, 88.5,
120.1, 126.5, 135.5, 136.7, 166.3; HRMS calcd for C_{14}H_{18}O_{3}Na [M-Na]^+: 257.11482. Found: 257.11449.

**methyl 2-((pent-2-ynyloxy)methyl)acrylate (1e)**: Prepared according to general procedure 1 from pent-2-yn-1-ol (240 mg, 2.9 mmol). Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (355 mg, 67%). IR (neat): 2977, 2852, 1718, 1638, 1438, 1089 cm\(^{-1}\); \(^1\)H NMR (CDCl\(_3\), 400 MHz): \(\delta\) 1.12 (3H, t, \(J = 7.5\) Hz), 2.21 (2H, qt, \(J = 7.5, 2.2\) Hz), 3.74 (3H, s), 4.15 (2H, t, \(J = 2.2\) Hz), 4.24 (2H, m), 5.87 (1H, m), 6.29 (1H, m); \(^{13}\)C NMR (CDCl\(_3\), 100 MHz): \(\delta\) 12.4, 13.7, 51.8, 58.4, 67.6, 74.9, 88.6, 126.3, 136.7, 166.2; HRMS calcd for C\(_{10}\)H\(_{14}\)O\(_3\)Na [M-Na]^+: 205.08352. Found: 205.08351.

**II.2 General Procedure 2: radical-polar crossover domino reaction (Table 1)**: Under argon, to a stirred solution of \(\beta\)-(propargyloxy)-enoate (0.2 mmol) in Et\(_2\)O (5 mL) was added dialkylzinc reagent R\(_2\)Zn (~1N in heptane or hexane, 3 equivalents) at room temperature. The reaction mixture was stirred at room temperature for 16 h. The reaction was hydrolyzed with an aqueous solution of HCl (1M). The layers were separated, the aqueous one being extracted twice with ether. The combined organic layers were washed with brine, dried over MgSO\(_4\) and the solvents evaporated under reduced pressure. The product was purified by flash chromatography on silica gel.

**methyl tetrahydro-4-methylene-3-pentylfuran-3-carboxylate (2)**: Prepared according to general procedure 2 from enoate 1a (77 mg, 0.5 mmol) and Bu\(_2\)Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (57 mg, 54%). IR (neat): 2954, 2928, 2859, 1731, 1379 cm\(^{-1}\); \(^1\)H NMR (CDCl\(_3\), 400 MHz): \(\delta\) 0.89 (3H, t, \(J = 7.0\) Hz), 1.20-1.32 (6H, m), 1.61 (1H, m), 1.96 (1H, m), 3.73 (3H, s), 3.74 (1H, d, \(J = 9.0\) Hz), 4.34 (1H, dt, \(J = 13.1, 2.2\) Hz), 4.37-4.43 (2H, m), 5.07 (1H, t, \(J = 2.1\) Hz), 5.22 (1H, t, \(J = 2.4\) Hz); \(^{13}\)C NMR (CDCl\(_3\), 100 MHz): \(\delta\) 13.9, 22.4, 25.2, 32.0, 37.1, 52.3, 56.8,
methyl tetrahydro-4-methylene-3-propylfuran-3-carboxylate (3) : Prepared according to general procedure 2 from enoate 1a (77 mg, 0.5 mmol) and Et₂Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (50 mg, 55 %). IR (neat) : 2959, 2875, 1730, 1218 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz) :  δ 0.91 (3H, t, J = 7.2 Hz), 1.18-1.34 (2H, m), 1.60 (1H, m), 1.95 (1H, m), 3.73 (3H, s), 3.75 (1H, d, J = 9.0 Hz), 4.30-4.42 (3H, m), 5.07 (1H, t, J = 2.1 Hz), 5.23 (1H, t, J = 2.4 Hz) ; ¹³C NMR (CDCl₃, 100 MHz) :  δ 14.4, 18.9, 39.3, 52.3, 56.8, 71.7, 75.0, 106.2, 150.4, 173.5. HRMS calcd for C₁₂H₂₀O₃Na [M-Na]⁺: 235.13047. Found: 235.13043.

(Z)-methyl tetrahydro-4-((trimethylsilyl)methylene)-3-pentylfuran-3-carboxylate (4) : Prepared according to general procedure 2 from enoate 1b (45 mg, 0.2 mmol) and Bu₂Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (39 mg, 67 %). IR (neat) : 2953, 1731, 1626, 1247, 691 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz) :  δ 0.08 (9H, s), 0.87 (3H, t, J = 7.1 Hz), 1.18-1.32 (6H, m), 1.52 (1H, m), 1.94 (1H, m), 3.68-3.69 (4H, m), 4.32 (1H, dd, J = 13.9, 2.4 Hz), 4.37-4.42 (2H, m), 5.69 (1H, t, J = 2.4 Hz) ; ¹³C NMR (CDCl₃, 100 MHz) :  δ 0.0, 14.7, 23.1, 26.0, 32.8, 37.9, 53.0, 59.3, 71.7, 74.8, 120.5, 158.7, 174.2 ; HRMS calcd for C₁₅H₂₈O₃NaSi [M-Na]⁺: 307.16999. Found: 307.17033.

(Z)-methyl tetrahydro-4-((trimethylsilyl)methylene)-3-propylfuran-3-carboxylate (5) : Prepared according to general procedure 2 from enoate 1b (45 mg, 0.2 mmol) and Et₂Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (47 mg, 91 %). IR (neat) : 2956, 1731, 1627, 1247, 838 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz) :  δ 0.09 (9H, s), 0.91 (3H, t, J = 7.3 Hz), 1.19-1.30 (2H, m), 1.53 (1H, ddd, J = 13.5, 11.3, 5.5 Hz), 1.94 (1H, ddd, J = 13.5, 11.3, 5.4 Hz), 3.69-3.72 (4H, m), 4.33 (1H, dd, J = 13.9, 2.4 Hz), 4.37-4.42 (2H, m), 5.70 (1H, t, J = 2.4 Hz) ; ¹³C NMR (CDCl₃, 100 MHz) :
\[ \delta = -0.7, 14.4, 19.0, 39.5, 52.3, 58.6, 71.0, 74.2, 119.9, 158.0, 173.4 \] ; HRMS calcd for C\textsubscript{13}H\textsubscript{24}O\textsubscript{3}NaSi [M-Na]\textsuperscript{+}: 279.13869. Found: 279.13857.

**(Z)-methyl tetrahydro-4-((trimethylsilyl)methylene)-3-isobutylfuran-3-carboxylate (6)**: Pre pared according to general procedure 2 from enoate 1b (46 mg, 0.2 mmol) and \textit{i}Pr\textsubscript{2}Zn (1.2 mL, 0.5 M in Et\textsubscript{2}O, 0.6 mmol)\textsuperscript{1}. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (27 mg, 49 %). IR (neat) : 2954, 1731, 1626, 837 cm\textsuperscript{-1}; \textit{\textsuperscript{1}H NMR} (CDCl\textsubscript{3}, 400 MHz) : \[ \delta = 0.09 \text{ (9H, s), 0.87 (3H, d, } J = 6.6 \text{ Hz), 0.89 (3H, d, } J = 6.6 \text{ Hz), 1.46 (1H, dd, } J = 13.9, 6.2 \text{ Hz), 1.60 (1H, m), 2.02 (1H, dd, } J = 13.9, 7.1 \text{ Hz), 3.66 (1H, d, } J = 9.0 \text{ Hz), 3.69 (3H, s), 4.28 (1H, dd, } J = 13.6, 2.4 \text{ Hz), 4.40 (1H, dd, } J = 13.6, 2.4 \text{ Hz), 4.53 (1H, d, } J = 9.0 \text{ Hz), 5.74 (1H, t, } J = 2.4 \text{ Hz); } \textit{\textsuperscript{13}C NMR} \text{ (CDCl}_3\text{, 100 MHz) : } \delta = -0.3, 23.2, 24.4, 26.5, 46.4, 52.8, 58.4, 71.0, 74.5, 120.8, 158.7, 174.1 \] ; HRMS calcd for C\textsubscript{14}H\textsubscript{26}O\textsubscript{3}NaSi [M-Na]\textsuperscript{+}: 293.15434. Found: 293.15470.

**(Z)-methyl 4-benzylidene-tetrahydro-3-pentylfuran-3-carboxylate (7)**: Prepared according to general procedure 2 from enoate 1c (59 mg, 0.25 mmol) and Bu\textsubscript{2}Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (60 mg, 81 %). IR (neat) : 2952, 2857, 1729, 842 cm\textsuperscript{-1}; \textit{\textsuperscript{1}H NMR} (CDCl\textsubscript{3}, 400 MHz) : \[ \delta = 0.87 (3H, t, } J = 6.9 \text{ Hz), 1.23-1.35 (6H, m), 1.69, (1H, m), 2.19 (1H, m), 3.75 (3H, s), 3.77 (1H, d, } J = 9.0 \text{ Hz), 4.47 (1H, d, } J = 9.0 \text{ Hz), 4.67 (1H, dd, } J = 13.9, 2.4 \text{ Hz), 4.73 (1H, dd, } J = 13.9, 2.4 \text{ Hz), 6.57 (1H, t, } J = 2.4 \text{ Hz), 7.16 (2H, d, } J = 8.6 \text{ Hz), 7.24-7.39 (3H, m); } \textit{\textsuperscript{13}C NMR} \text{ (CDCl}_3\text{, 100 MHz) : } \delta = 14.4, 22.6, 24.2, 32.3, 37.6, 52.5, 58.2, 71.0, 74.4, 123.0, 126.9, 128.3, 128.6, 137.1, 143.4, 174.0 \] ; HRMS calcd for C\textsubscript{18}H\textsubscript{26}O\textsubscript{3}Na [M-Na]\textsuperscript{+}: 311.16177. Found: 311.16211.

**(Z)-methyl 4-benzylidene-tetrahydro-3-propylfuran-3-carboxylate (8)**: Prepared according to general procedure 2 from enoate 1c (45 mg, 0.2 mmol) and Et\textsubscript{2}Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (40 mg,

79 %). IR (neat) : 2956, 2872, 1728, 1493, 1216, 1066, 693 cm$^{-1}$; $^1$H NMR (CDCl$_3$, 400 MHz) : δ 0.97 (3H, t, $J = 7.2$ Hz), 1.23-1.40 (2H, m), 1.71 (1H, ddd, $J = 13.5, 11.3, 5.7$ Hz), 2.10 (1H, ddd, $J = 13.5, 11.2, 5.4$ Hz), 3.76 (3H, s), 3.79 (1H, d, $J = 9.0$ Hz), 4.48 (1H, d, $J = 9.0$ Hz), 4.68 (1H, dd, $J = 13.9, 2.4$ Hz), 4.74 (1H, dd, $J = 13.9, 2.4$ Hz), 6.59 (1H, t, $J = 2.4$ Hz), 7.18 (2H, m), 7.26 (1H, m), 7.37 (2H, m); $^{13}$C NMR (CDCl$_3$, 100 MHz) : δ 14.4, 19.0, 39.6, 52.4, 57.9, 70.7, 74.1, 122.8, 127.1, 128.2, 128.5, 136.8, 143.2, 173.7; HRMS calcd for C$_{16}$H$_{20}$O$_3$Na [M−Na]$^+$: 283.13047. Found: 283.13022.

(4Z)-methyl 4-(cyclohexenylmethylene)-tetrahydro-3-pentylfuran-3-carboxylate (9) : Prepared according to general procedure 2 from enoate 1d (45 mg, 0.2 mmol) and Bu$_2$Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (33 mg, 59 %). IR (neat) : 2929, 2859, 1729, 1434, 730 cm$^{-1}$; $^1$H NMR (CDCl$_3$, 400 MHz) : δ 0.88 (3H, t, $J = 7.0$ Hz), 1.18-1.31 (6H, m), 1.52-1.68 (5H, m), 1.98 (1H, m), 2.12 (4H, m), 3.64 (1H, d, $J = 9.0$ Hz), 3.71 (3H, s), 4.38 (1H, d, $J = 9.0$ Hz), 4.57 (2H, AB system, $J = 13.1$ Hz), 5.64 (1H, m), 5.96 (1H, m); $^{13}$C NMR (CDCl$_3$, 100 MHz) : δ 13.9, 21.8, 22.4, 22.7, 25.3, 25.8, 27.8, 32.1, 37.4, 52.2, 57.5, 70.5, 73.9, 125.7, 129.4, 135.2, 139.0, 174.0; HRMS calcd for C$_{18}$H$_{28}$O$_3$Na [M−Na]$^+$: 315.19307. Found: 315.19309.

methyl tetrahydro-3-pentyl-4-propyldenefuran-3-carboxylate (10) : Prepared according to general procedure 2 from enoate 1e (36 mg, 0.2 mmol) and Bu$_2$Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (30 mg, 64 %, Z:E = 64:36). $^1$H NMR (CDCl$_3$, 400 MHz) : δ 0.88 (3H, m), 0.94 (3H-(E), t, $J = 7.5$ Hz), 0.98 (3H-(Z), t, $J = 7.5$ Hz), 1.18-1.40 (6H, m), 1.58 (1H-(Z), m), 1.80 (1H-(E), m), 1.90-2.00 (3H-(Z) + 1H-(E), m), 2.05 (2H-(E), m), 3.68 (1H-(Z), d, $J = 9.0$ Hz), 3.72 (3H, s), 3.84 (1H-(E), d, $J = 8.8$ Hz), 4.21 (1H-(E), d, $J = 8.8$ Hz), 4.28-4.40 (2H + 1H-(Z), m), 5.33 (1H-(E), tt, $J = 7.7, 1.9$ Hz), 5.49 (1H-(Z), tt, $J = 7.2, 2.4$ Hz); $^{13}$C NMR (CDCl$_3$, 100 MHz) : δ 13.7, 13.8, 13.9, 14.0, 21.6, 22.4, 22.5, 22.9, 24.4, 25.2, 32.1, 32.3, 34.7, 37.2, 52.2 (2C),
Stereochemical (Z) / (E) assignment was deduced from nOe experiments performed on unsubstituted product 2 which showed that vinylic protons syn to the carbomethoxy moiety are less shielded than vinylic protons anti to the carbomethoxy group. Consequently, for the Et-substituted product 10, the major isomer having a less shielded vinylic proton corresponds to the Z diastereoisomer.

II.3 General Procedure 3: radical-polar crossover domino reaction and iodolysis (Table 2, entries 6, 8): Under argon, to a stirred solution of β-(propargyloxy)-enoate (0.2 mmol) in Et₂O (5 mL) was added dialkylzinc reagent R₂Zn (0.6 mL, ~1N in heptane or hexane, 0.6 mmol) at room temperature. The reaction mixture was stirred at room temperature for 16 h. The reaction mixture was cooled to -10°C and a solution of I₂ (303 mg, 1.2 mmol) in THF (1 mL) was added. After having stirred the solution at RT for 3 h, a saturated solution of Na₂S₂O₃ (5 mL) was added and the mixture was diluted with Et₂O (10 mL). The layers were separated, the aqueous one being extracted twice with ether. The combined organic layers were washed with brine, dried over MgSO₄ and concentrated. The product was purified by flash chromatography on silica gel.

(E)-methyl tetrahydro-4-(iodo(trimethylsilyl)methylene)-3-pentylfuran-3-carboxylate (15): Prepared according to general procedure 3 from enoate 1b (45 mg, 0.2 mmol) and Bu₂Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (59 mg, 72 %). IR (neat): 2953, 2862, 1732, 1248, 838 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 0.25 (9H, s), 0.88 (3H, t, J = 7.0 Hz), 1.18-1.42 (6H, m), 1.72 (1H, m), 2.45 (1H, td, J = 13.3, 4.4 Hz), 3.72 (3H, s), 4.02 (2H, s), 4.37 (2H, AB system, J = 13.1 Hz); ¹³C NMR
(CDCl$_3$, 100 MHz) : $\delta$ 0.0, 13.4, 21.8, 22.9, 31.4, 31.6, 52.0, 62.8, 73.4, 77.3, 99.7, 158.1, 173.1 ; HRMS calcd for C$_{15}$H$_{27}$O$_3$NaSi [M-Na]$^+$: 433.06664. Found: 433.06686.

$$(E)$-methyl tetrahydro-4-(iodo(phenyl)methylene)-3-pentylfuran-3-carboxylate (17) :$$

Prepared according to general procedure 3 from enoate 1c (45 mg, 0.2 mmol) and Bu$_2$Zn. Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (66 mg, 79 %). IR (neat) : 2951, 2860, 1730, 1233, 1082, 730, 696 cm$^{-1}$; $^1$H NMR (CDCl$_3$, 400 MHz) : $\delta$ 0.96 (3H, t, $J = 6.7$ Hz), 1.30-1.48 (5H, m), 1.55 (1H, m), 1.86, (1H, m), 2.48 (1H, m), 3.84 (3H, s), 4.12 (2H, AB system, $J = 8.8$ Hz), 4.30 (2H, AB system, $J = 13.4$ Hz), 7.22-7.30 (3H, m), 7.31-7.38 (2H, m); $^{13}$C NMR (CDCl$_3$, 100 MHz) : $\delta$ 14.1, 22.5, 23.7, 32.1, 32.3, 52.7, 60.2, 73.5, 78.6, 88.9, 127.4, 128.3, 128.5, 144.2, 149.1, 173.7 ; HRMS calcd for C$_{18}$H$_{23}$O$_3$Na [M-Na]$^+$: 437.05841. Found: 437.05863.

II.4 General Procedure 4 : radical-polar crossover domino reaction and allylation (Table 2, entries 7, 9) : Under argon, to a stirred solution of $\beta$-(propargyloxy)-enoate (0.2 mmol) in Et$_2$O (5 mL) was added diethylzinc Et$_2$Zn (0.6 mL, 1M hexane, 0.6 mmol) at room temperature. The reaction mixture was stirred at room temperature for 16 h. THF (3 mL) was added and the mixture was cooled to 0°C before CuCN•2LiCl (0.6 mL, 1M in THF, 0.6 mmol) and allyl bromide (0.15 mL, 1.8 mmol) were added. After being stirred for 3h at RT the reaction mixture was quenched with an aqueous solution of NH$_4$Cl/ NH$_4$OH (2/1) (5 mL) and diluted with Et$_2$O (10 mL). The layers were separated, the aqueous one being extracted twice with Et$_2$O. The combined organic layers were washed with brine, dried over MgSO$_4$ and concentrated. The product was purified by flash chromatography on silica gel.

$(Z)$-methyl tetrahydro-4-(1-(trimethylsilyl)but-3-enyldene)-3-pentylfuran-3-carboxylate (16) : Prepared according to general procedure 4 from enoate 1b (45 mg, 0.2 mmol). Purification by chromatography using ether/pentane (gradient) as eluent gave the title
compound (30 mg, 51\%). IR (neat) : 2956, 2873, 1728, 1241, 835 cm\(^{-1}\); \(^1\)H NMR (CDCl\(_3\), 400 MHz) : \(\delta\) 0.13 (9H, s), 0.91 (3H, \(J = 7.3\) Hz), 1.22 (1H, m), 1.42 (1H, m), 1.85 (2H, m), 2.85 (1H, m), 2.95 (1H, m), 3.66 (3H, s), 3.89 (1H, d, \(J = 8.8\) Hz), 4.10 (1H, d, \(J = 8.8\) Hz), 4.42 (2H, AB system, \(J = 12.8\) Hz), 4.9-5.03 (2H, m), 5.70 (1H, m); \(^1\)C NMR (CDCl\(_3\), 100 MHz) : \(\delta\) 0.0, 14.8, 18.1, 36.4, 37.6, 52.5, 57.4, 73.2, 78.0, 115.7, 130.6, 137.0, 152.1, 175.6; HRMS calcd for C\(_{16}\)H\(_{28}\)O\(_3\)NaSi [M-Na]- : 319.16999. Found: 319.16986.

\((Z)\)-methyl tetrahydro-4-(1-phenylbut-3-enylidene)-3-propylfuran-3-carboxylate (18) :

Prepared according to general procedure 4 from enoate 1c (45 mg, 0.2 mmol). Purification by chromatography using ether/pentane (gradient) as eluent gave the title compound (24 mg, 42\%). IR (neat) : 2957, 2872, 1726, 1236, 701 cm\(^{-1}\); \(^1\)H NMR (CDCl\(_3\), 400 MHz) : \(\delta\) 1.00 (3H, \(J = 7.2\) Hz), 1.41 (1H, m), 1.55 (1H, m), 2.00 (2H, m), 3.15 (2H, m), 3.78 (3H, s), 3.95 (1H, d, \(J = 9.0\) Hz), 4.14-4.24 (3H, m), 4.90-4.95 (2H, m), 5.55 (1H, m), 7.10 (2H, d, \(J = 7.9\) Hz), 7.28-7.40 (3H, m); \(^1\)C NMR (CDCl\(_3\), 100 MHz) : \(\delta\) 14.6, 18.0, 37.4, 38.4, 52.4, 56.0, 72.8, 78.1, 116.3, 127.0, 127.7, 128.3, 133.1, 134.6, 138.7, 141.7, 175.3; HRMS calcd for C\(_{19}\)H\(_{24}\)O\(_3\)Na [M-Na]+ : 323.16177. Found: 323.16165.
III.1 HRMS analysis:

Erreur = - 3.6 ppm
Calcul des masses monoisotopiques – 1.00728 Th (-H').
-22.98922 Th (-Na').
-38.96316 Th (-K').
44% deuterated compound

Erreur =
Calcul des masses monoisotopiques – 1.00728 Th (-H⁺).
–22.98922 Th (-Na⁺).
–38.96316 Th (-K⁺).
III.2 $^2$H-NMR and $^1$H-NMR analysis (solvent: CCl$_4$ (9) / CDCl$_3$ (1):

$^2$H-NMR (CCl$_4$ / CDCl$_3$)

$^1$H-NMR (CCl$_4$ / CDCl$_3$)