Mild and Selective Etherification of Wheat Straw Lignin and Lignin Model Alcohols by Moisture-Tolerant Zirconium Catalysis

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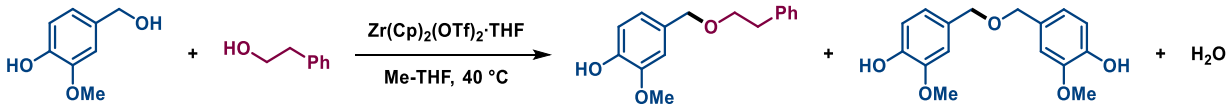
1. General Information

All reactions were carried out in glassware that was not pre-dried unless otherwise stated. Water used for reactions and HPLC analysis was obtained from a Milli-Q® system. Trifluoromethanesulfonic acid (TfOH) was stored and handled under N_2 atmosphere, using Hamilton syringes. Molecular sieves (3Å, powder) were heat gun-dried under vacuum for 20 minutes and cooled under N_2 prior to use. All other solvents and reagents were purchased from commercial suppliers and used without further purification unless otherwise noted. TLC analyses were performed on pre-coated silica gel 60 F254 plates, and visualized using UV light or phosphomolybdic acid stain (solution in EtOH). Flash column chromatography was conducted using 40-60 µm, 230-400 mesh, 60 Å silica gel as stationary phase. NMR spectra were recorded using either a Bruker Avance II 400 MHz or a Bruker Avance 500 MHz spectrometer at 298 K using $CDCl_3$ as solvent (unless otherwise stated). Chemical shifts are given in ppm relative to the residual solvent peak (^{1}H NMR: $CDCl_3$ δ 7.26; ^{13}C NMR: $CDCl_3$ δ 77.16) with multiplicity (br = broad, s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet), coupling constants in Hz and integration. Kinetic data was analyzed by Agilent 1260 Infinity Quaternary LC (Eclipse Plus 18C column) with a gradient of acetonitrile and 0.1% formic acid in Milli-Q water at a flow rate of 1.0 mL/min, using 4,4'-di-tert-butylbiphenyl (DTBB) as internal standard. High-resolution mass spectrometry analyses were performed using a Thermo Scientific Q Exactive HF Hybrid Quadrupole-Orbitrap HESI. Full analytical data is given if the compound is novel.

2. Vanillyl alcohol etherification - conditions screening

Model reaction:



2.1. Solvent screening

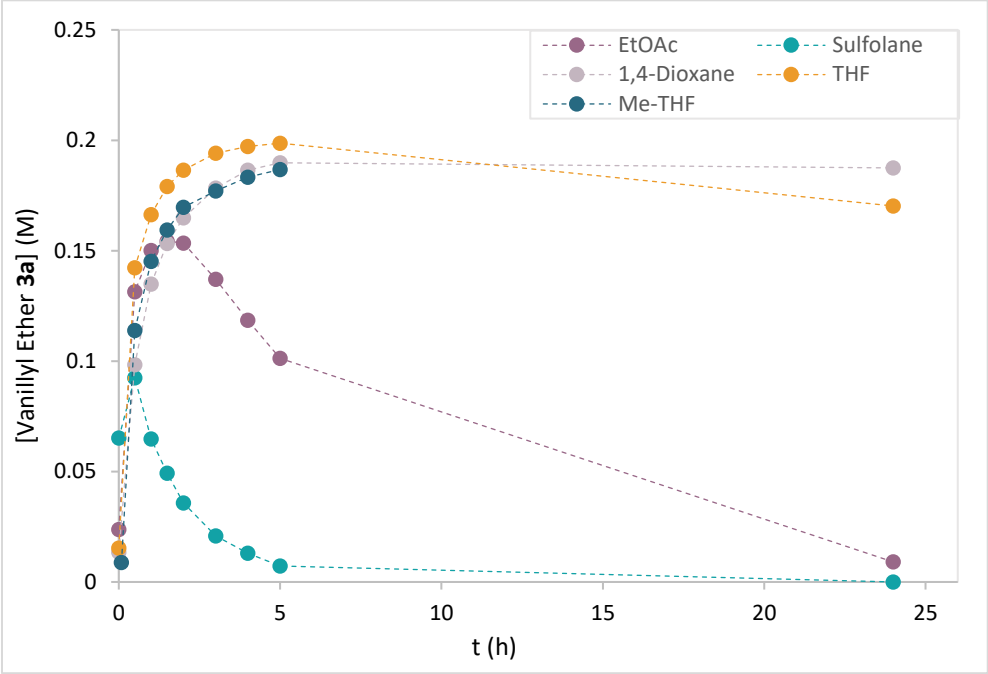


Figure S1. Solvent screening. Conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), 0.02 M $Zr(Cp)_2(CF_3SO_3)_2$·THF, DTBB as internal standard (0.01 M), 30 °C, 24 h, 0.25 mmol **1a** scale.

2.2. Temperature screening

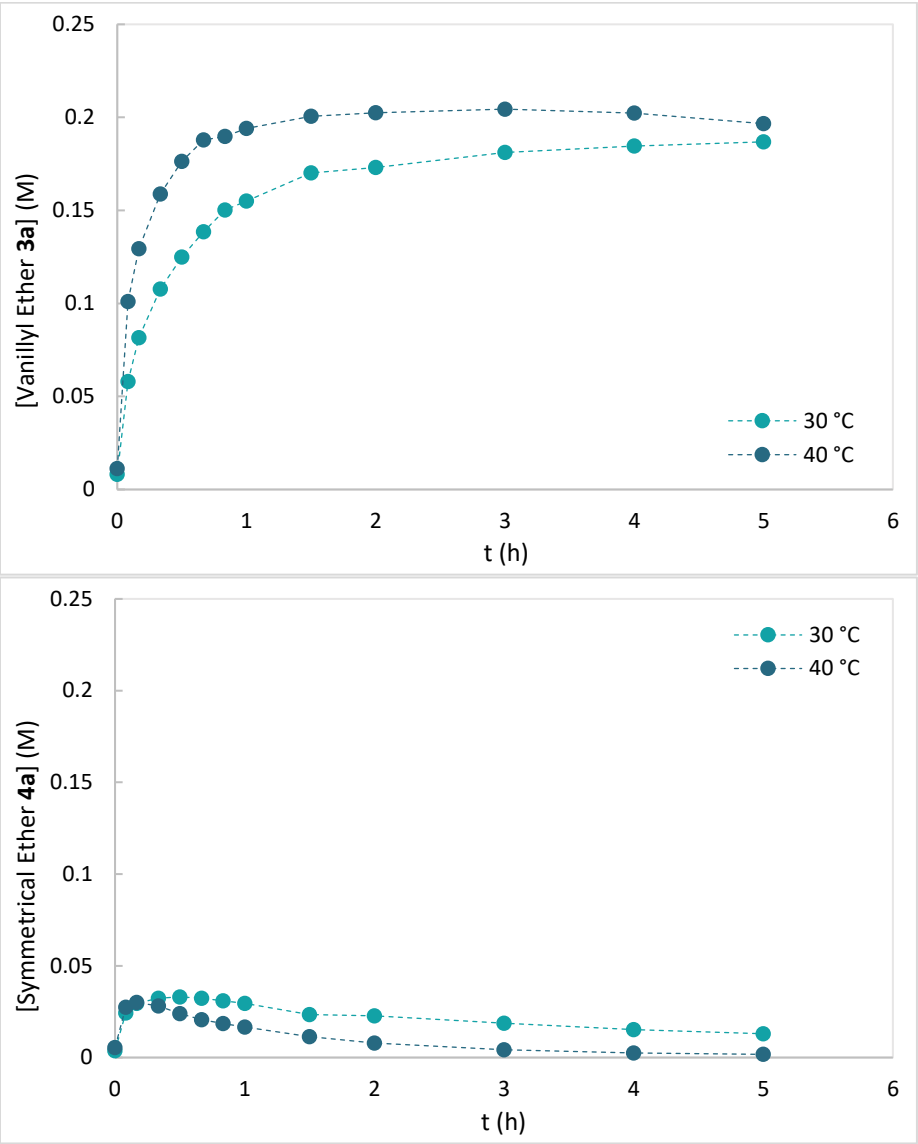


Figure S2. Temperature screening. Conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), 0.02 M $Zr(Cp)_2(CF_3SO_3)_2$·THF, DTBB as internal standard (0.01 M), Me-THF, 5 h, 0.25 mmol **1a** scale.

2.3. Catalyst screening

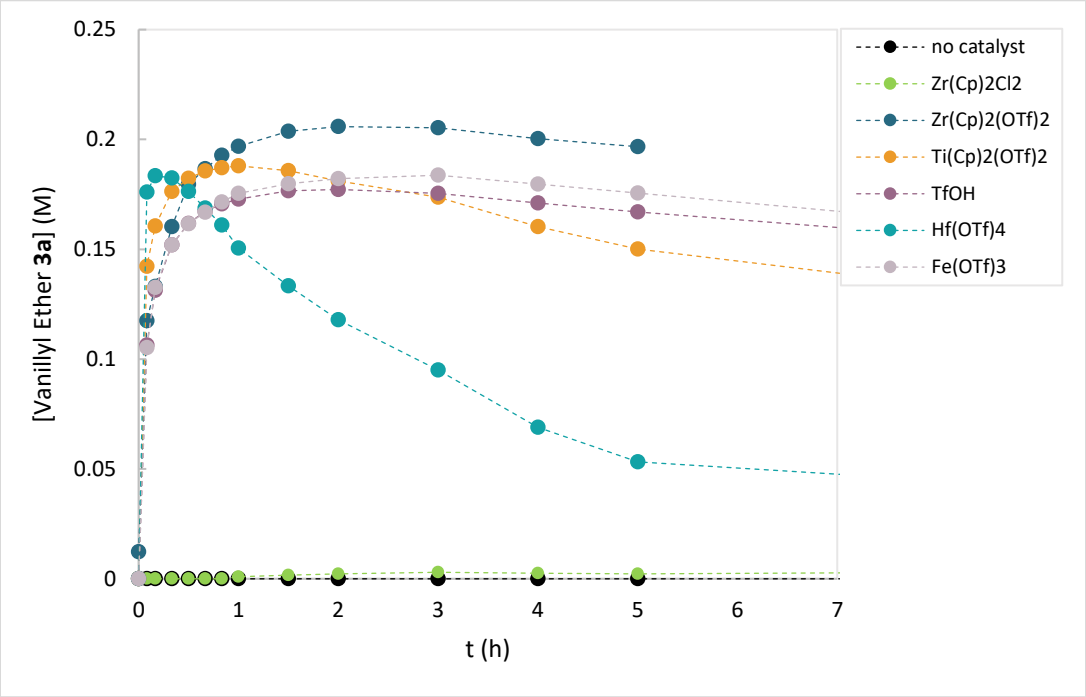


Figure S3. Catalyst screening. Conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), catalyst (0.02 M), DTBB as internal standard (0.01 M), Me-THF, 40 °C, 0.25 mmol **1a** scale.

3. Kinetic analysis

Kinetic experiments were carried out in accordance with general procedure C (Section 4.3). Comprehensive tutorials of "different excess" and "same excess" experiments are found in the Reaction Progress Kinetic Analysis literature,[1, 2] whereas detailed information about retrieval of orders in catalyst and reagents are found in the Visual Time Normalization Analysis literature.[3]

3.1. "Different excess" experiments - Determination of order in [catalyst]

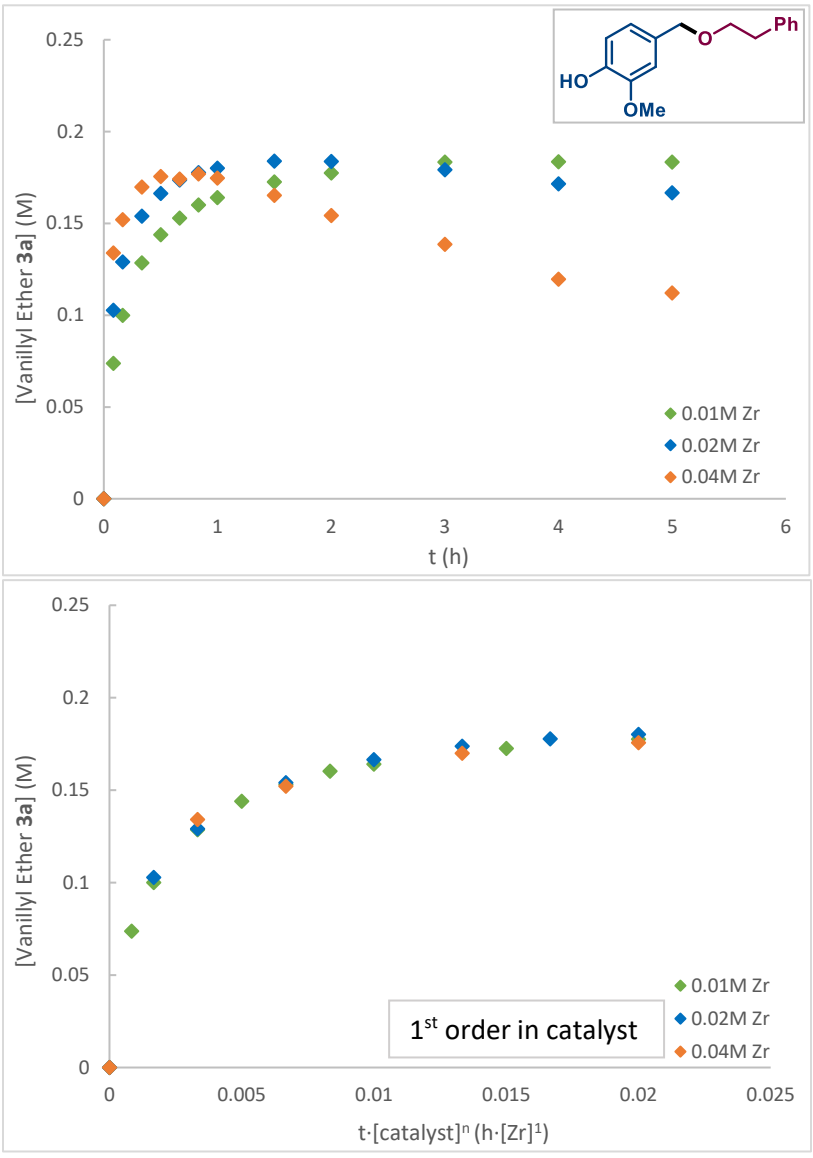


Figure S4. Order in [catalyst] for the formation of product **3a** for reaction time 0 – 5 h. Conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (x M), DTBB as internal standard (0.01 M), Me-THF, 40 °C, 0.25 mmol **1a** scale.

3.2. "Different excess" experiments - Determination of order in [vanillyl alcohol 1a]

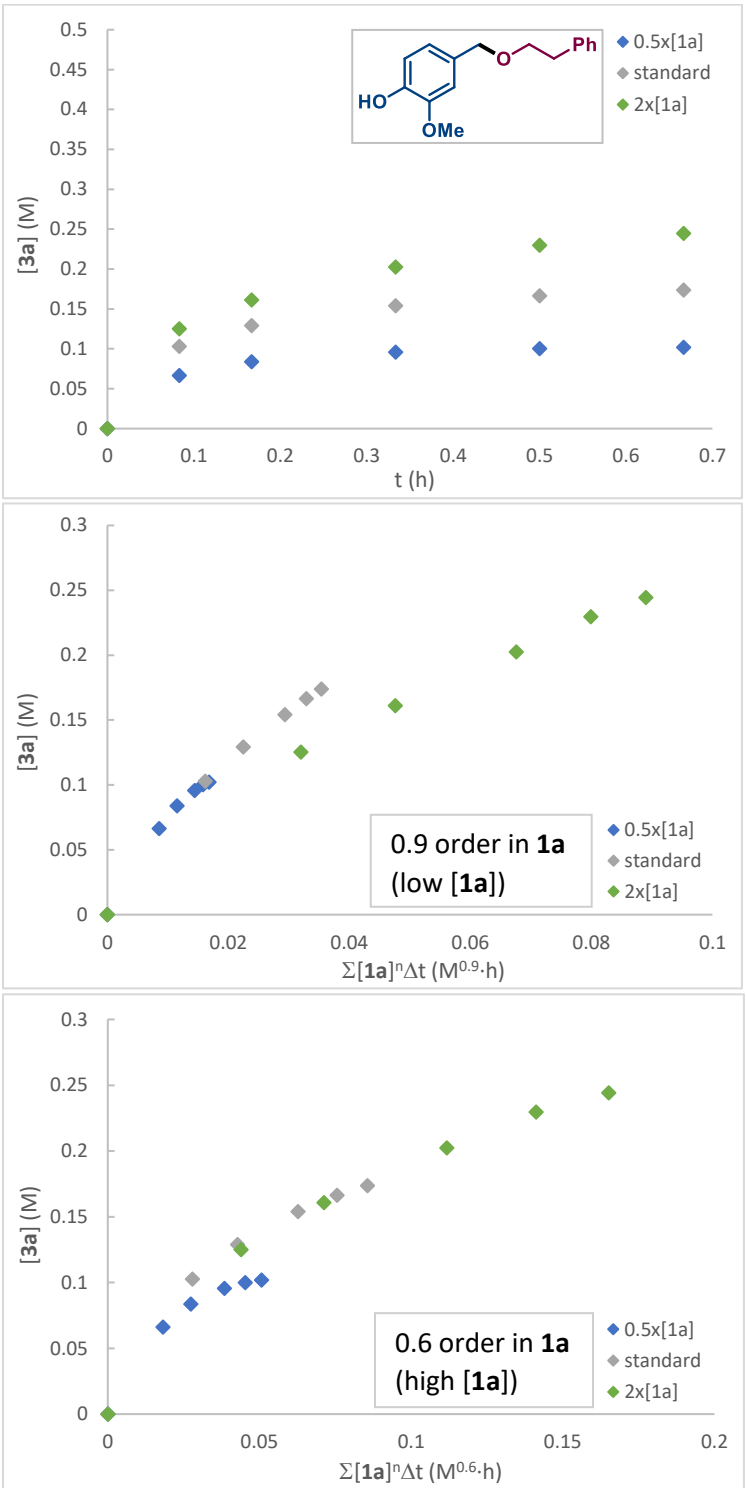


Figure S5. Order in [**1a**] for the formation of product **3a** for reaction time 0 – 40 min. Standard conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.02 M), DTBB as internal standard (0.01 M), Me-THF, 40 °C, 0.25 mmol **1a** scale.

3.3. "Different excess" experiments - Determination of order in [2-phenylethanol 2a]

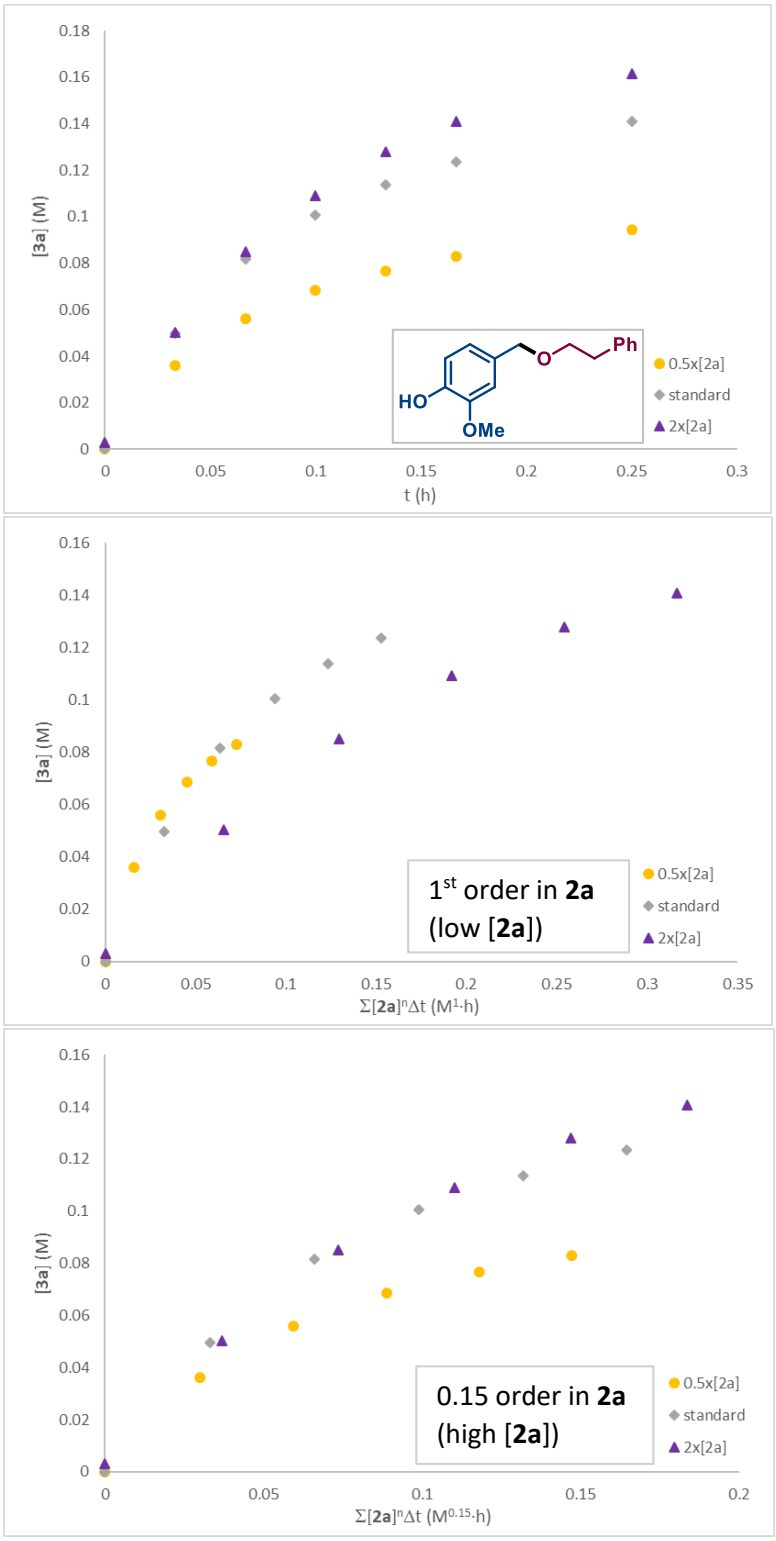


Figure S6. Order in [**2a**] for the formation of product **3a** for reaction time 0 – 15 min. Standard conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.02 M), DTBB as internal standard (0.01 M), Me-THF, 40 °C, 0.25 mmol **1a** scale.

3.4 *Same excess* experiments

Same excess experiments followed the general etherification procedure, with conditions mimicking 25% conversion of vanillyl alcohol: vanillyl alcohol **1a** (0.188 M), 2-phenylethanol **2a** (0.938 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.02 M), DTBB as internal standard (0.01 M), Me-THF, 40 °C; and same excess conditions mimicking 25% conversion of vanillyl alcohol with addition of the corresponding amount of H_2O at the outset of the reaction: Milli-Q H_2O (0.06 M), vanillyl alcohol **1a** (0.188 M), 2-phenylethanol **2a** (0.938 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.02 M), DTBB as internal standard (0.01 M), Me-THF, 40 °C, 0.25 mmol **1a** scale. Values for **1a** are normalized to $[\mathbf{1a}]_0$.

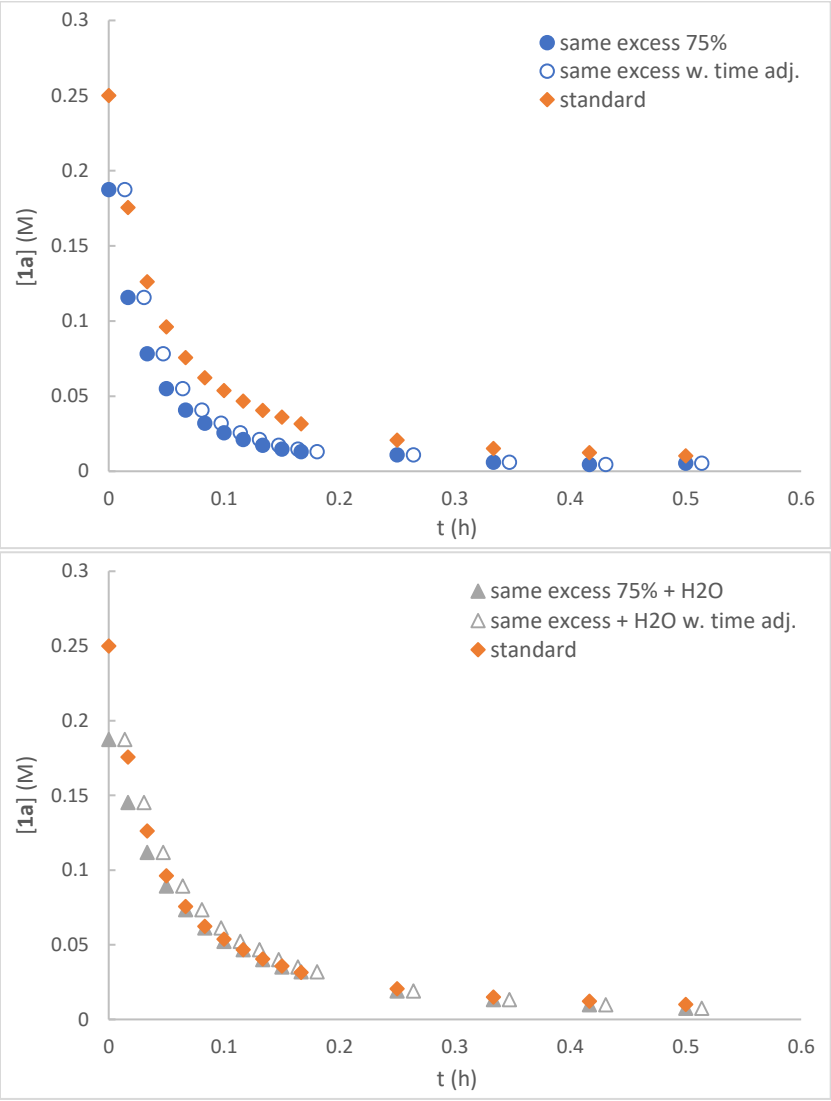


Figure S7. Same excess experiments. Standard conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.02 M), DTBB as internal standard (0.01 M), Me-THF, 40 °C.

3.5 Water tolerance experiments

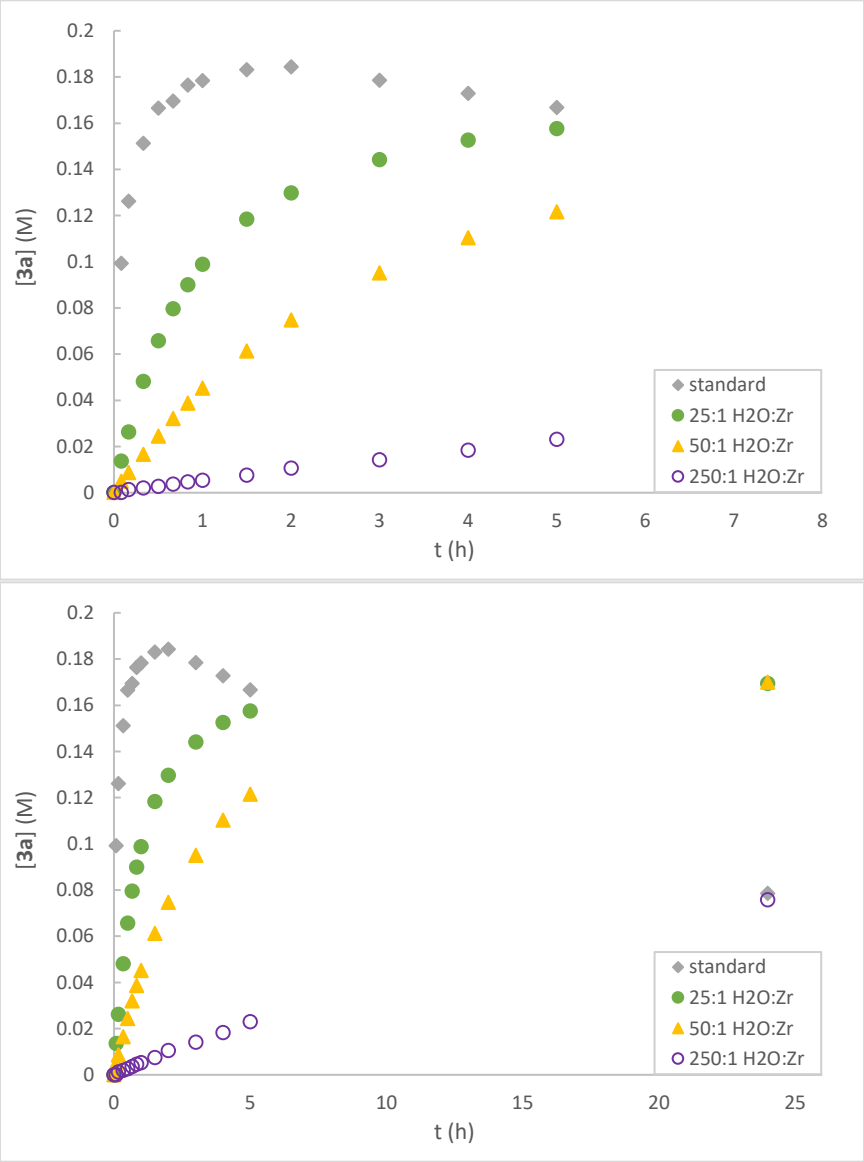


Figure S8. Ether formation profiles in presence of increasing amounts of H_2O (9 µl, 18 µl, 90 µl). Standard conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.02 M), DTBB as internal standard (0.01 M), Me-THF, 40 °C, 0.25 mmol **1a** scale.

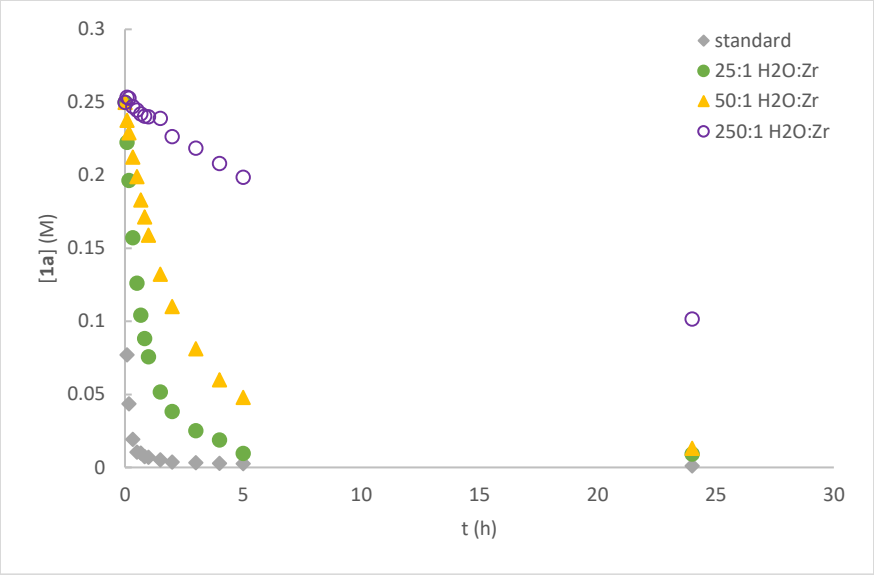


Figure S9. Vanillyl alcohol consumption profiles in presence of increasing amounts of H_2O (9 µl, 18 µl, 90 µl). Standard conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.02 M), DTBB as internal standard (0.01 M), Me-THF, 40 °C, 0.25 mmol **1a** scale.

3.6 Molecular sieves addition

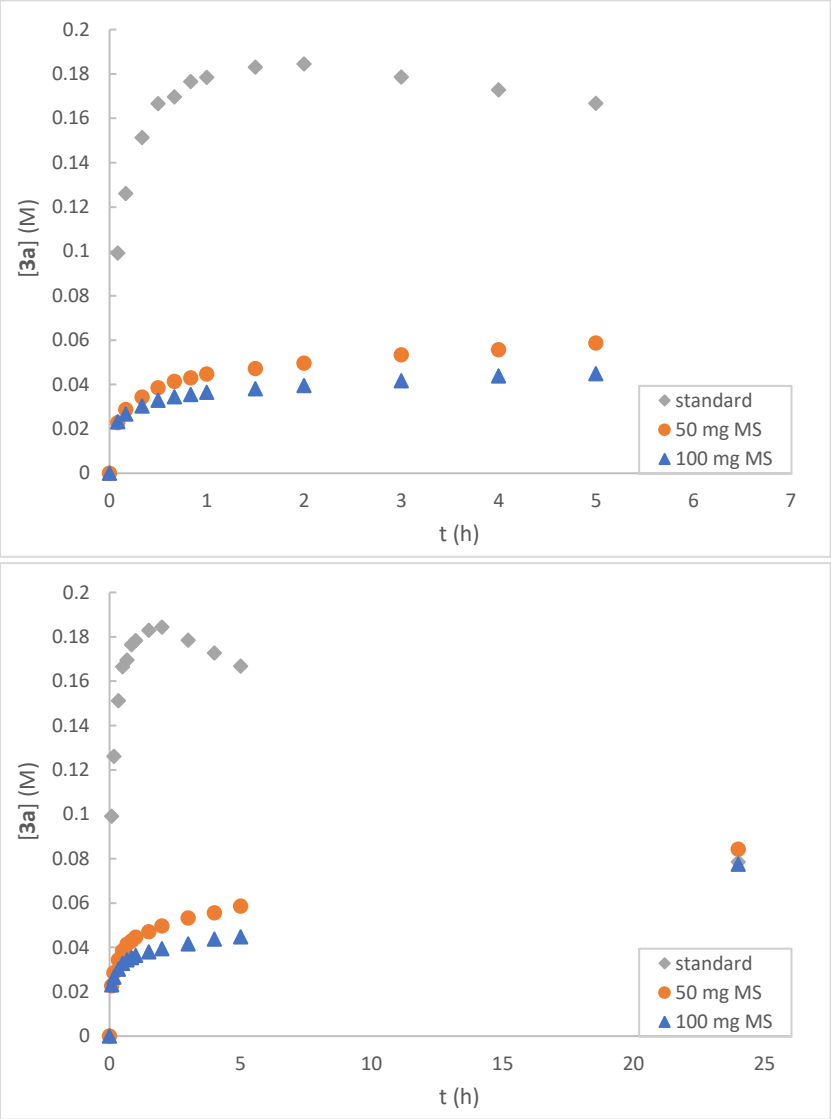


Figure S10. Reaction behavior in presence of increasing amounts of 3Å MS (50 mg, 100 mg). Standard conditions: vanillyl alcohol **1a** (0.25 M), 2-phenylethanol **2a** (1 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.02 M), DTBB as internal standard (0.01 M), Me-THF, 40 °C, 0.25 mmol **1a** scale.

3.7. Effect of reactant concentration and mode of addition

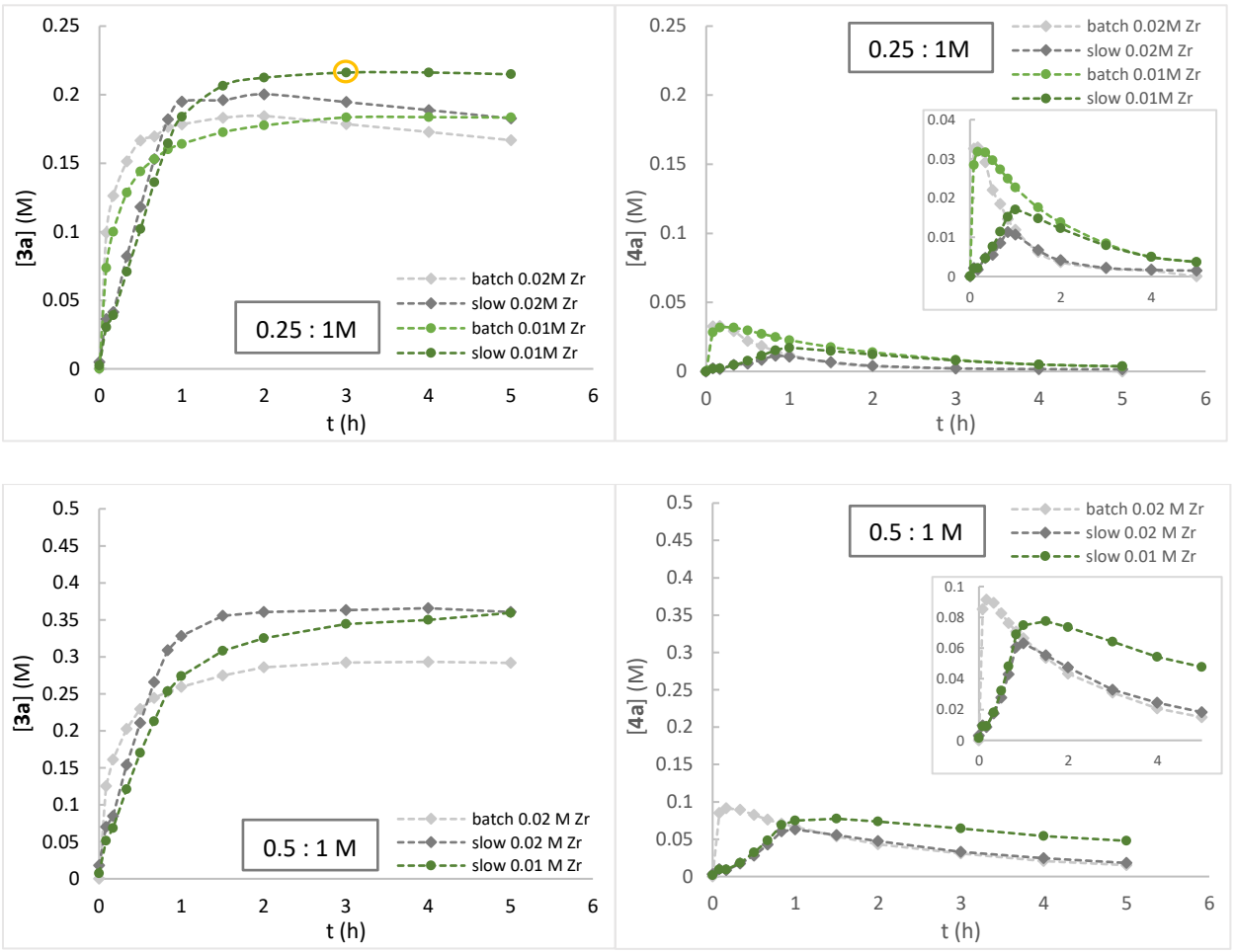
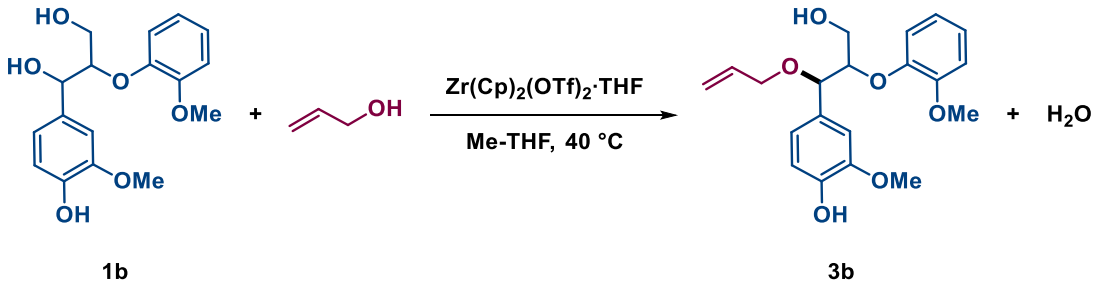


Figure S11. Effect of reactant concentration and mode of addition on yield of **3a** and **4a**. Standard conditions (batch addition): **1a** (0.25 M or 0.5 M), **2a** (1 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.01 M or 0.02 M), Me-THF, 40 ˚C. Yields were determined by HPLC analysis using DTBB as internal standard. Slow addition: **1a** added in five portions of 0.05 mmol or 0.1 mmol over 40 min.

4. Lignin model etherification kinetic analysis

Model reaction:



1b **3b**

4.1. Determination of order in [catalyst]

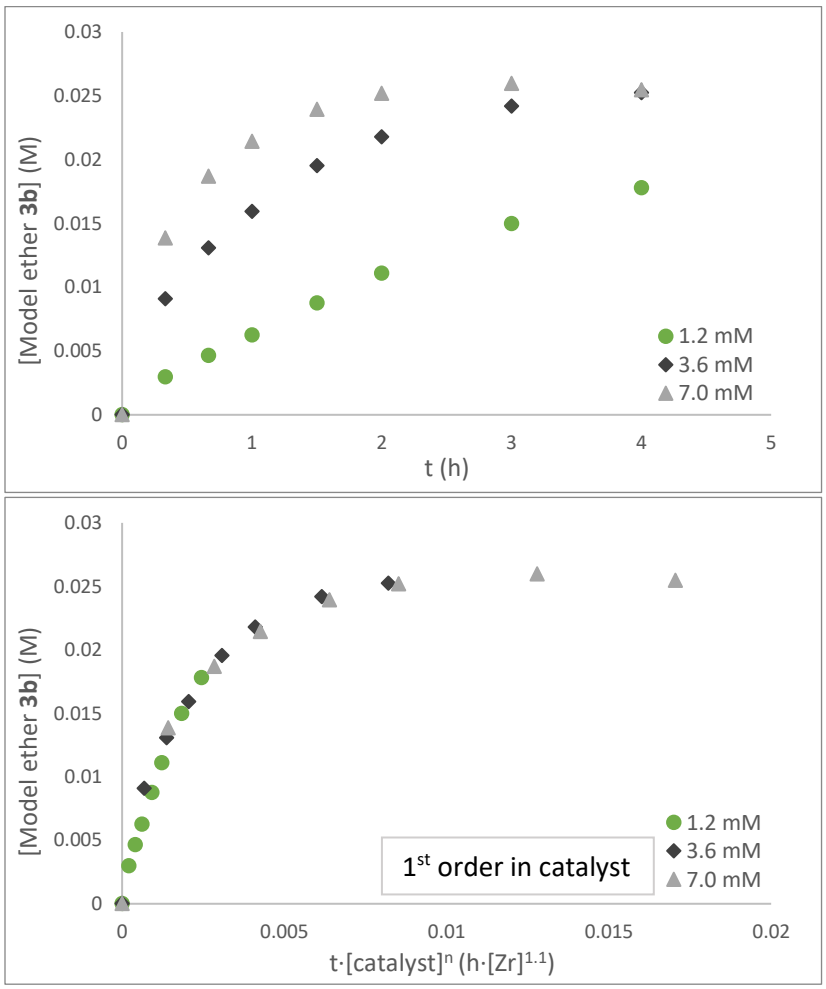


Figure S12. Order in [catalyst] for the formation of product **3b** for reaction time 0 – 4 h. Conditions: model compound **1b** (0.03 M), allyl alcohol (0.33 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (x mM), DTBB as internal standard (8 mM), Me-THF, 40 °C.

4.2. Determination of order in [model compound]

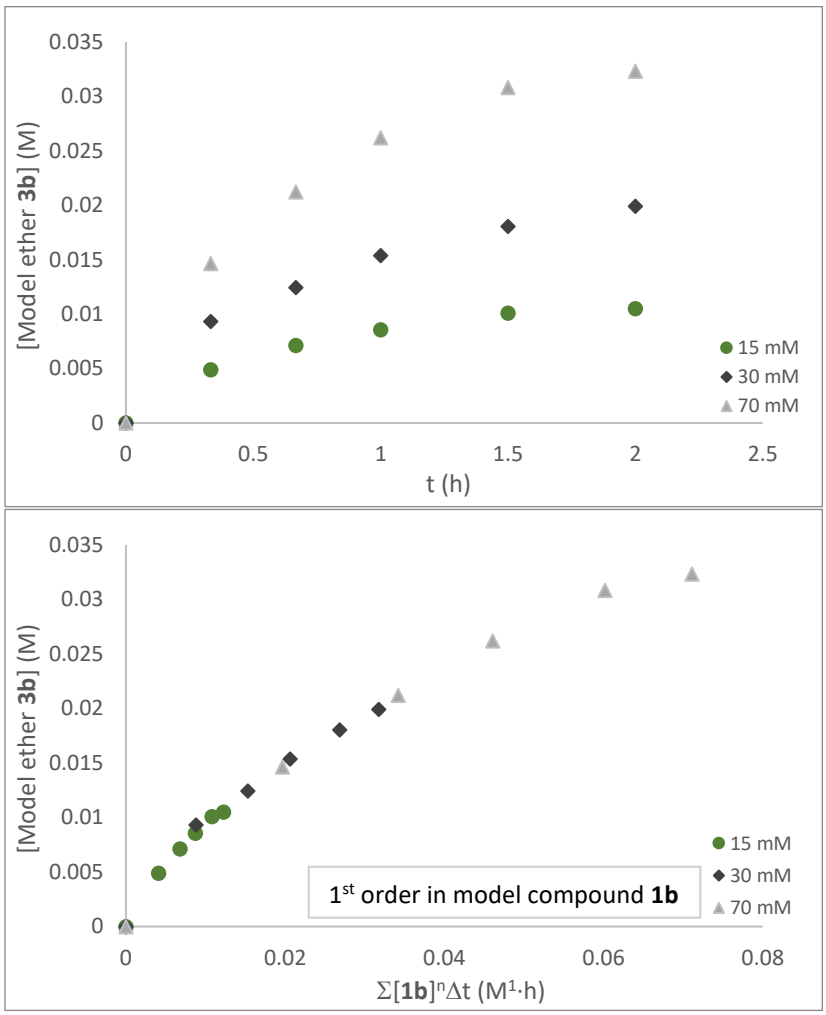


Figure S13. Order in [**1b**] for the formation of product **3b** for reaction time 0 – 2 h. Conditions: model compound **1b** (x mM), allyl alcohol (0.33 M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (3 mM), DTBB as internal standard (4.6 mM), Me-THF, 40 °C.

4.3. Variation of [allyl alcohol]

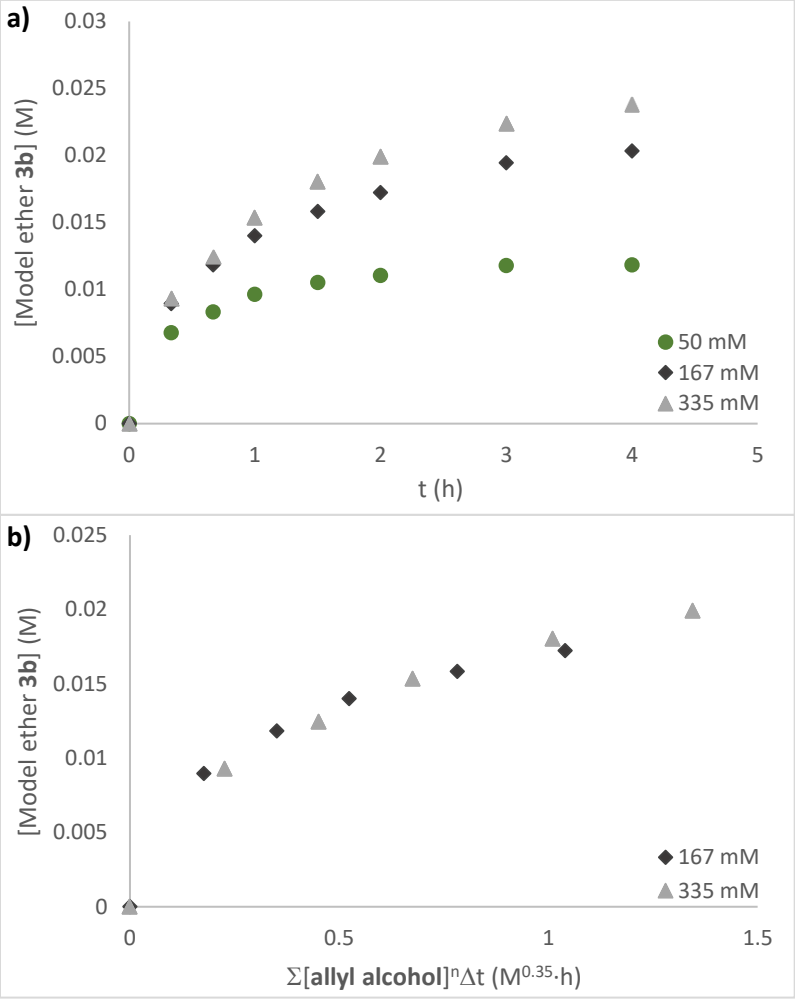
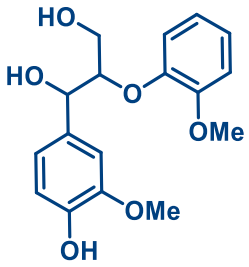


Figure S14. a) Effect of [**allyl alcohol**]$_0$ on yield of **3b**. Conditions: model compound **1b** (0.03 M), allyl alcohol (x mM), $Zr(Cp)_2(CF_3SO_3)_2$·THF (0.003 M), DTBB as internal standard (3.9 mM), Me-THF, 40 °C. **b)** Order in [**allyl alcohol**]$_0$ for the formation of product **3b** for reaction time 0 – 2 h. Conditions: model compound **1b** (30 mM), allyl alcohol (x M), $Zr(Cp)_2(CF_3SO_3)_2$·THF (3 mM), DTBB as internal standard (4.6 mM), Me-THF, 40 °C. The concentration of allyl alcohol over time was calculated based on [**allyl alcohol**]$_0$ and **3b** formation, all other concentrations were monitored by off-line HPLC analysis.

5. General procedures and analytical data for compounds 1b, 3a-p



Lignin model **1b** (guaiacylglycerol-β-guaiacyl ether) was synthesized according to a reported procedure.[4] Analytical data matches with the reported literature.[5] ^{1}H NMR (400 MHz, $CDCl_3$) (mixture of diastereomers *ca.* 1.2:1) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.18 – 6.79 (m, 7H), 5.61 (s, 0.6H), 5.58 (s, 0.5H), 5.01 – 4.93 (m, 1H), 4.19 – 4.13 (m, 0.5H), 4.03 – 3.99 (m, 0.6H), 3.95 – 3.86 (m, 6H), 3.69 – 3.60 (m, 2H), 3.53 – 3.41 (m, 1H), 2.70 – 2.66 (m, 1H).

5.1. General etherification procedure A (slow addition)

The catalyst $Zr(Cp)_2(CF_3SO_3)_2$·THF (5.9 mg, 0.01 mmol) was weighed into a 4 mL glass vial under air atmosphere. To this, the first portion of the indicated lignin-derived alcohol (0.05 mmol) was added. The corresponding nucleophile (1 mmol) was added via Hamilton syringe. 2-MeTHF was added to the vial up to 1 mL of total volume. The vial was equipped with a stir bar and a screw cap, then placed in an oil bath at 40 °C. At intervals of 10 min, additional portions of the benzylic alcohol (4 x 0.05 mmol) were added into the reaction vial. The reaction was stirred for the indicated time, then brought to room temperature and directly subjected to column chromatography on silica gel (see individual compounds for eluent composition).

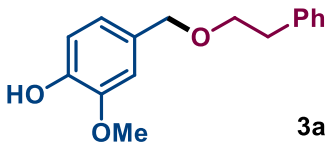
5.2. General etherification procedure B (batch addition)

The catalyst $Zr(Cp)_2(CF_3SO_3)_2$·THF (5.9 mg, 0.01 mmol) was weighed into a 4 mL glass vial under air atmosphere. To this, the indicated lignin-derived alcohol (0.25 mmol) was added. The corresponding nucleophile (1 mmol) was added via Hamilton syringe. 2-MeTHF was added to the vial up to 1 mL of total volume. The vial was equipped with a stir bar and a screw cap, then placed in an oil bath at 40 °C. The reaction was stirred for the indicated time, then brought to room temperature and directly subjected to column chromatography on silica gel (see individual compounds for eluent composition).

5.3. General etherification procedure C (for kinetic analysis)

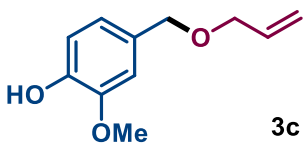
The catalyst was weighed into a 4 mL glass vial under air atmosphere. To this, vanillyl alcohol **1a** or model compound **1b** was added, according to the mode of addition (batch or sequential) reported for individual experiments. The corresponding nucleophile was added via Hamilton syringe. The solvent was added into the vial up to 1 mL of total volume. The vial was equipped with a stir bar and a screw cap, then placed in an oil bath at 40 °C, unless otherwise stated. At indicated times, 15 µL of reaction mixture was removed via Hamilton syringe and diluted with 0.5 mL of 10% v/v aqueous CH_3CN (HPLC gradient grade), filtered in a filter vial (polypropylene housing, PTFE membrane) and subjected to HPLC analysis.

5.4. Synthetic details and analytical data for products 3a-p



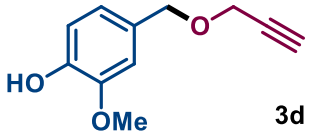
3a

Ether **3a** was synthesized according to general procedure **A** using 2-phenylethanol **2a** as nucleophile and a reaction time of 3 h. The product was isolated as a colorless oil in 85% yield (54.5 mg, 0.211 mmol, isolated with 0.14 mmol **2a**, calculated by ^{1}H-NMR) by flash column chromatography on silica gel (20% EtOAc in petroleum ether). R_f = 0.60 (30% EtOAc in petroleum ether). Alternatively, compound **3a** was synthesized according to the general procedure **B**. The product was isolated in 68% yield (44 mg, 0.17 mmol, isolated with 0.21 mmol **2a**, calculated by ^{1}H-NMR). ^{1}H NMR (400 MHz, $CDCl_3$) 7.18 (m, 5H), 6.65-6.85 (m, 3H), 5.52 (s, 1H), 4.36 (s, 2H), 3.76 (s, 3H), 3.6 (t, J = 7.1 Hz, 2H), 2.85 (t, J = 7.1, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 146.7, 145.3, 139.2, 130.5, 129.2, 128.5, 126.3, 121.0, 114.1, 110.5, 73.1, 71.0, 56.0, 36.5. HRMS (HESI): *m/z* calcd for $C_{16}H_{18}O_3$+Na^+: 281.1148 [*M*+Na]$^+$; found 281.1159.



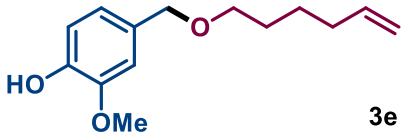
3c

Allyl ether **3c** was synthesized according to general procedure **A** using allyl alcohol as nucleophile and a reaction time of 4 h. The product was isolated as a colorless oil in 72% yield (35 mg, 0.178 mmol) by flash column chromatography on silica gel (20% EtOAc in pentane). R_f = 0.46 (20% EtOAc in petroleum ether). Alternatively, compound **3c** was synthesized according to the general procedure **B** on 0.5 mmol scale. The product was isolated in 58% yield (56 mg, 0.288 mmol) Analytical data matches with the reported literature.[6] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.93 – 6.85 (m, 2H), 6.82 (dd, *J* = 8.0, 1.9 Hz, 1H), 5.96 (ddt, *J* = 17.2, 10.3, 5.7 Hz, 1H), 5.64 (s, 1H), 5.30 (dq, *J* = 17.3, 1.7 Hz, 1H), 5.21 (dd, *J* = 10.3, 1.5 Hz, 1H), 4.44 (s, 2H), 4.01 (dt, *J* = 5.7, 1.5 Hz, 2H), 3.89 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 146.7, 145.4, 135.0, 130.3, 121.3, 117.33, 114.2, 110.7, 72.3, 71.0, 56.0.



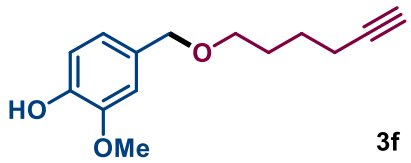
3d

Propargyl ether **3d** was synthesized according to general procedure **A** using propargyl alcohol as nucleophile and a reaction time of 3 h. The product was isolated as a colorless oil in 69% yield (33 mg, 0.172 mmol) by flash column chromatography on silica gel (20% EtOAc in petroleum ether). R_f = 0.32 (10% EtOAc in petroleum ether). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.95 – 6.78 (m, 3H), 5.68 (br s, 1H), 4.53 (s, 2H), 4.15 (d, *J* = 2.4 Hz, 2H), 3.89 (s, 3H), 2.47 (t, *J* = 2.4 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.7, 145.6, 129.2, 121.7, 114.2, 111.0, 79.8, 74.7, 71.7, 56.8, 56.0. HRMS (HESI): *m/z* calcd for $C_{11}H_{11}O_3$: 191.0714 [*M*-H]$^-$; found 191.0709.



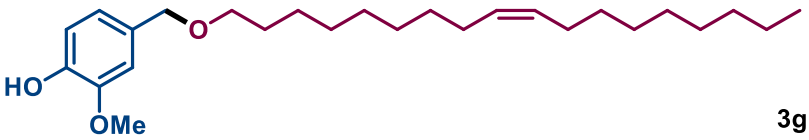
3e

Ether **3e** was synthesized according to general procedure **A** using 5-hexen-1-ol as nucleophile and a reaction time of 3 h. The product was isolated as a colorless oil in 76% yield (45 mg, 0.191 mmol) by flash column chromatography on silica gel (10% to 20% EtOAc in pentane). R_f = 0.67 (10% EtOAc in pentane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.93 – 6.85 (m, 2H), 6.81 (dd, *J* = 8.1, 1.7 Hz, 1H), 5.80 (ddt, *J* = 16.9, 10.2, 6.7 Hz, 1H), 5.67 (br s, 1H), 5.06 – 4.89 (m, 2H), 4.42 (s, 2H), 3.89 (s, 3H), 3.45 (t, *J* = 6.6 Hz, 2H), 2.07 (tdt, *J* = 7.9, 6.6, 1.4 Hz, 2H), 1.68 – 1.58 (m, 2H), 1.52 – 1.42 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 146.7, 145.3, 138.9, 130.7, 121.1, 114.6, 114.2, 110.6, 73.0, 70.1, 56.0, 33.7, 29.3, 25.6. HRMS (HESI): *m/z* calcd for $C_{14}H_{20}O_3$+Na^+: 259.1305 [*M*+Na]$^+$; found 259.1308.



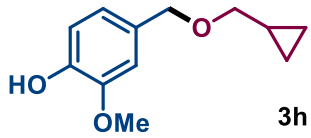
3f

Ether **3f** was synthesized according to general procedure **A** using 5-hexyn-1-ol as nucleophile and a reaction time of 3 h. The product was isolated as a colorless oil in 72% yield (42 mg, 0.179 mmol) by flash column chromatography on silica gel (10% to 20% EtOAc in pentane). R_f = 0.35 (10% EtOAc in pentane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.92 – 6.84 (m, 2H), 6.81 (dd, *J* = 8.0, 1.8 Hz, 1H), 5.61 (br s, 1H), 4.42 (s, 2H), 3.89 (s, 3H), 3.47 (t, *J* = 6.3 Hz, 2H), 2.21 (td, *J* = 7.0, 2.6 Hz, 2H), 1.94 (t, *J* = 2.6 Hz, 1H), 1.79 – 1.67 (m, 2H), 1.67 – 1.58 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.7, 145.3, 130.6, 121.1, 114.2, 110.6, 84.5, 73.0, 69.6, 68.5, 56.0, 28.9, 25.4, 18.3. HRMS (HESI): *m/z* calcd for $C_{14}H_{18}O_3$+Na^+: 257.1148 [*M*+Na]$^+$; found 257.1148.



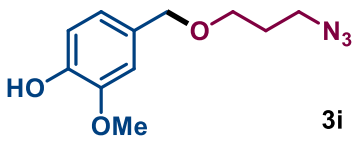
3g

Ether **3g** was synthesized according to general procedure **A** using oleyl alcohol as nucleophile and a reaction time of 3 h. The product was isolated as a colorless oil in 66% yield (67 mg, 0.164 mmol) by flash column chromatography on silica gel (10% EtOAc in pentane) and prep-TLC (22:1 DCM:MeOH). R_f = 0.62 (5% EtOAc in pentane). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.88 – 6.86 (m, 2H), 6.84 – 6.77 (m, 1H), 5.58 (s, 1H), 5.38 – 5.33 (m, 2H), 4.41 (s, 2H), 3.90 (s, 3H), 3.43 (t, *J* = 6.7 Hz, 2H), 2.03 – 1.96 (m, 4H), 1.60 – 1.58 (m, 2H), 1.40 – 1.20 (m, 22H), 0.88 (t, *J* = 6.7 Hz, 3H). ^{13}C NMR (125 MHz, $CDCl_3$): 14.1, 22.7, 26.3, 27.2, 29.3, 29.8, 31.9, 55.9, 70.3, 77.9, 113.4, 114.0, 121.0, 128.9, 130.0, 145.1, 146.6. HRMS (HESI): *m/z* calcd for $C_{26}H_{44}O_3$+Na^+: 427.3183 [*M*+Na]$^+$; found 427.3180.



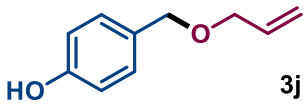
3h

Ether **3h** was synthesized according to general procedure **A** using cyclopropylmethanol as nucleophile and a reaction time of 3 h. The product was isolated as a colorless oil in 67% yield (35 mg, 0.168 mmol) by flash column chromatography on silica gel (20% EtOAc in petroleum ether). R_f = 0.28 (20% EtOAc in petroleum ether). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.90 (d, *J* = 1.8 Hz, 1H), 6.86 (d, *J* = 8.0 Hz, 1H), 6.81 (dd, *J* = 8.0, 1.8 Hz, 1H), 4.45 (s, 2H), 3.89 (s, 3H), 3.28 (d, *J* = 6.9 Hz, 2H), 1.15 – 1.02 (m, 1H), 0.58 – 0.48 (m, 2H), 0.19 (dt, *J* = 6.0, 4.5 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 146.7, 145.3, 130.6, 121.2, 114.2, 110.6, 74.8, 72.7, 56.0, 10.8, 3.2. HRMS (HESI): *m/z* calcd for $C_{12}H_{16}O_3$+Na^+: 231.0992 [*M*+Na]$^+$; found 231.0994.



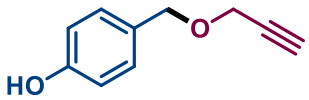
3i

Ether **3i** was synthesized according to general procedure **A** using 3-azido-1-propanol as nucleophile and a reaction time of 3 h. The product was isolated as a yellow oil in 26% yield (16 mg, 0.065 mmol) by flash column chromatography on silica gel (10% to 20% EtOAc in petroleum ether). R_f = 0.34 (20% EtOAc in petroleum ether). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.92 – 6.85 (m, 2H), 6.81 (dd, *J* = 8.0, 1.9 Hz, 1H), 4.42 (s, 2H), 3.90 (s, 3H), 3.54 (t, *J* = 6.0 Hz, 2H), 3.41 (t, *J* = 6.7 Hz, 2H), 1.91 – 1.83 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 146.7, 145.5, 130.2, 121.2, 114.3, 110.6, 73.3, 66.8, 56.0, 48.7, 29.3. HRMS (HESI): *m/z* calcd for $C_{11}H_{14}N_3O_3$: 231.1041 [*M*-H]$^-$; found 231.1040.



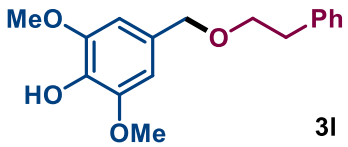
3j

Allyl ether **3j** was synthesized according to general procedure **A** using allyl alcohol as nucleophile and a reaction time of 3 h. The product was isolated as a colorless oil in 78% yield (32 mg, 0.195 mmol) by flash column chromatography on silica gel (20% EtOAc in petroleum ether). R_f = 0.58 (20% EtOAc in petroleum ether). Analytical data matches with the reported literature.[7] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.23 – 7.16 (m, 2H), 6.80 – 6.69 (m, 2H), 6.08 (s, 1H), 5.95 (ddt, *J* = 17.3, 10.3, 5.8 Hz, 1H), 5.31 (dq, *J* = 17.3, 1.7 Hz, 1H), 5.22 (dq, *J* = 10.3, 1.4 Hz, 1H), 4.46 (s, 2H), 4.09 – 3.99 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.7, 134.6, 129.9, 129.8, 117.8, 115.5, 72.0, 71.0.



3k

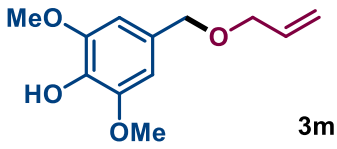
Propargyl ether **3k** was synthesized according to general procedure **A** using propargyl alcohol as nucleophile and a reaction time of 3 h. The product was isolated as a colorless oil in 67% yield (27 mg, 0.167 mmol) by flash column chromatography on silica gel (20% EtOAc in petroleum ether). R_f = 0.64 (20% EtOAc in petroleum ether). Analytical data matches with the reported literature.[8] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.27 – 7.18 (m, 2H), 6.83 – 6.74 (m, 2H), 5.56 (br s, 1H), 4.54 (s, 2H), 4.16 (d, *J* = 2.4 Hz, 2H), 2.48 (t, *J* = 2.4 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.7, 130.3, 129.2, 115.5, 79.7, 74.9, 71.3, 56.8.



3l

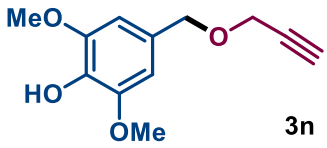
Ether **3l** was synthesized according to general procedure **A** using 2-phenylethanol **2a** as nucleophile and a reaction time of 1.5 h. The product was isolated as a colorless oil in 56% yield (40 mg, 0.139 mmol,

isolated with 0.79 mmol **2a**, calculated by ^{1}H-NMR) by flash column chromatography on silica gel (30% EtOAc in petroleum ether) and further purified by prep-TLC (20:1 DCM:MeOH). R_f = 0.60 (30% EtOAc in petroleum ether). Alternatively, compound **3l** was synthesized according to the general procedure **B**. The product was isolated in 32% yield (23 mg, 0.08 mmol, isolated with 0.23 mmol **2a**, calculated by ^{1}H-NMR). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 – 7.17 (m, 5H), 6.52 (s, 2H), 5.46 (s, 1H), 4.44 (s, 2H), 3.85 (s, 6H), 3.69 (t, *J* = 7.1 Hz, 2H), 2.93 (t, *J* = 7.0 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 147.1, 139.2, 134.2, 129.6, 129.1, 128.5, 126.3, 104.5, 73.3, 71.1, 56.4, 36.5. HRMS (HESI): *m/z* calcd for $C_{17}H_{20}O_4$+Na^+: 311.1254 [*M*+Na]$^+$; found 311.1257.



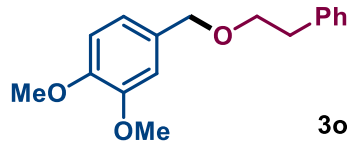
3m

Allyl ether **3m** was synthesized according to general procedure **A** using allyl alcohol as nucleophile and a reaction time of 1.5 h. The product was isolated as a yellow oil in 48% yield (27 mg, 0.12 mmol) by flash column chromatography on silica gel (30% EtOAc in petroleum ether). R_f = 0.35 (30% EtOAc in petroleum ether). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.58 (s, 2H), 5.96 (ddt, *J* = 17.3, 10.4, 5.7 Hz, 1H), 5.51 (br s, 1H), 5.30 (dd, *J* = 17.2, 1.7 Hz, 1H), 5.21 (dd, *J* = 10.4, 1.5 Hz, 1H), 4.43 (s, 2H), 4.02 (dt, *J* = 5.7, 1.4 Hz, 2H), 3.88 (s, 6H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 147.1, 134.9, 134.3, 129.4, 117.4, 104.8, 72.5, 71.1, 56.4. HRMS (HESI): *m/z* calcd for $C_{12}H_{16}O_4$+Na^+: 247.0941 [*M*+Na]$^+$; found 247.0943.



3n

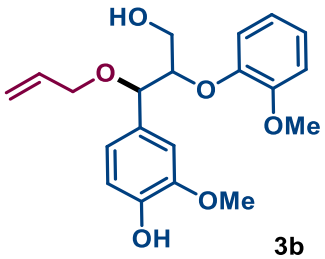
Propargyl ether **3n** was synthesized according to general procedure **A** using propargyl alcohol as nucleophile and a reaction time of 1.5 h. The product was isolated as a yellow oil in 25% yield (14 mg, 0.063 mmol) by flash column chromatography on silica gel (30% EtOAc in petroleum ether). R_f = 0.43 (30% EtOAc in petroleum ether). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.60 (s, 2H), 4.53 (s, 2H), 4.16 (d, *J* = 2.4 Hz, 2H), 3.89 (s, 6H), 2.47 (t, *J* = 2.4 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 147.1, 134.6, 128.4, 105.2, 79.8, 74.8, 72.0, 57.0, 56.4. HRMS (HESI): *m/z* calcd for $C_{12}H_{14}O_4$+Na^+: 245.0784 [*M*+Na]$^+$; found 245.0794.



3o

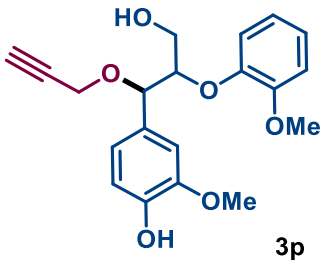
Ether **3o** was synthesized according to general procedure **A** using 2-phenylethanol **2a** as nucleophile and a reaction time of 3 h. The product was isolated as a colorless oil in 28% yield (19 mg, 0.07 mmol, isolated with 0.22 mmol **2a**, calculated by ^{1}H-NMR) by flash column chromatography on silica gel (20% EtOAc in petroleum ether). R_f = 0.43 (30% EtOAc in petroleum ether). Alternatively, compound **3o** was synthesized according to the general procedure **B**. The product was isolated in 26% yield (18 mg, 0.07 mmol). ^{1}H NMR

(400 MHz, $CDCl_3$) δ 7.29 – 7.18 (m, 5H), 6.85 – 6.82 (m, 3H), 4.47 (s, 2H), 3.87 (s, 3H), 3.84 (s, 3H), 3.68 (t, *J* = 7.1 Hz, 2H), 2.93 (t, *J* = 7.1 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 149.1, 148.6, 139.2, 131.1, 129.1, 128.4, 126.3, 120.2, 111.0, 111.0, 73.0, 71.0, 56.0, 55.9, 36.5. HRMS (HESI): *m/z* calcd for $C_{17}H_{20}O_3$+Na^+: 295.1305 [*M*+Na]$^+$; found 295.1303.



3b

Ether **3b** was synthesized according to general procedure **B** (0.22 mmol scale) using allyl alcohol as nucleophile (1.46 mmol, 6.6 equiv.), 9 mol% $Zr(Cp)_2(CF_3SO_3)_2$·THF and a reaction time of 4 h. The product was isolated as a yellow oil in 75% yield (60 mg, 0.167 mmol) by flash column chromatography on silica gel (2% to 3% MeOH in DCM). R_f = 0.72 (66% EtOAc in petroleum ether). ^{1}H NMR (400 MHz, $CDCl_3$) (mixture of diastereomers *ca.* 1:1) δ 7.28 (dd, *J* = 7.8, 1.7 Hz, 0.5H), 7.02 (td, *J* = 7.7, 1.7 Hz, 0.5H), 6.97 – 6.81 (m, 5H), 6.76 (td, *J* = 7.7, 1.6 Hz, 0.5H), 6.54 (dd, *J* = 8.0, 1.6 Hz, 0.5H), 5.97 – 5.84 (m, 1H), 5.73 (br, 0.5H), 5.69 (br, 0.5H), 5.29 – 5.21 (m, 1H), 5.19 – 5.12 (m, 1H), 4.57 (t, *J* = 7.0 Hz, 1H), 4.24 – 4.18 (m, 0.5H), 4.16 – 4.08 (m, 0.5H), 4.05 – 3.98 (m, 1H), 3.97 – 3.92 (m, 1H), 3.91 – 3.85 (m, 5H), 3.84 (s, 1.5H), 3.81 (s, 1.5H), 3.51 – 3.36 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.2, 151.1, 148.8, 147.8, 147.0, 146.8, 145.8, 145.5, 134.9, 134.6, 131.0, 130.1, 123.54, 123.49, 121.6, 121.4, 120.96, 120.94, 120.3, 117.2, 116.9, 114.5, 114.3, 112.13, 112.05, 110.13, 109.7, 87.8, 86.7, 81.6, 80.5, 69.90, 69.85, 62.2, 61.9, 56.1, 55.9. HRMS (HESI): *m/z* calcd for $C_{20}H_{24}O_6$+Na^+: 383.1465 [*M*+Na]$^+$; found 383.1452.



3p

Ether **3p** was synthesized according to general procedure **B** (0.1 mmol scale) using propargylic alcohol as nucleophile (1 mmol, 10 equiv.), 1 mol% of $Zr(Cp)_2(CF_3SO_3)_2$·THF and a reaction time of 3 h. The product was isolated as colorless oil in 50% yield (18 mg, 0.05 mmol) by flash column chromatography on silica gel (66% EtOAc in petroleum ether). R_f = 0.66 (66% EtOAc in petroleum ether). ^{1}H NMR (400 MHz, CDCl3) δ 7.24 – 7.17 (m, 0.5H), 7.06 – 6.97 (m, 0.5H), 6.97 – 6.87 (m, 4H), 6.84 (td, *J* = 8.5, 1.6 Hz, 1H), 6.76 (td, *J* = 7.7, 1.6 Hz, 0.5H), 6.56 (dd, *J* = 8.0, 1.6 Hz, 0.5H), 5.70 (br, 0.5H), 5.67 (br, 0.5H), 4.77 (t, *J* = 7.4 Hz, 1H), 4.29 – 4.09 (m, 2H), 4.06 – 3.90 (m, 2H), 3.87 (s, 4H), 3.85 (s, 1.5H), 3.80 (s, 1.5H), 3.57 – 3.36 (m, 1H), 2.44 (t, *J* = 2.4 Hz, 0.5H), 2.40 (t, *J* = 2.4 Hz, 0.5H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 151.2, 148.7, 147.8, 147.1, 146.8, 146.1, 145.8, 129.9, 129.1, 123.72, 123.69, 121.7, 121.5, 121.4, 121.30, 121.29, 120.5, 114.5, 114.4, 112.2,

112.1, 110.4, 109.8, 87.7, 86.7, 81.0, 79.83, 79.76, 79.6, 74.8, 74.6, 62.2, 62.0, 56.2, 56.13, 56.11, 56.00, 55.98, 55.9. HRMS (HESI): *m*/*z* calcd for $C_{20}H_{22}O_6$+Na^+: 381.1309 [*M*+Na]$^+$; found 381.1322.

6. Lignin extraction and allylation

Wheat straws were roughly ground into 1-2 cm pieces and extracted with EtOH 96% overnight using a Soxhlet extraction apparatus yielding extractive-free wheat straw. The extractive-free wheat straw was milled through a 40-mesh screen using a Wiley Mini Mill 3383-L70 (Thomas Scientific). The resulting powder underwent ball milling with a Retch PM-400 planetary ball mill using stainless-steel jars and stainless-steel grinding balls.

The ratio of jar volume (L) -grinding balls (g): sample weight (g) was 1: 800: 40. The ball milling was performed at 300 rpm in 1 hour milling intervals with pauses of 30 minutes in between each interval. The total milling time was 18 h.

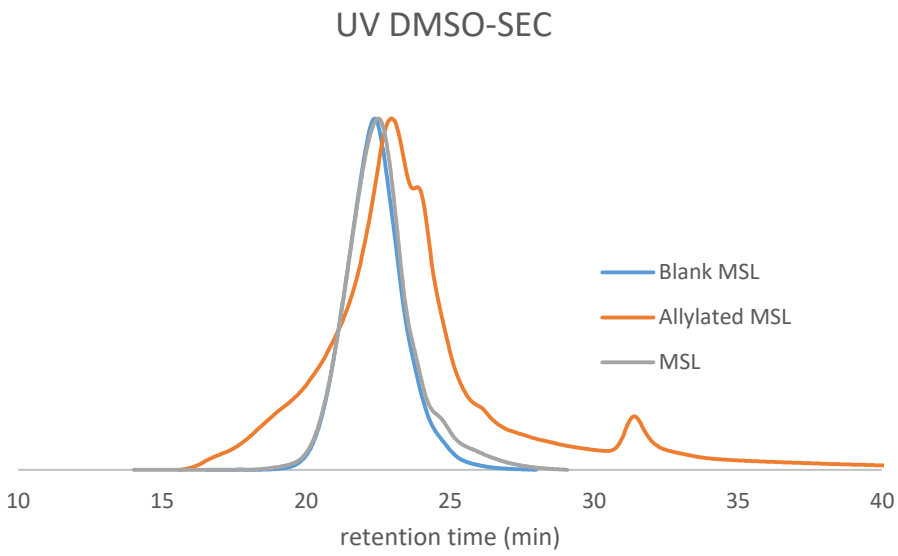
Milled straw lignin (MSL) was extracted according to the protocol by Björkman. A dispersion of ball-milled wheat straw (4% wt./v) in aqueous 1-4 dioxane (96% v/v) was mechanically stirred at room temperature for 72 h. The resulting mixture was centrifuged and the supernatant dried using a rotary evaporator and subsequently lyophilized to obtain MSL. No further purification was applied to the resulting material.

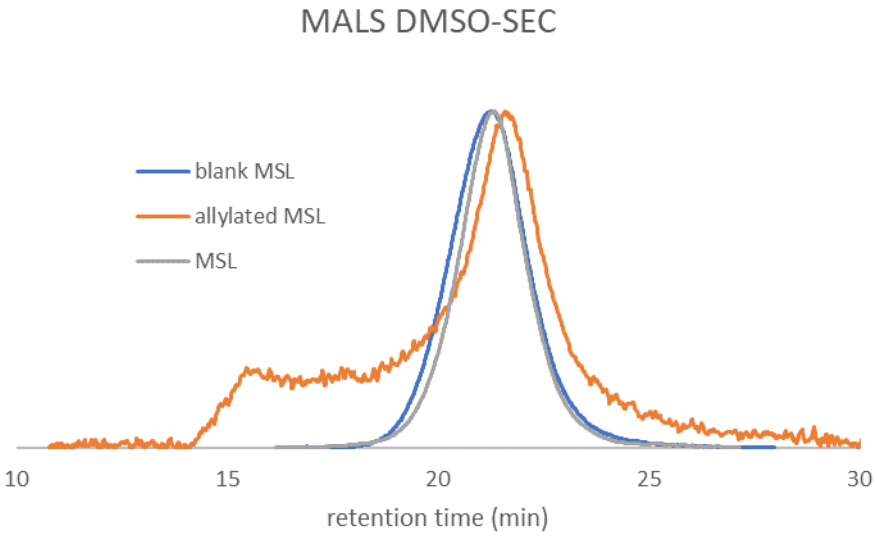
MSL catalytic allylation

MSL (100 mg) was reacted together with allyl alcohol (400 μL) in presence of zirconocene triflate (48 mg) in Me-THF (600 μL). The reaction was carried out at 40 °C. After 6 h the solvents were removed by using a rotary evaporator and the residual catalyst was extracted with DCM (3 x 1 mL). The resulting solids were dried and analysed by NMR and FT-IR.

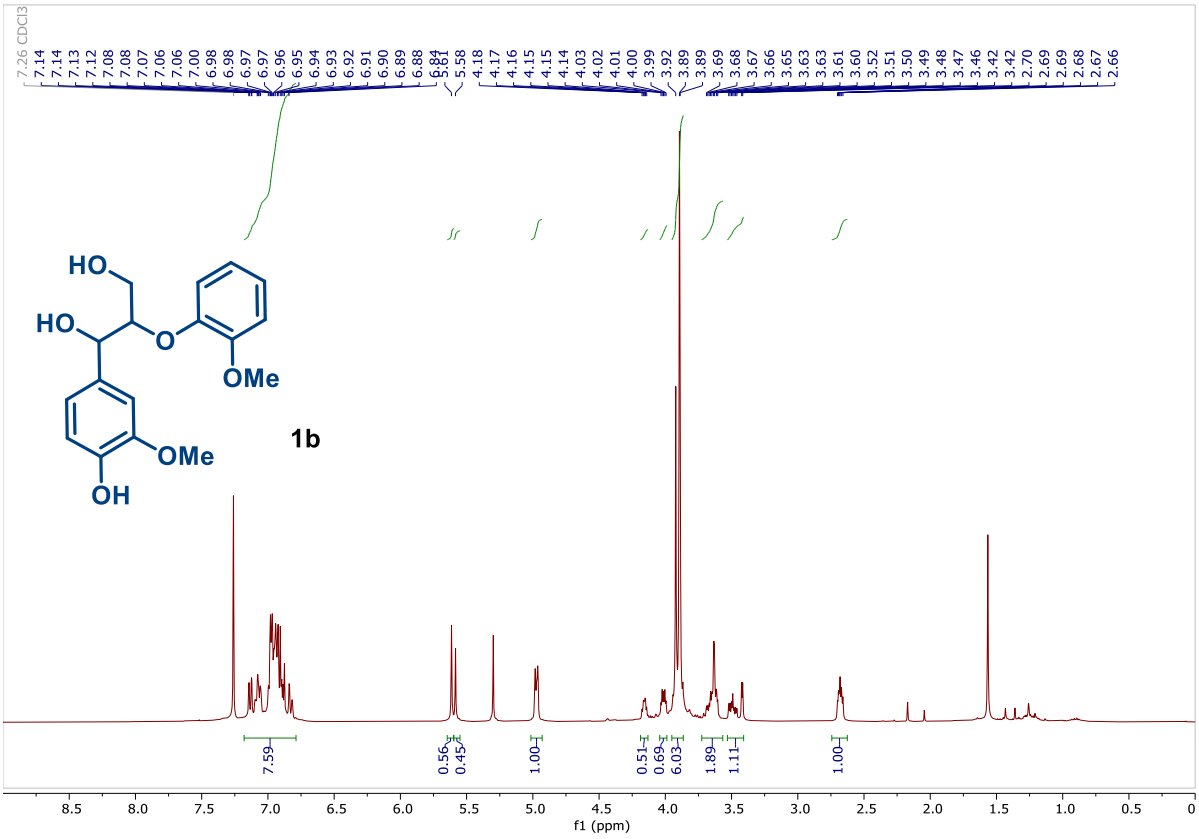
The blank reaction was run according to the same procedure except for the zirconocene-based catalyst.

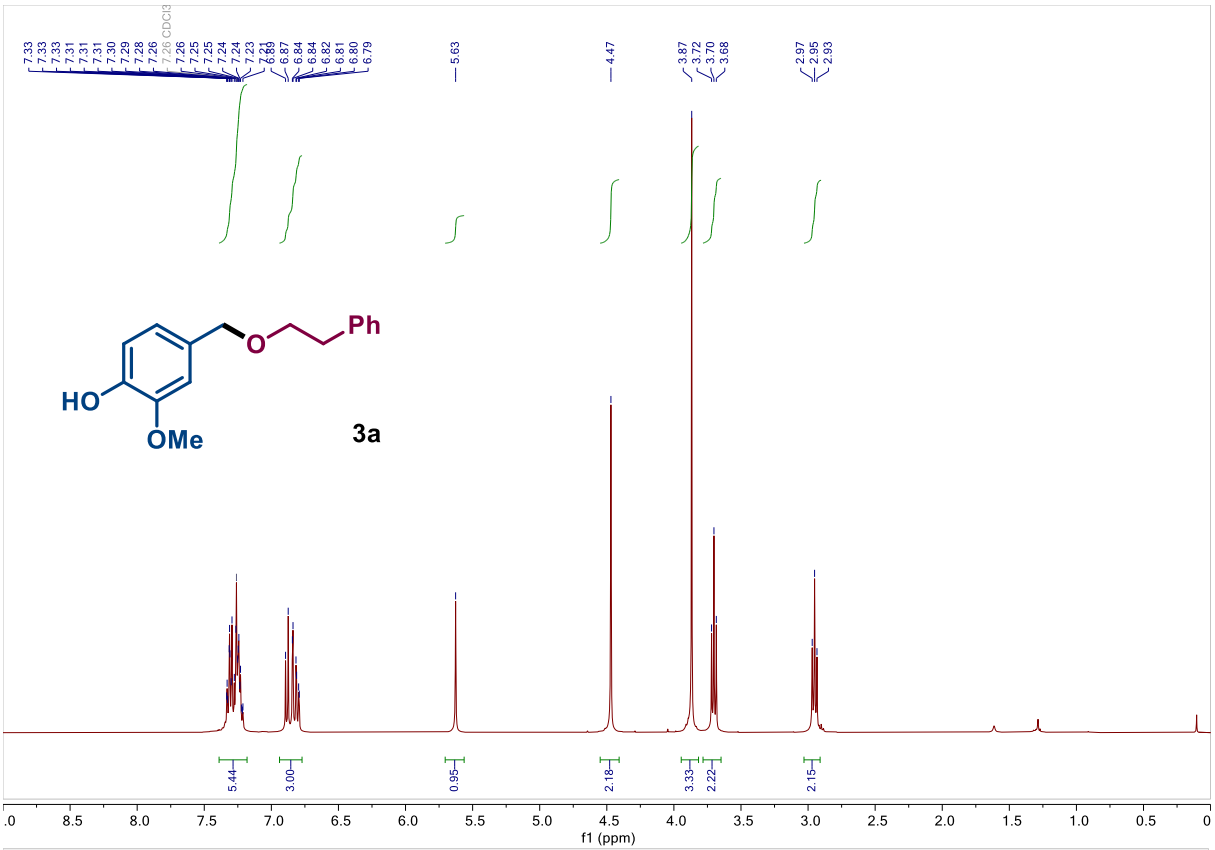
Size exclusion chromatography





7. NMR spectra




7.33
7.33
7.33
7.31
7.31
7.31
7.30
7.29
7.28
7.26
7.26 CDCl3
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7.25
7.25
7.24
7.24
7.23
6.88
6.87
6.84
6.84
6.82
6.81
6.80
6.79
5.63
4.47
3.87
3.72
3.70
3.68
2.97
2.95
2.93
Ph
O
HO
OMe
3a
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3.00
0.95
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3.33
2.22
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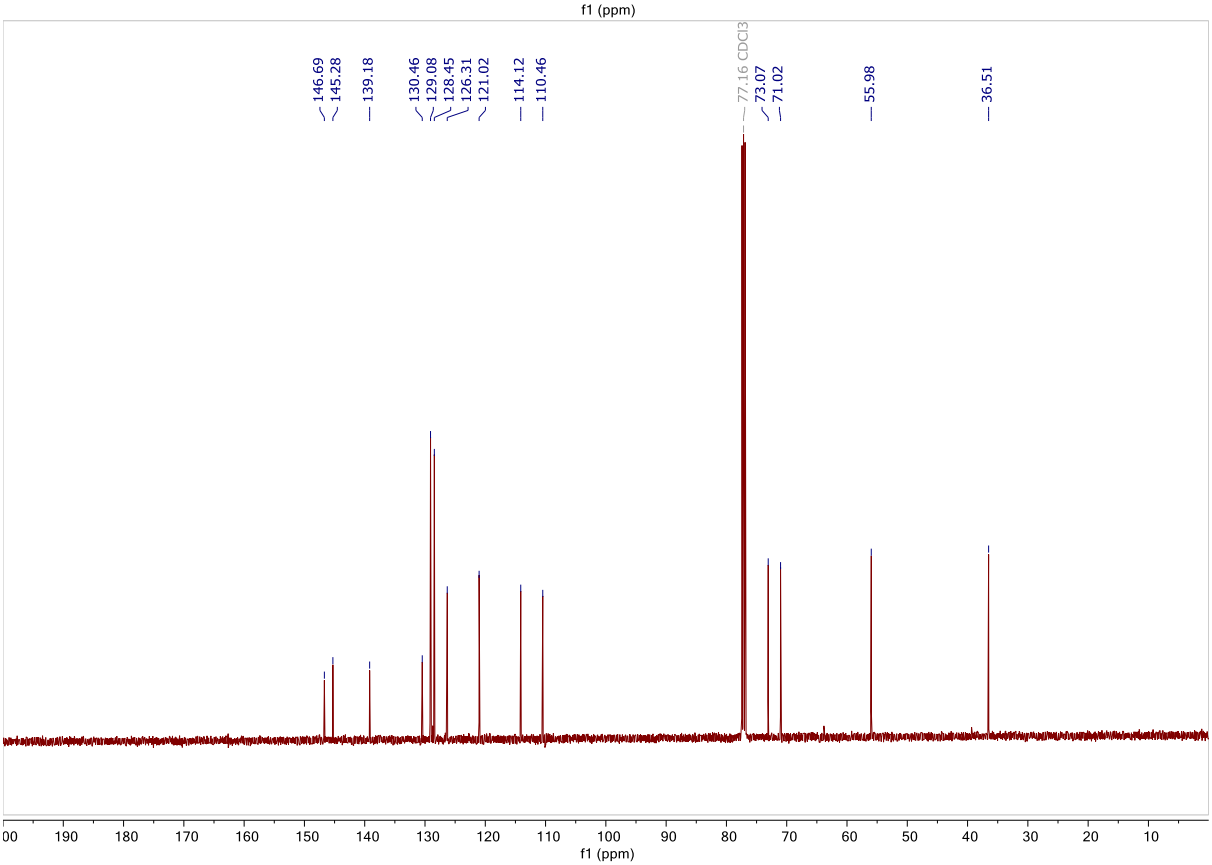
f1 (ppm)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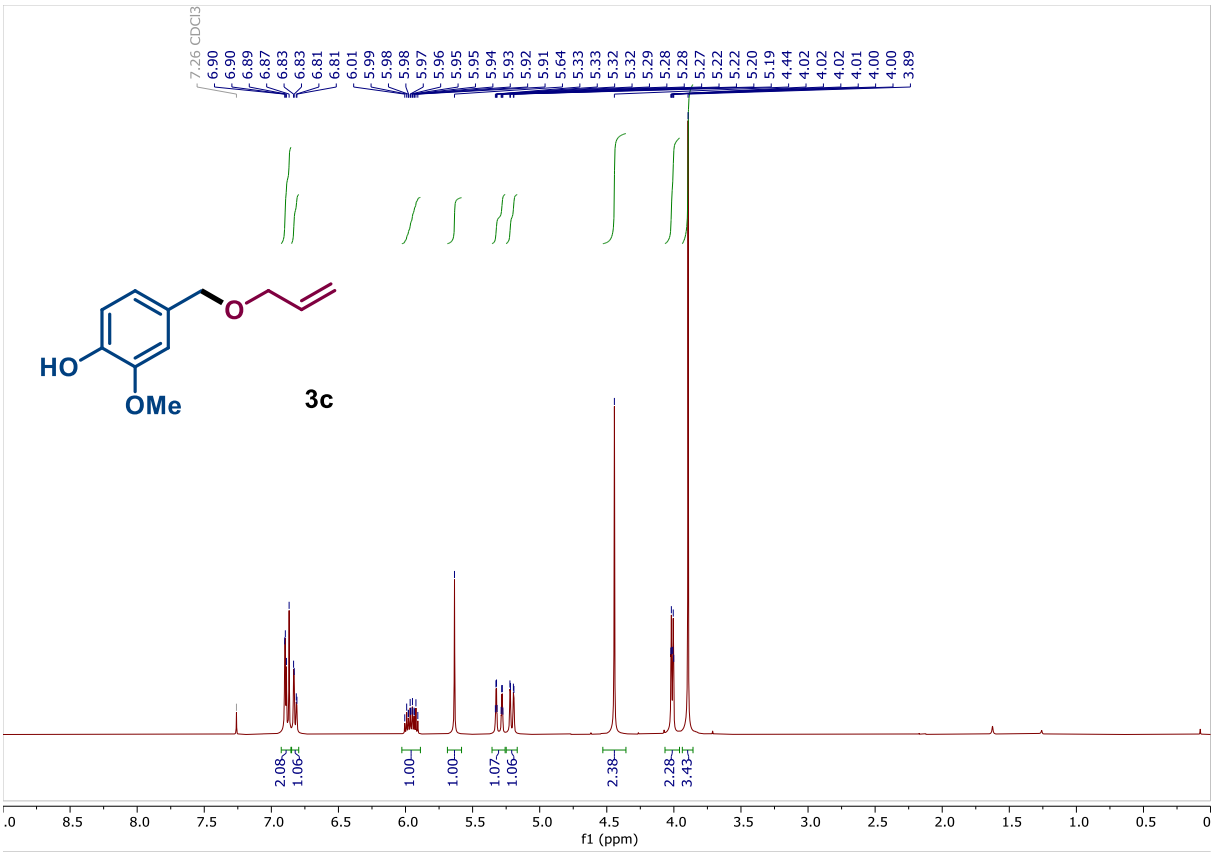
f1 (ppm)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4.02
4.01
4.00
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HO
OMe
3c
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1.06
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1.07
1.06
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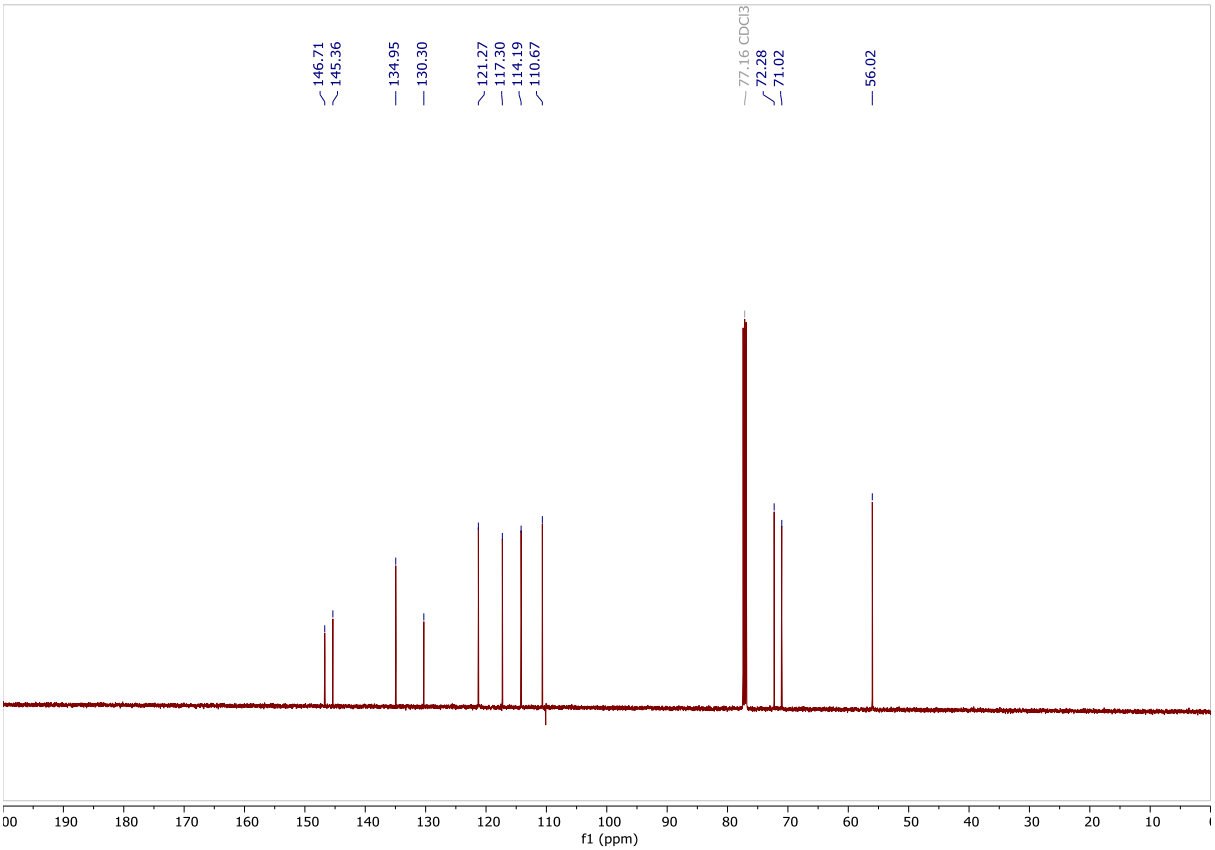
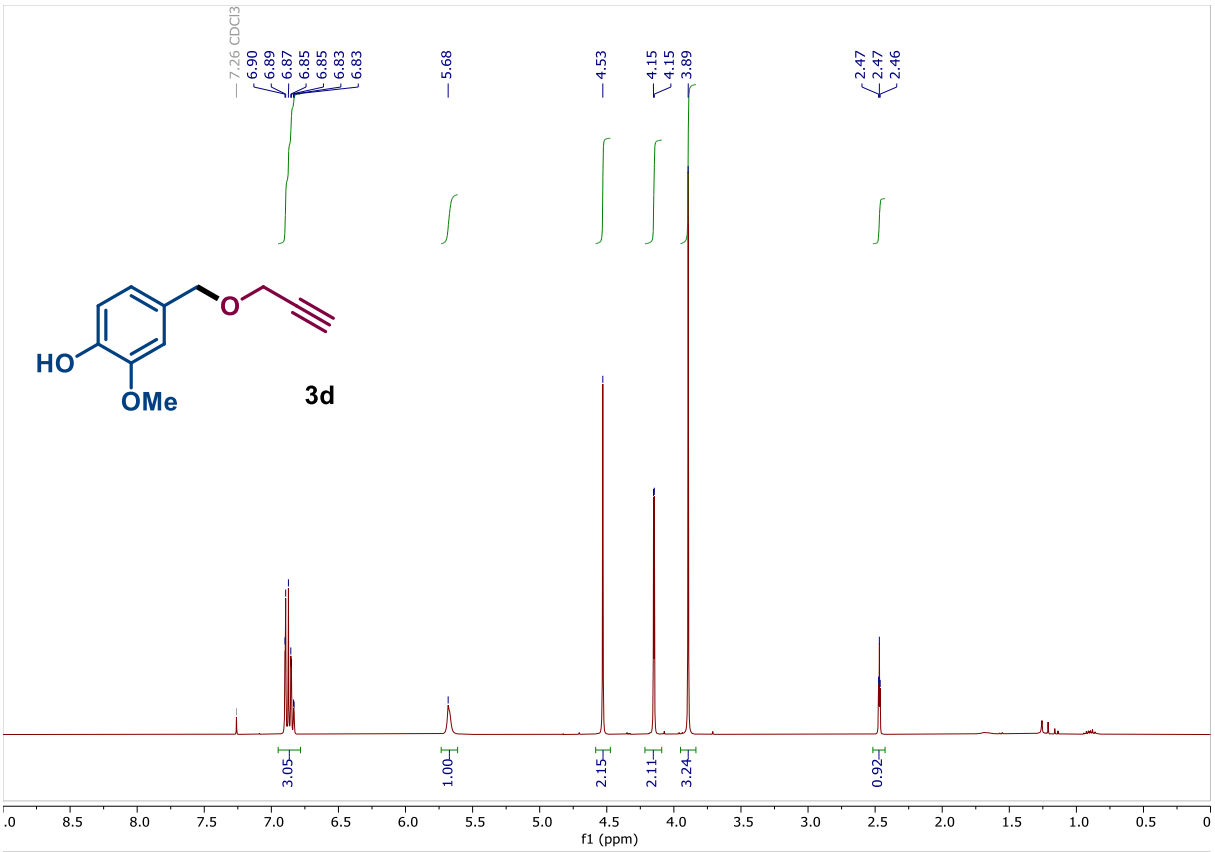
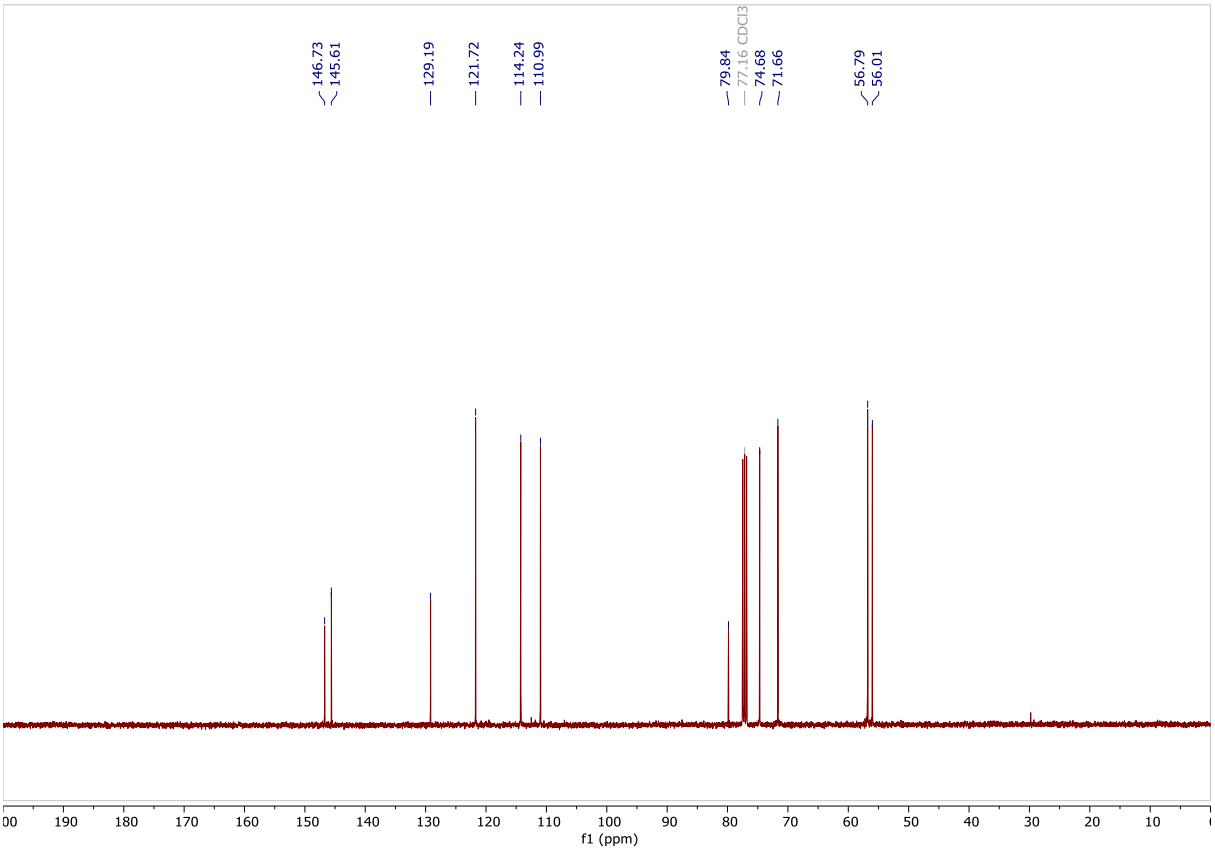
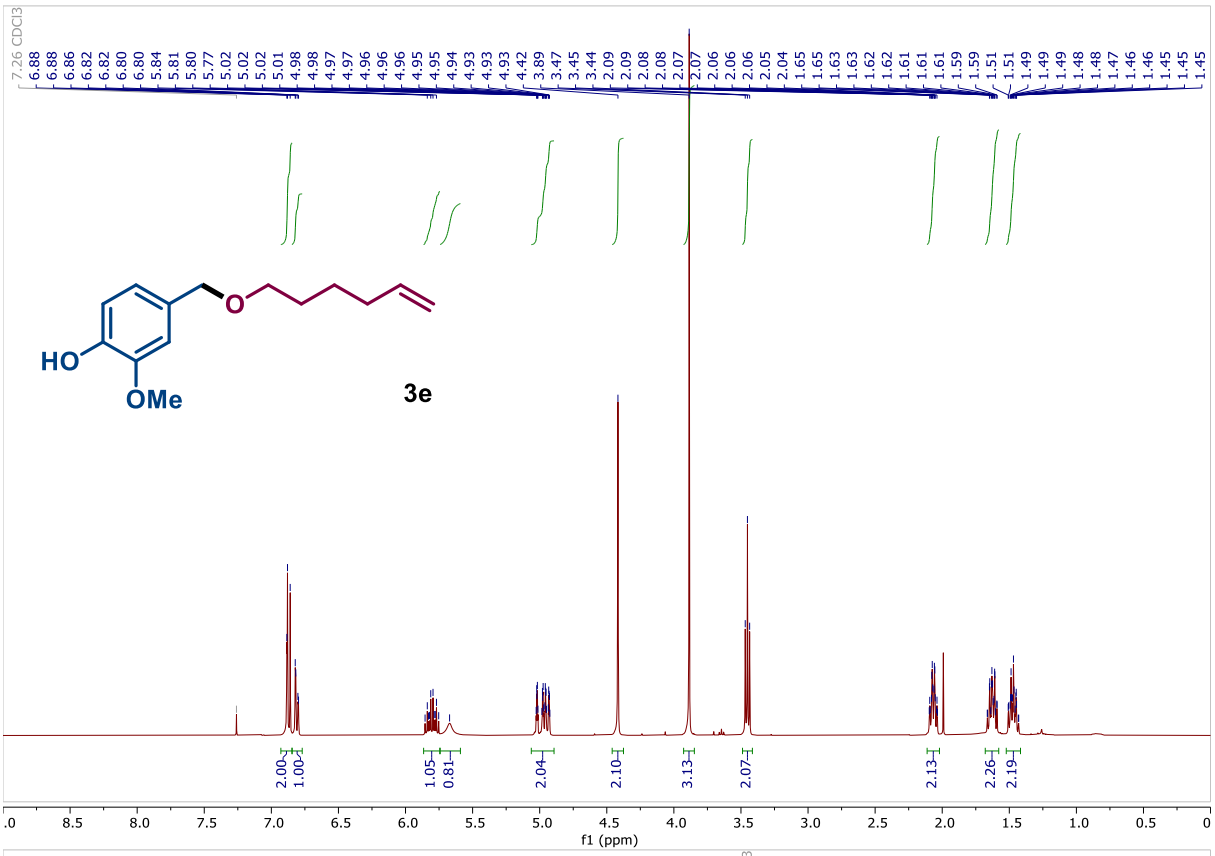
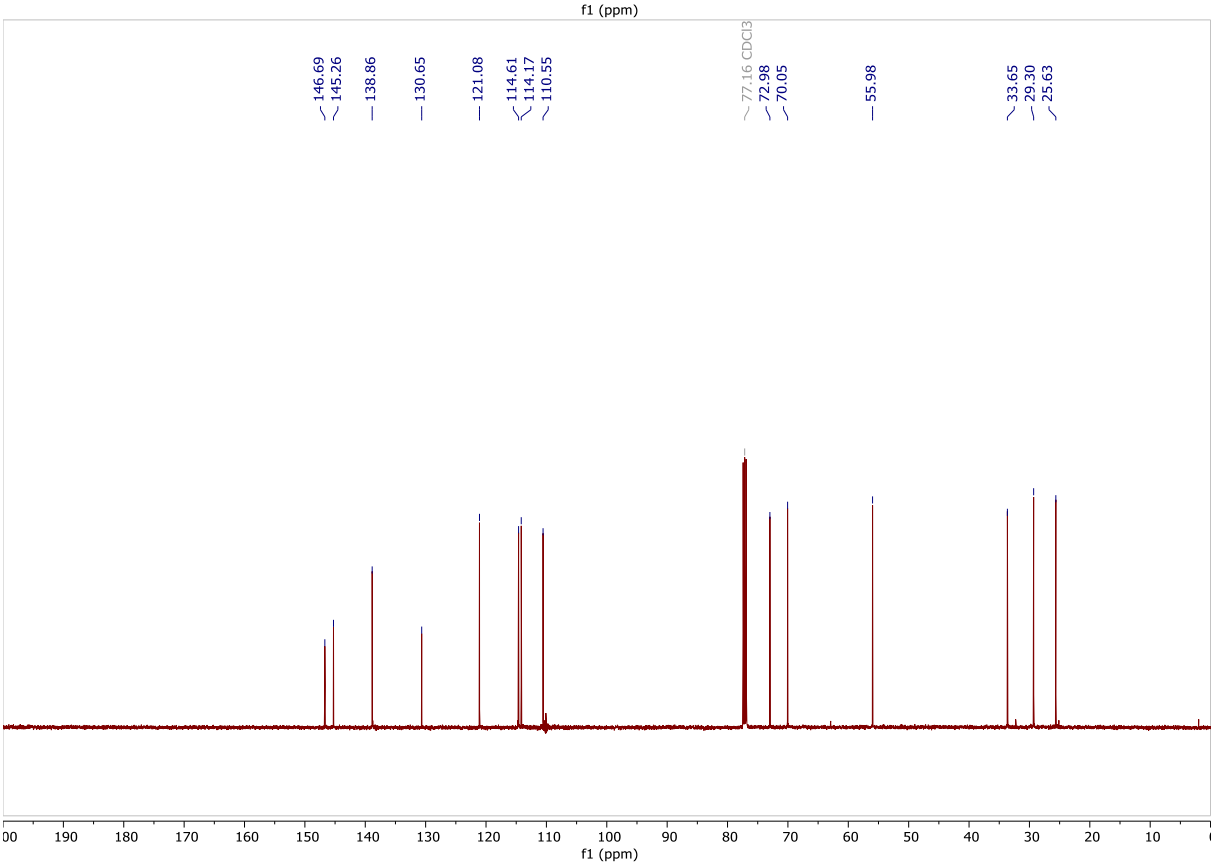
2.28
3.43
f1 (ppm)

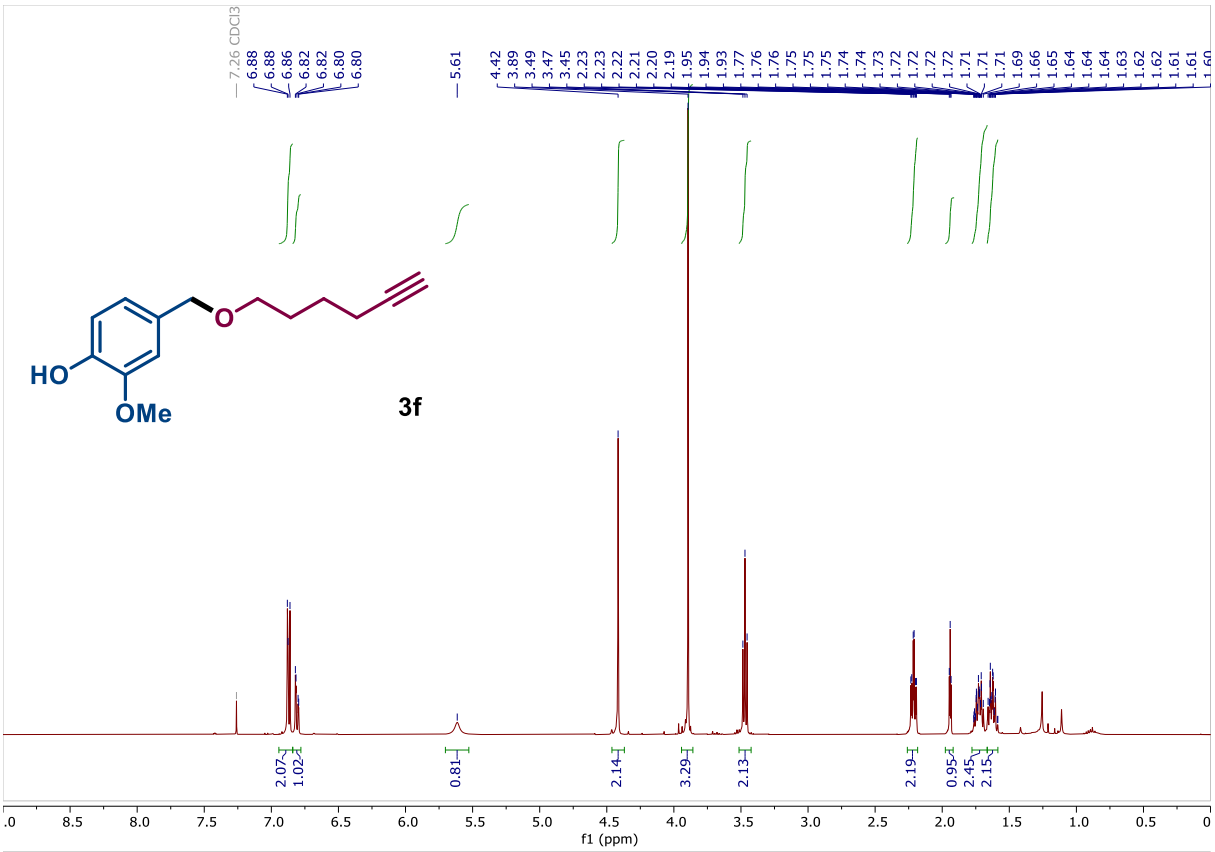

146.71
145.36
134.95
130.30
121.27
117.30
114.19
110.67
77.16 CDCl3
72.28
71.02
56.02
f1 (ppm)

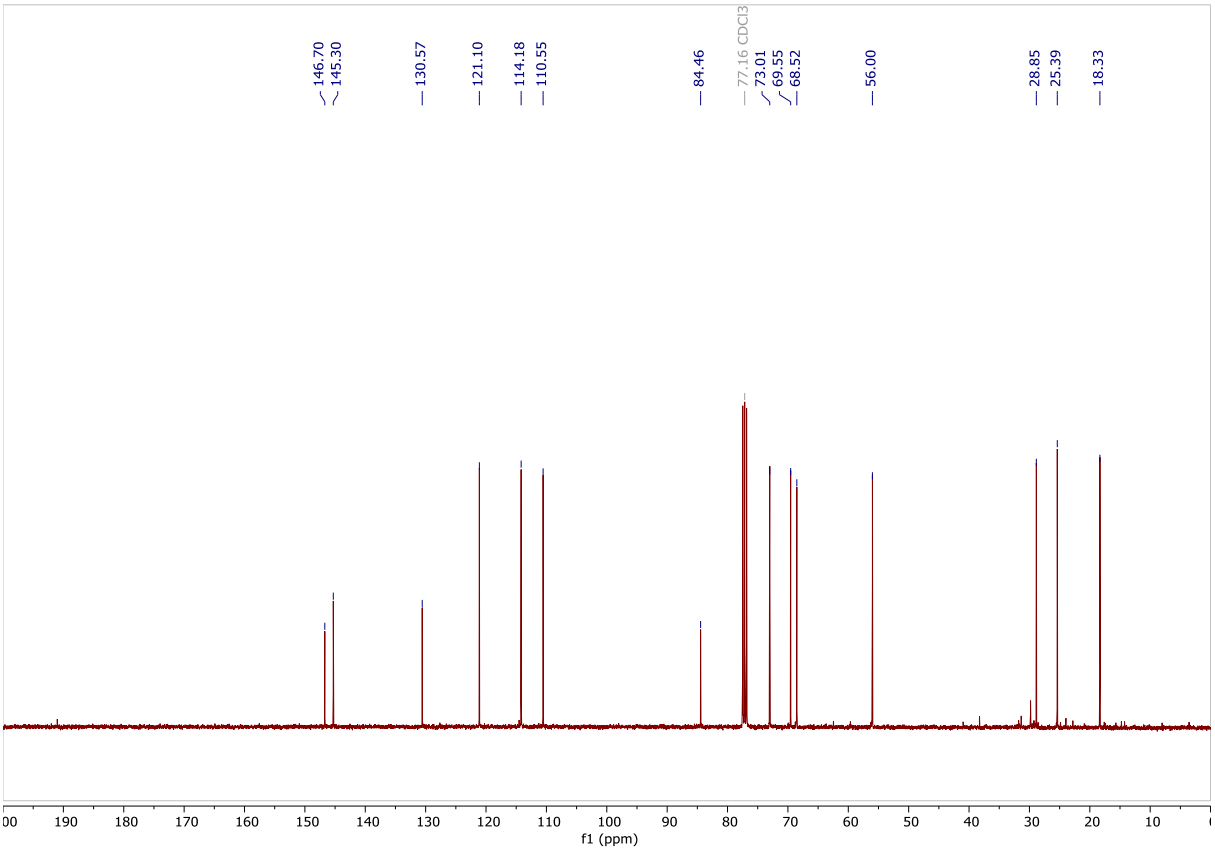

7.26 CDCl3
6.90
6.89
6.87
6.85
6.85
6.83
6.83
5.68
4.53
4.15
4.15
3.89
2.47
2.47
2.46
HO
OMe
O
3d
3.05
1.00
2.15
2.11
3.24
0.92
f1 (ppm)

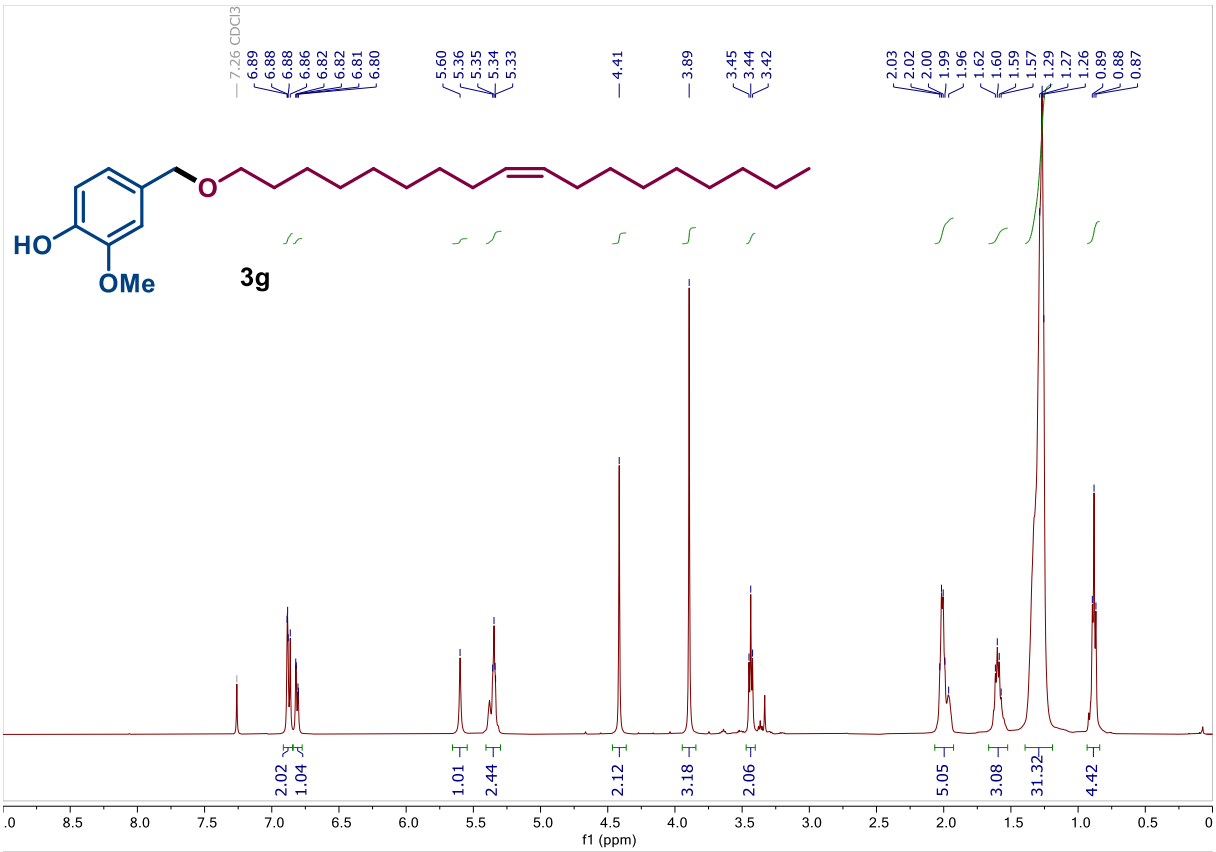

146.73
145.61
129.19
121.72
114.24
110.99
79.84
77.16 CDCl3
74.68
71.66
56.79
56.01
f1 (ppm)

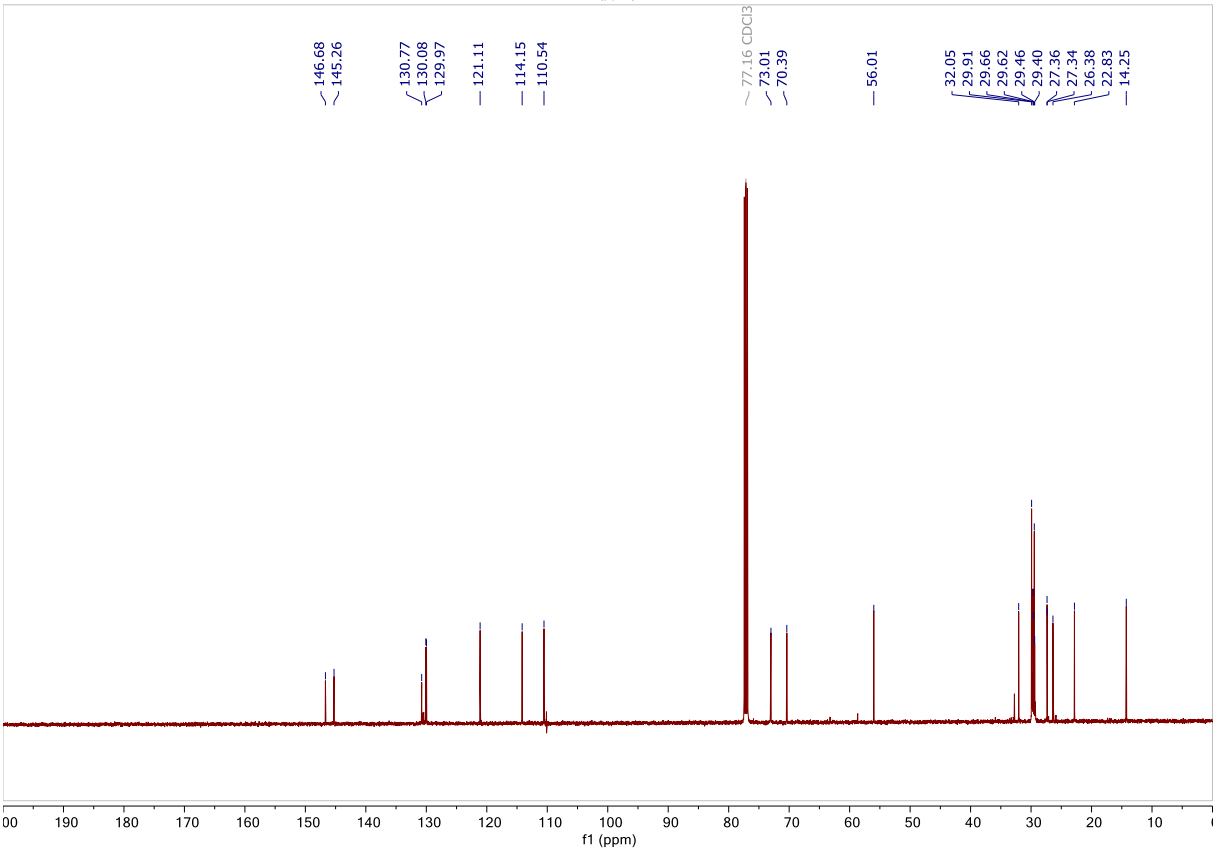

7.26 CDCl3
HO
OMe
O
3e
2.00
1.00
1.05
0.81
2.04
2.10
3.13
2.07
2.13
2.26
2.19
f1 (ppm)

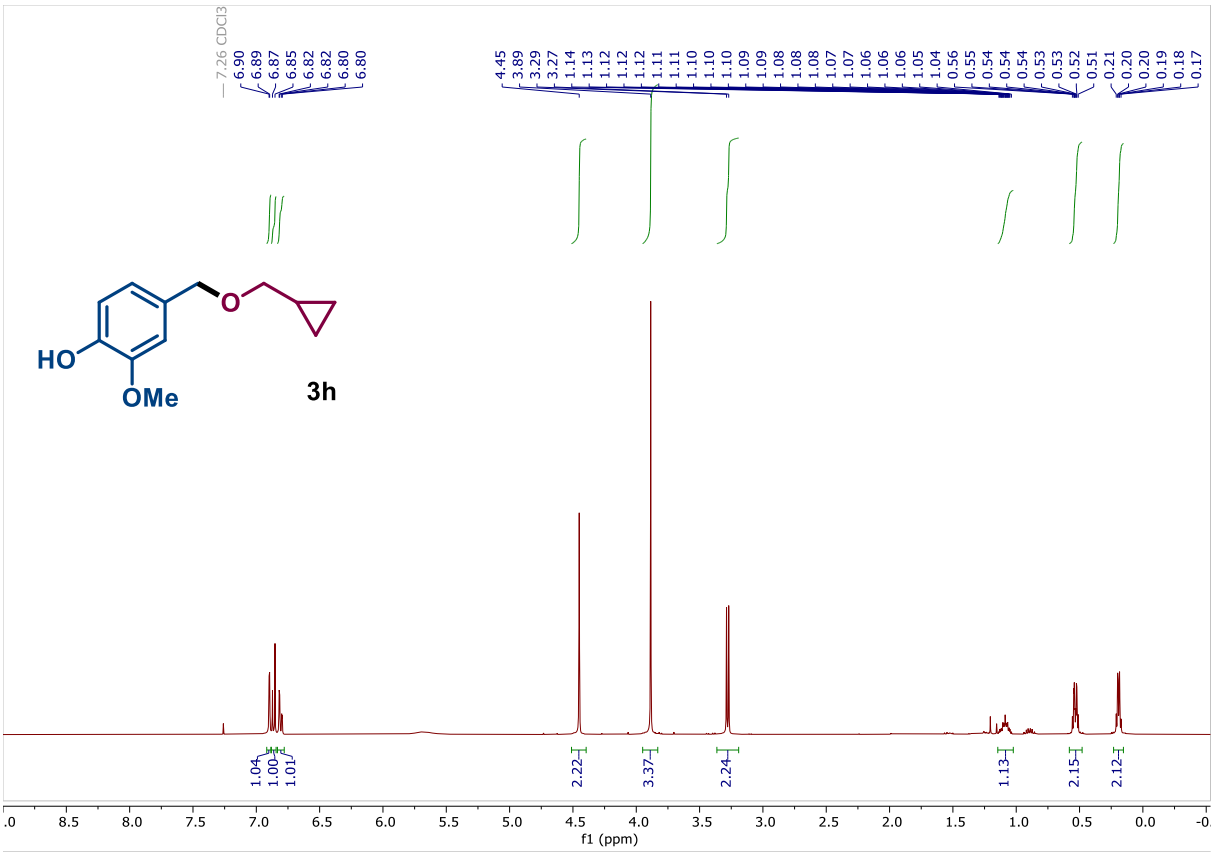

146.69
145.26
138.86
130.65
121.08
114.61
114.17
110.55
77.16 CDCl3
72.98
70.05
55.98
33.65
29.30
25.63
f1 (ppm)

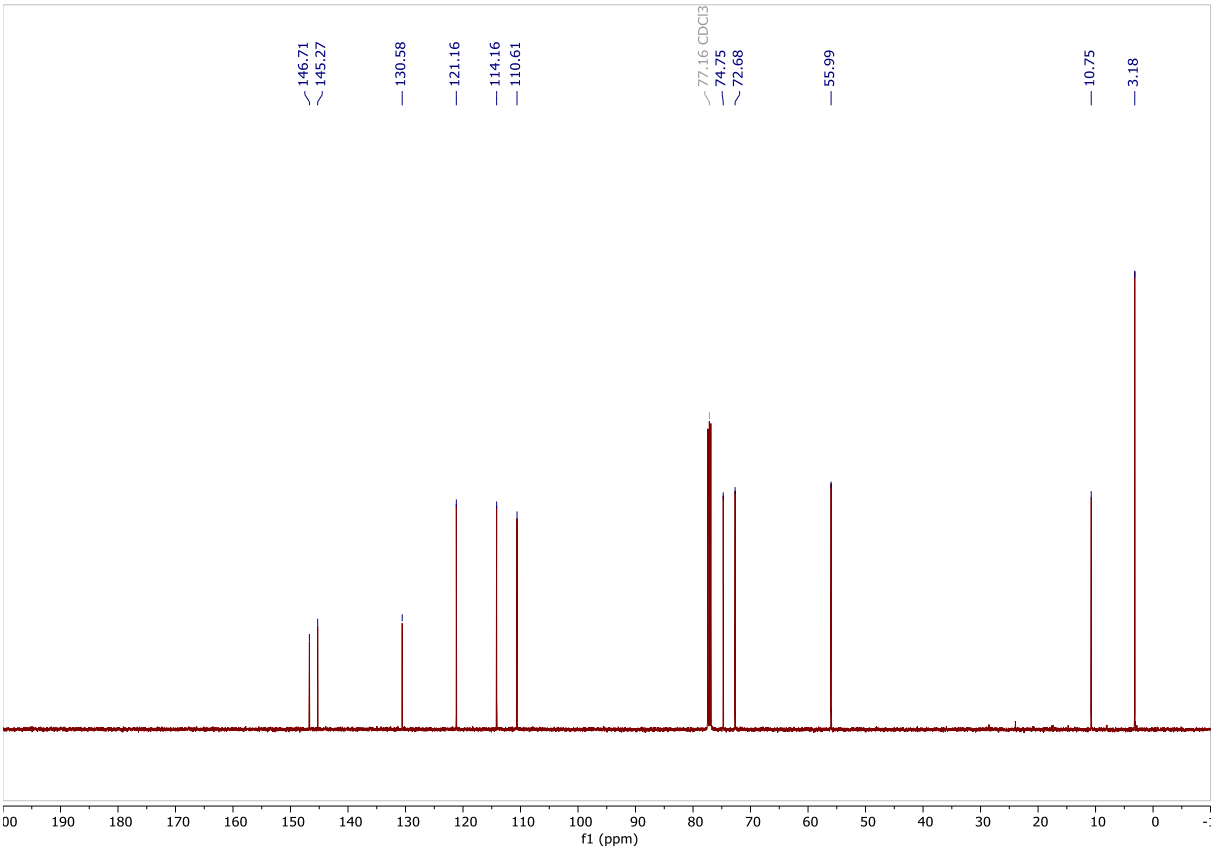

7.26 CDCl3
6.88
6.88
6.86
6.82
6.82
6.80
6.80
5.61
4.42
3.89
3.49
3.47
3.45
2.23
2.22
2.21
2.20
2.19
1.95
1.94
1.93
1.77
1.76
1.76
1.75
1.75
1.75
1.74
1.74
1.73
1.72
1.72
1.72
1.72
1.71
1.71
1.71
1.69
1.66
1.65
1.64
1.64
1.64
1.63
1.62
1.61
1.61
1.60
HO
OMe
O
3f
2.07
1.02
0.81
2.14
3.29
2.13
2.19
0.95
2.45
2.15
f1 (ppm)

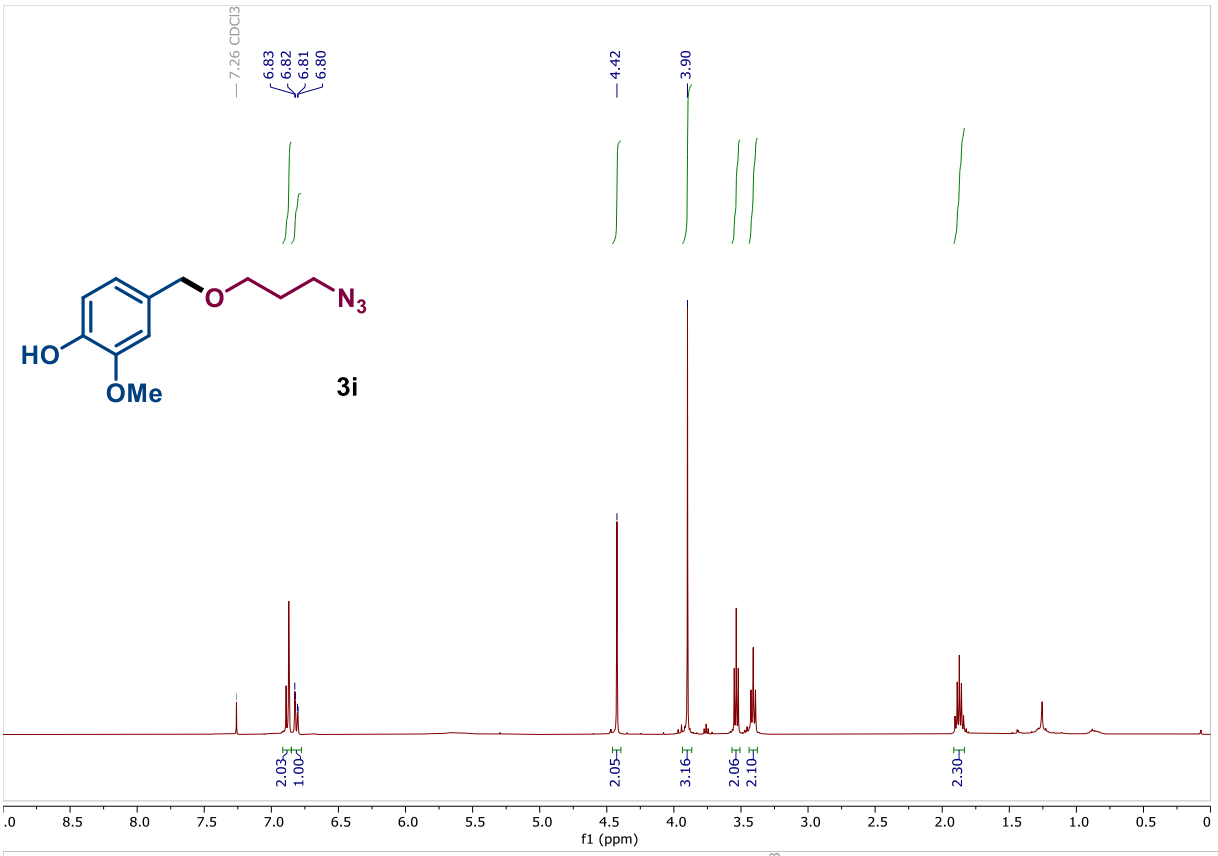

146.70
145.30
130.57
121.10
114.18
110.55
84.46
77.16 CDCl3
73.01
69.55
68.52
56.00
28.85
25.39
18.33
f1 (ppm)

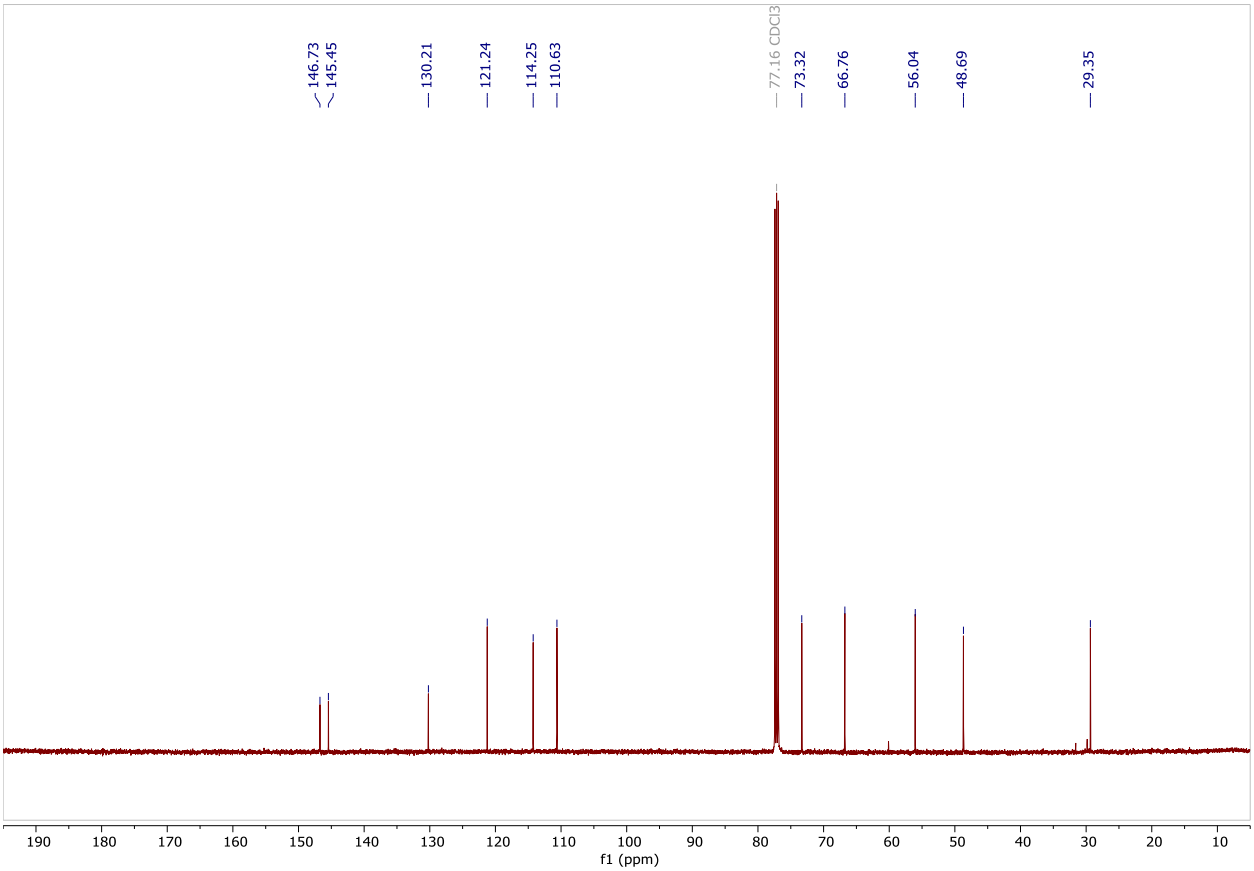

7.26 CDCl3
6.89
6.88
6.88
6.86
6.82
6.82
6.81
6.80
5.60
5.36
5.35
5.34
5.33
4.41
3.89
3.45
3.44
3.42
2.03
2.02
2.00
1.99
1.96
1.62
1.60
1.59
1.57
1.29
1.27
1.26
0.89
0.88
0.87
HO
OMe
O
3g
2.02
1.04
1.01
2.44
2.12
3.18
2.06
5.05
3.08
31.32
4.42
f1 (ppm)

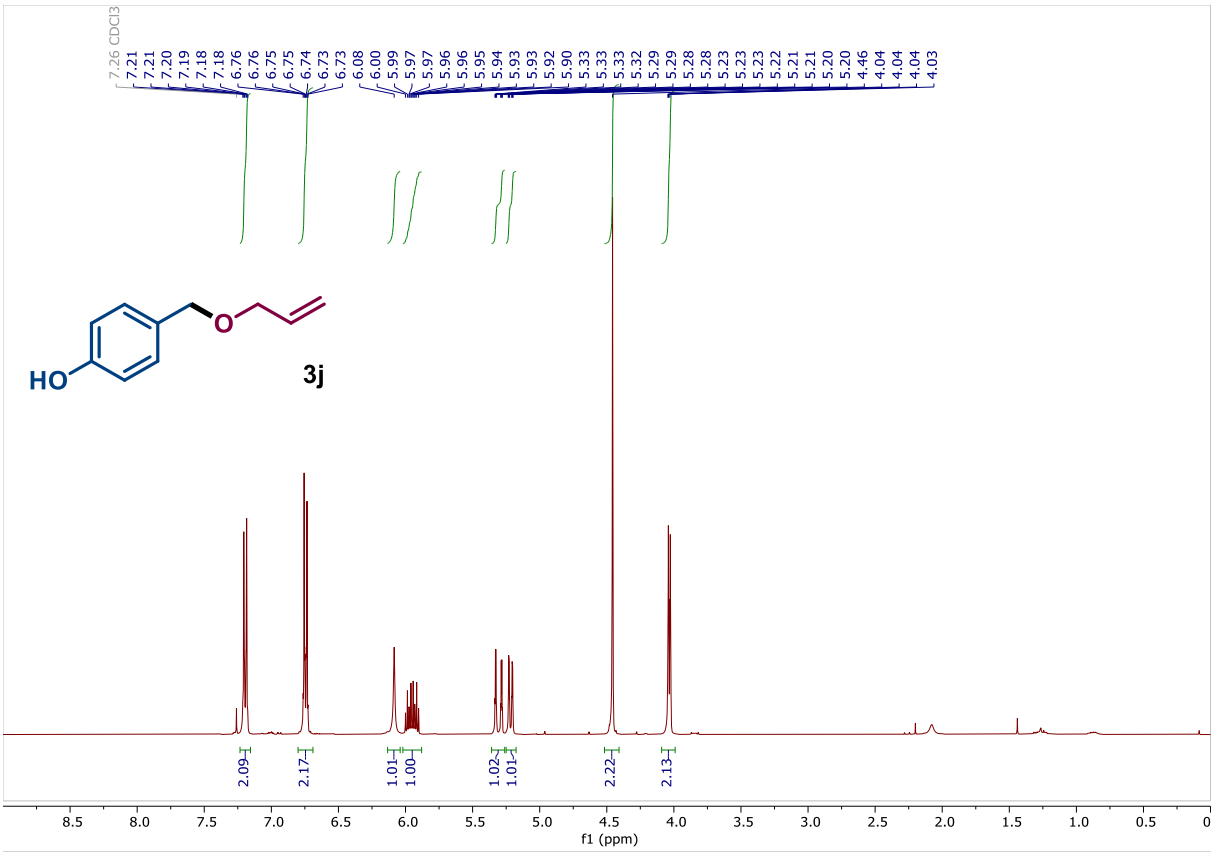

146.68
145.26
130.77
130.08
129.97
121.11
114.15
110.54
77.16 CDCl3
73.01
70.39
56.01
32.05
29.91
29.66
29.62
29.46
29.40
27.36
27.34
26.38
22.83
14.25
f1 (ppm)

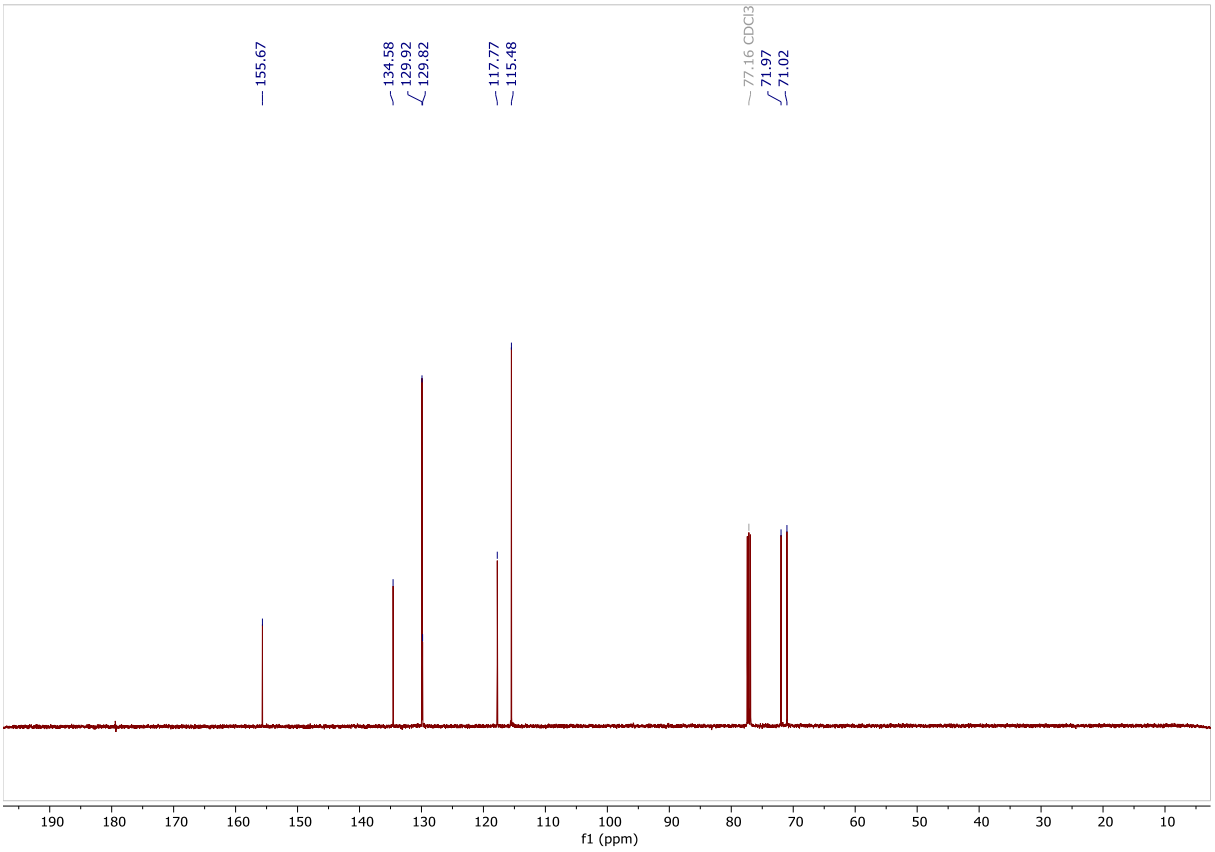

7.26 CDCl3
6.90
6.89
6.87
6.85
6.82
6.82
6.80
6.80
4.45
3.89
3.29
3.27
1.14
1.13
1.12
1.12
1.12
1.11
1.11
1.10
1.10
1.10
1.09
1.09
1.08
1.08
1.08
1.07
1.07
1.06
1.06
1.06
1.05
1.04
0.56
0.55
0.54
0.54
0.54
0.53
0.53
0.52
0.51
0.21
0.20
0.20
0.19
0.18
0.17
HO
OMe
O
3h
1.04
1.00
1.01
2.22
3.37
2.24
1.13
2.15
2.12
f1 (ppm)

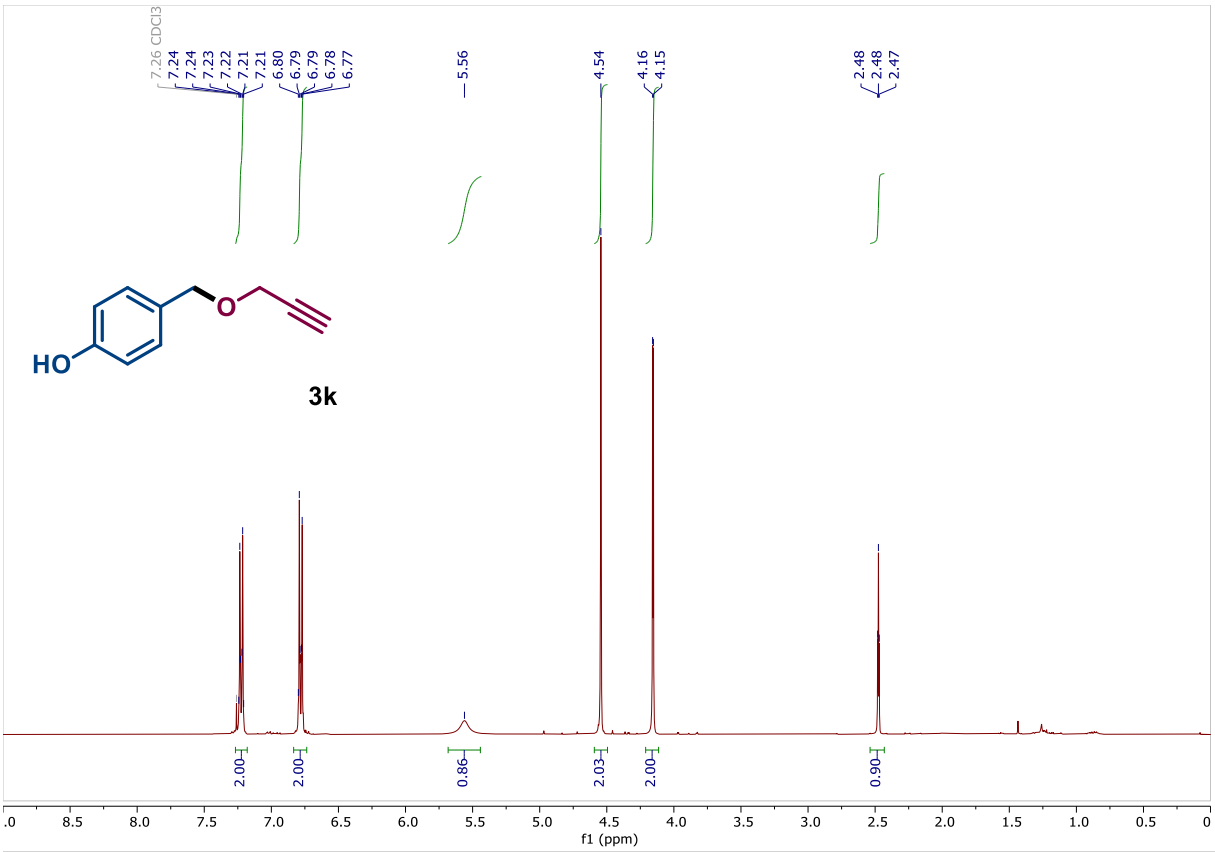

146.71
145.27
130.58
121.16
114.16
110.61
77.16 CDCl3
74.75
72.68
55.99
10.75
3.18
f1 (ppm)

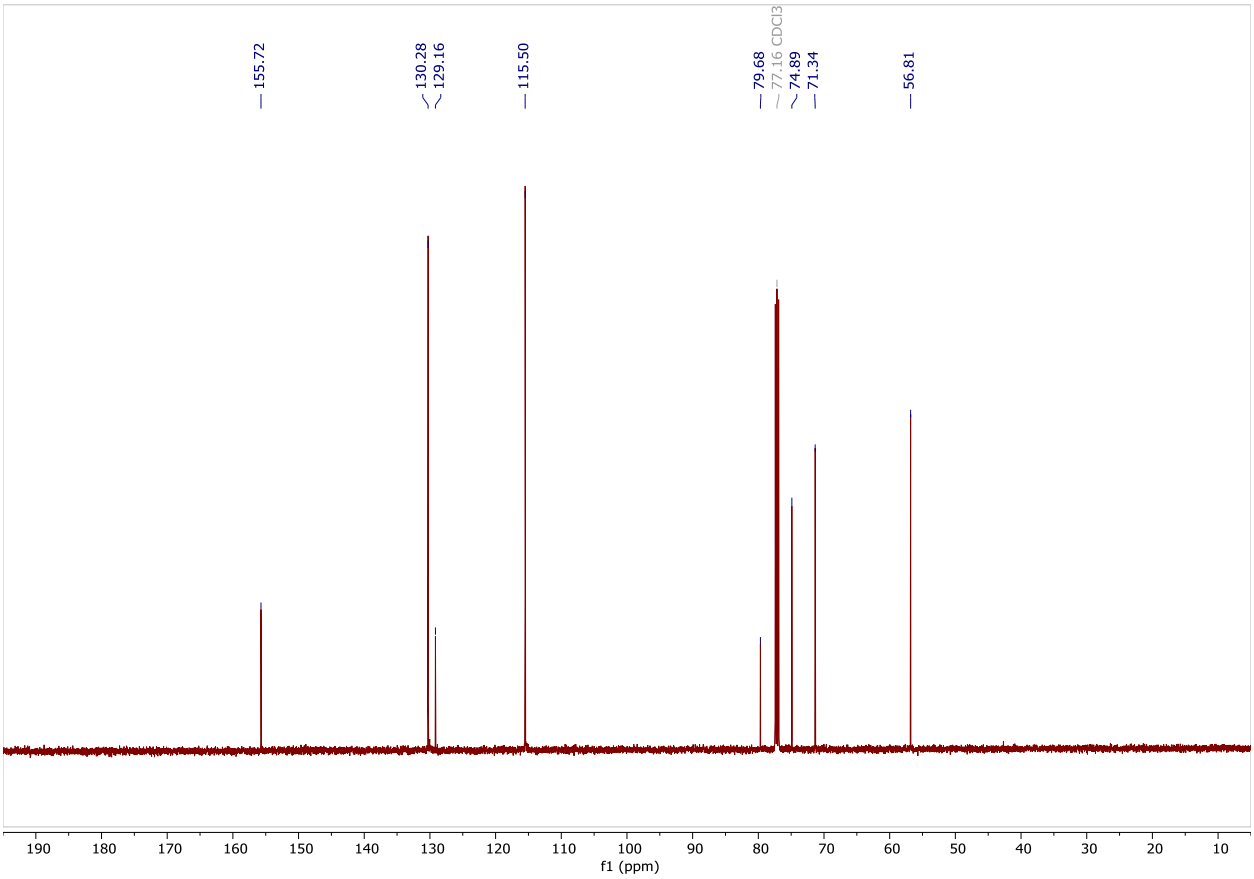

7.26 CDCl3
6.83
6.82
6.81
6.80
4.42
3.90
HO
OMe
O
N3
3i
2.03
1.00
2.05
3.16
2.06
2.10
2.30
f1 (ppm)

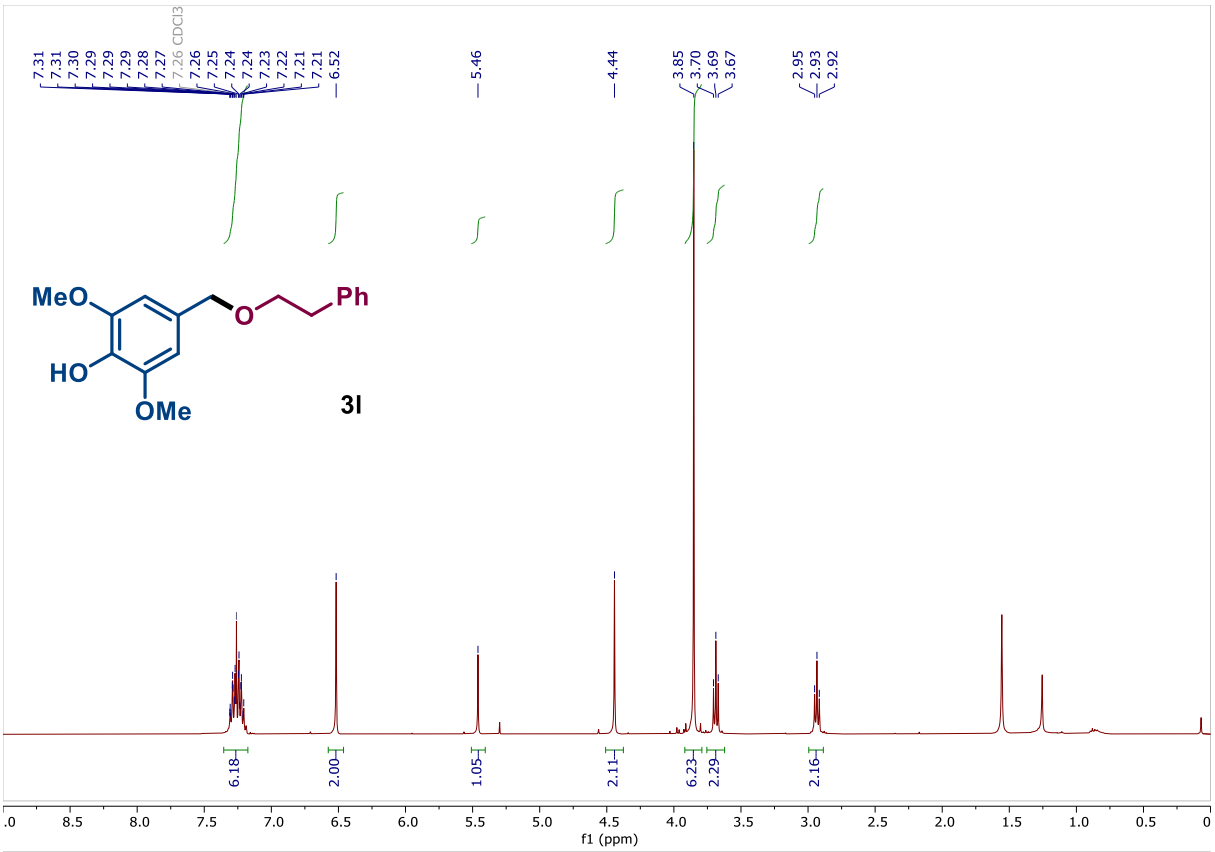

146.73
145.45
130.21
121.24
114.25
110.63
77.16 CDCl3
73.32
66.76
56.04
48.69
29.35
f1 (ppm)

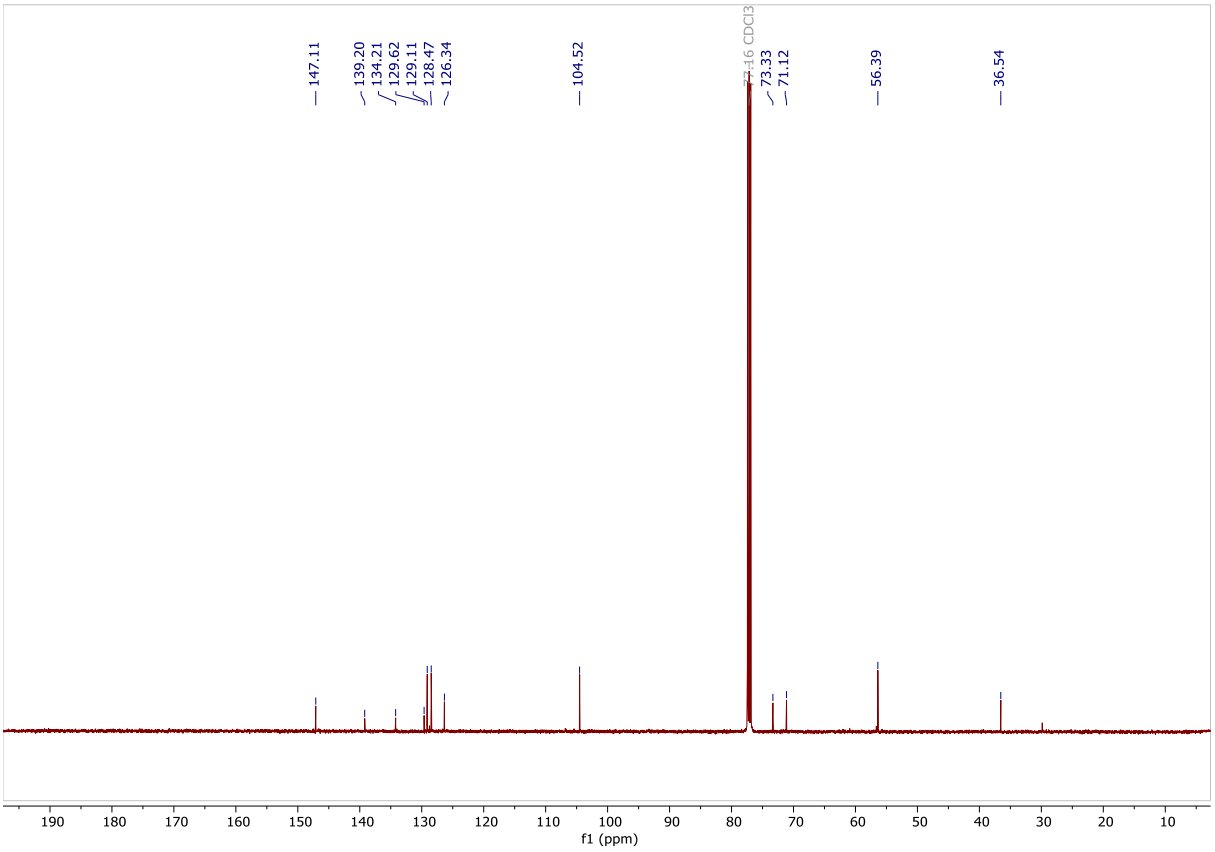

7.26 CDCl3
7.21
7.21
7.20
7.19
7.18
7.18
6.76
6.76
6.75
6.75
6.74
6.73
6.73
6.08
6.00
5.99
5.97
5.97
5.96
5.96
5.95
5.94
5.93
5.93
5.92
5.90
5.33
5.33
5.32
5.29
5.29
5.28
5.28
5.23
5.23
5.23
5.22
5.21
5.21
5.20
5.20
4.46
4.04
4.04
4.04
4.03
HO
O
3j
2.09
2.17
1.01
1.00
1.02
1.01
2.22
2.13
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
f1 (ppm)

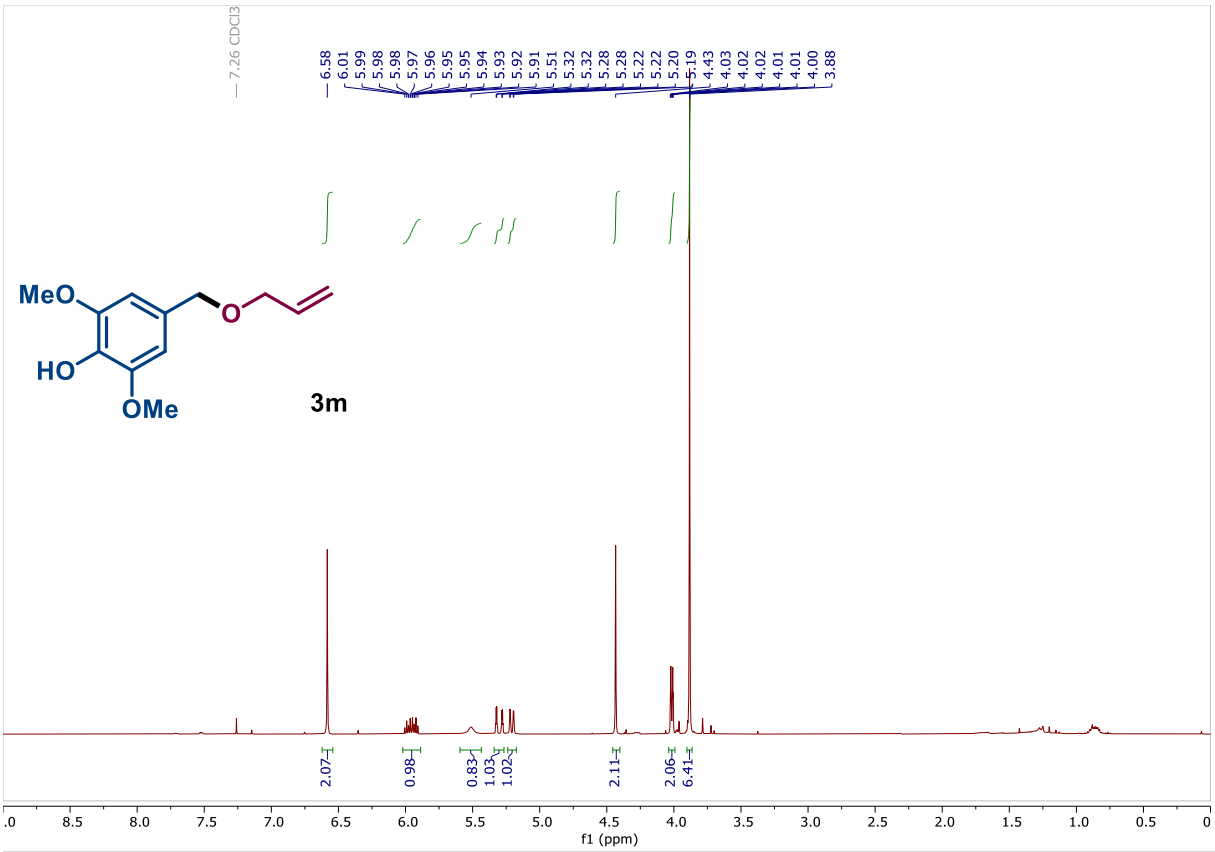

155.67
134.58
129.92
129.82
117.77
115.48
77.16 CDCl3
71.97
71.02
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
f1 (ppm)

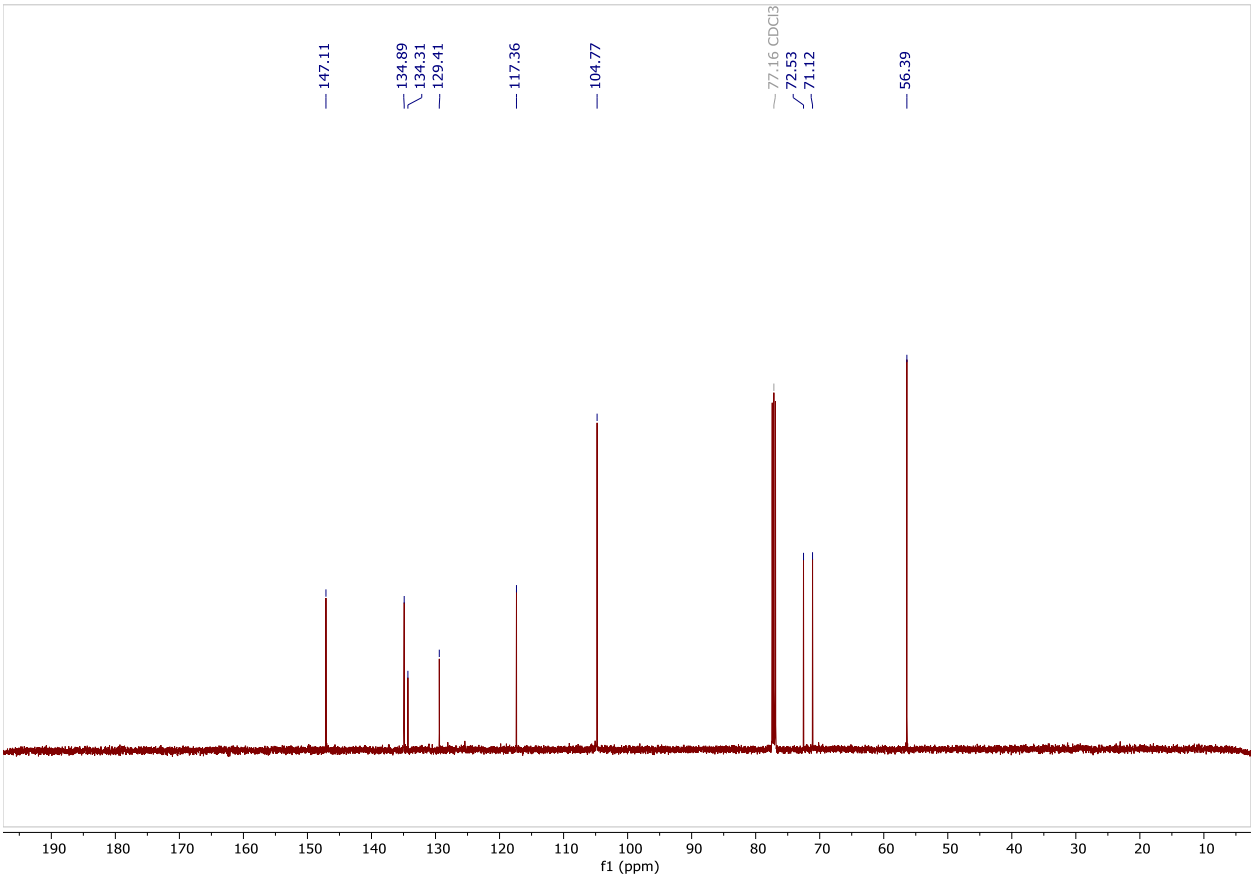

7.26 CDCl3
7.24
7.24
7.23
7.22
7.21
7.21
6.80
6.79
6.79
6.78
6.77
5.56
4.54
4.16
4.15
2.48
2.48
2.47
HO
O
3k
2.00
2.00
0.86
2.03
2.00
0.90
f1 (ppm)

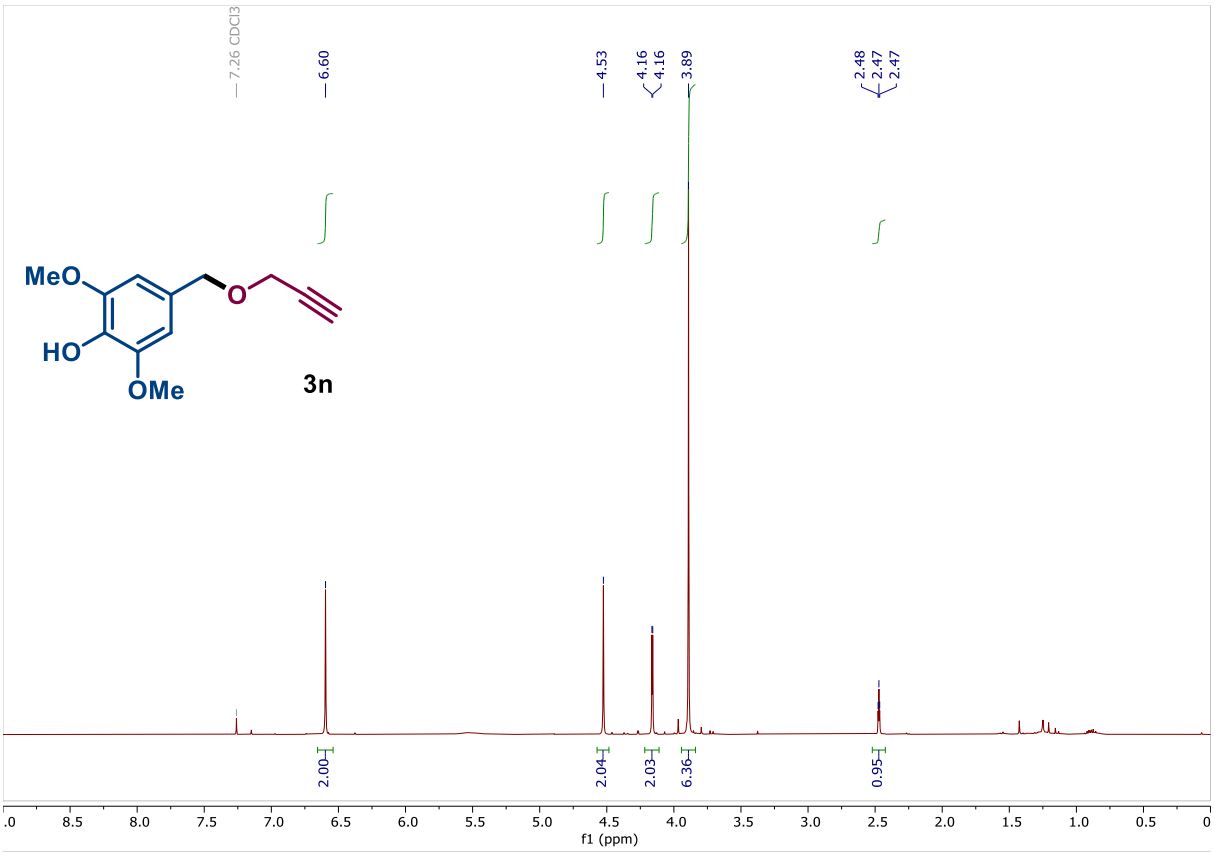

155.72
130.28
129.16
115.50
79.68
77.16 CDCl3
74.89
71.34
56.81
f1 (ppm)

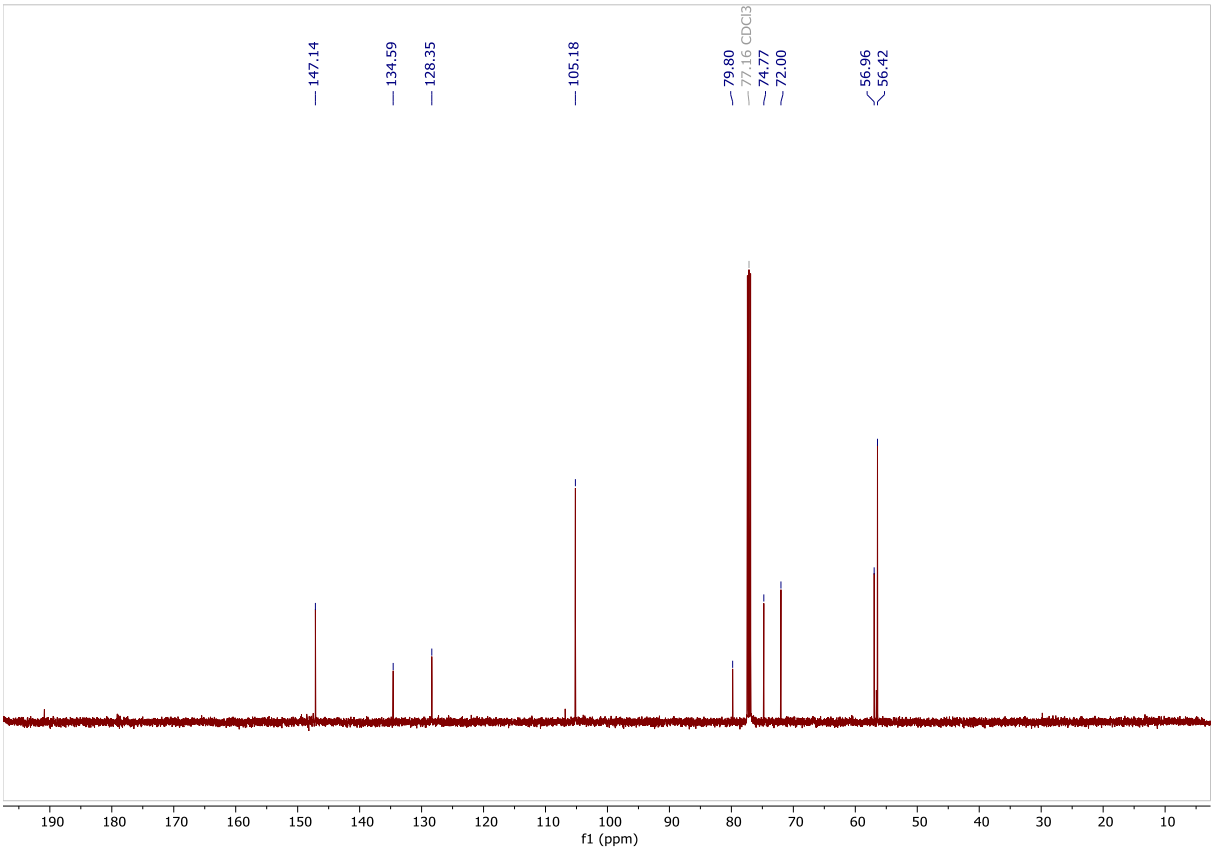

7.31
7.31
7.30
7.29
7.29
7.29
7.28
7.27
7.26 CDCl3
7.26
7.25
7.24
7.24
7.23
7.22
7.21
7.21
6.52
5.46
4.44
3.85
3.70
3.69
3.67
2.95
2.93
2.92
MeO
HO
OMe
O
Ph
3l
6.18
2.00
1.05
2.11
6.23
2.29
2.16
f1 (ppm)


147.11
139.20
134.21
129.62
129.11
128.47
126.34
104.52
77.16 CDCl3
73.33
71.12
56.39
36.54
f1 (ppm)


7.26 CDCl3
6.58
6.01
5.99
5.98
5.98
5.97
5.96
5.95
5.95
5.94
5.93
5.92
5.91
5.51
5.32
5.32
5.28
5.28
5.22
5.22
5.20
5.19
4.43
4.03
4.02
4.02
4.01
4.01
4.00
3.88
MeO
HO
OMe
O
3m
2.07
0.98
0.83
1.03
1.02
2.11
2.06
6.41
f1 (ppm)


147.11
134.89
134.31
129.41
117.36
104.77
77.16 CDCl3
72.53
71.12
56.39
f1 (ppm)


7.26 CDCl3
6.60
4.53
4.16
4.16
3.89
2.48
2.47
2.47
MeO
HO
OMe
O
3n
2.00
2.04
2.03
6.36
0.95
f1 (ppm)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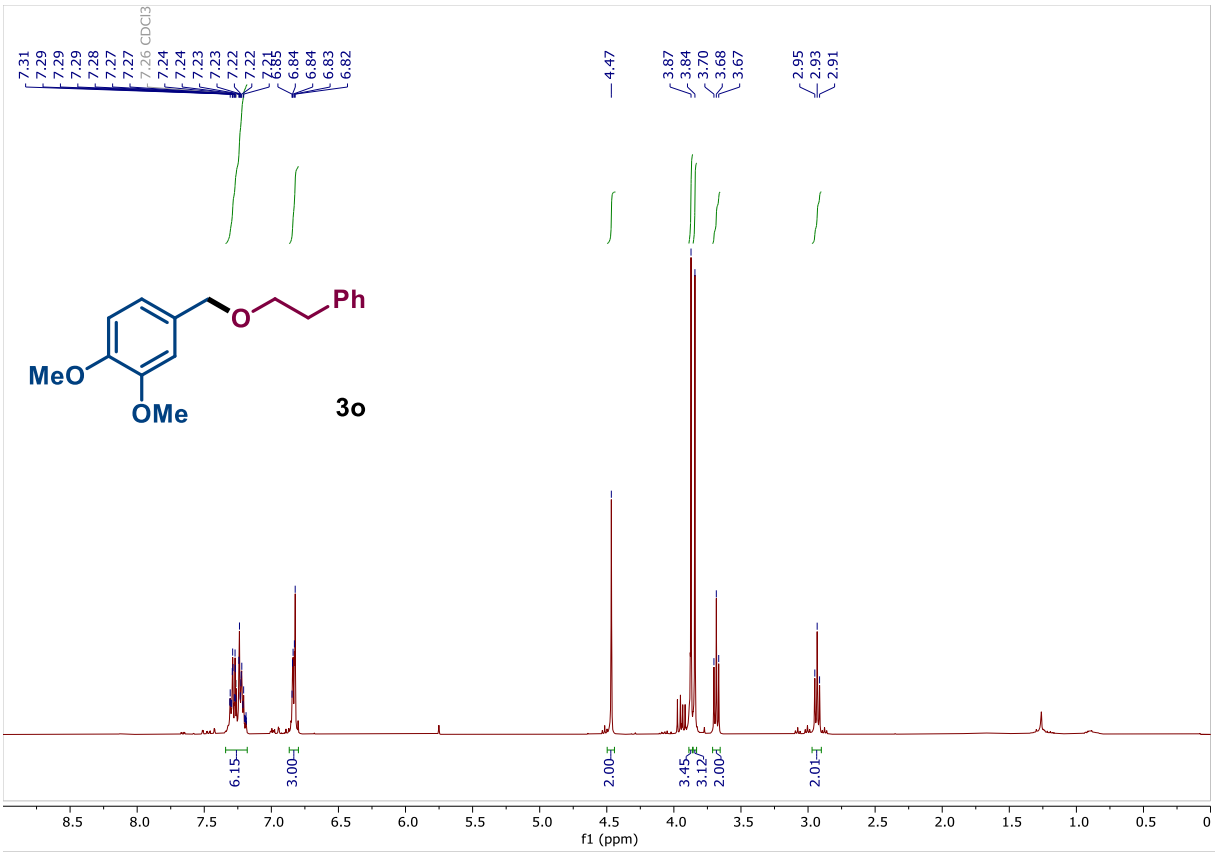
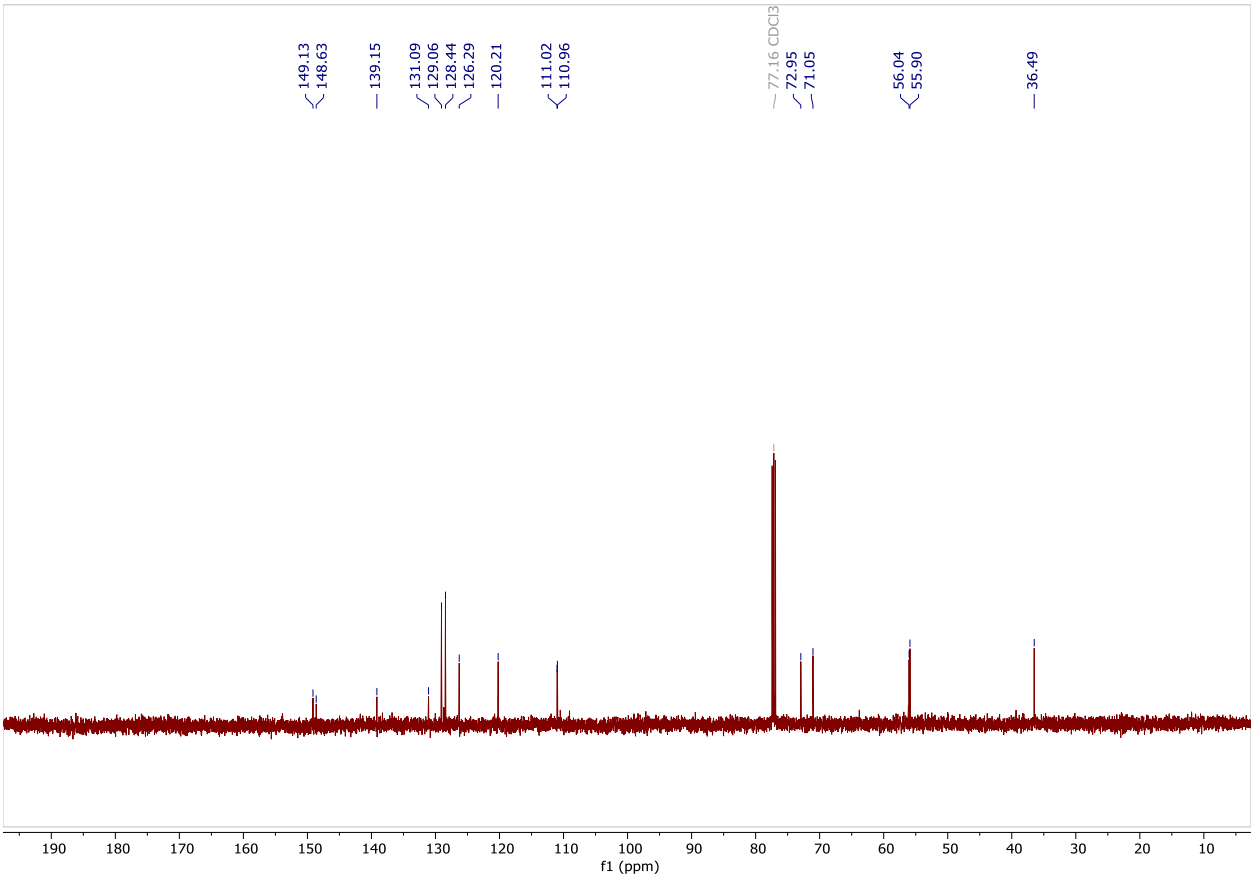
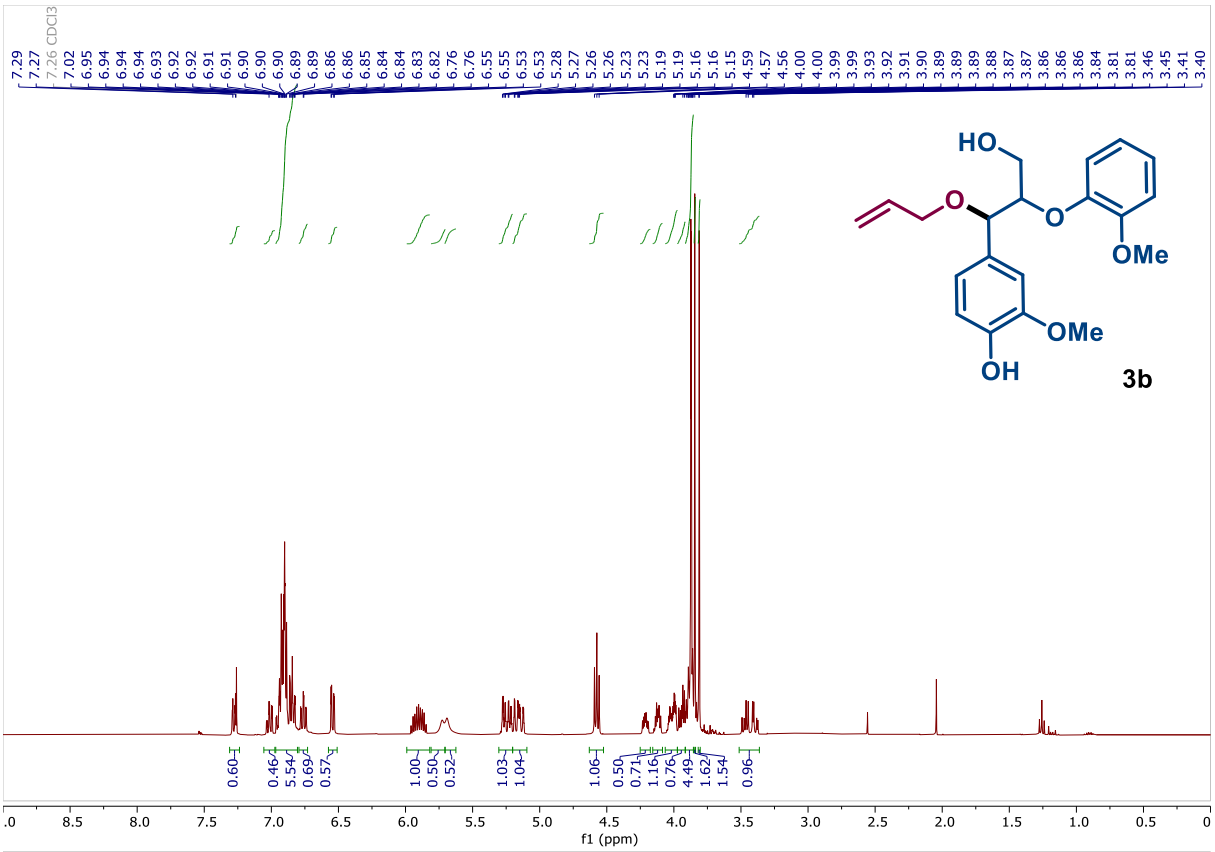
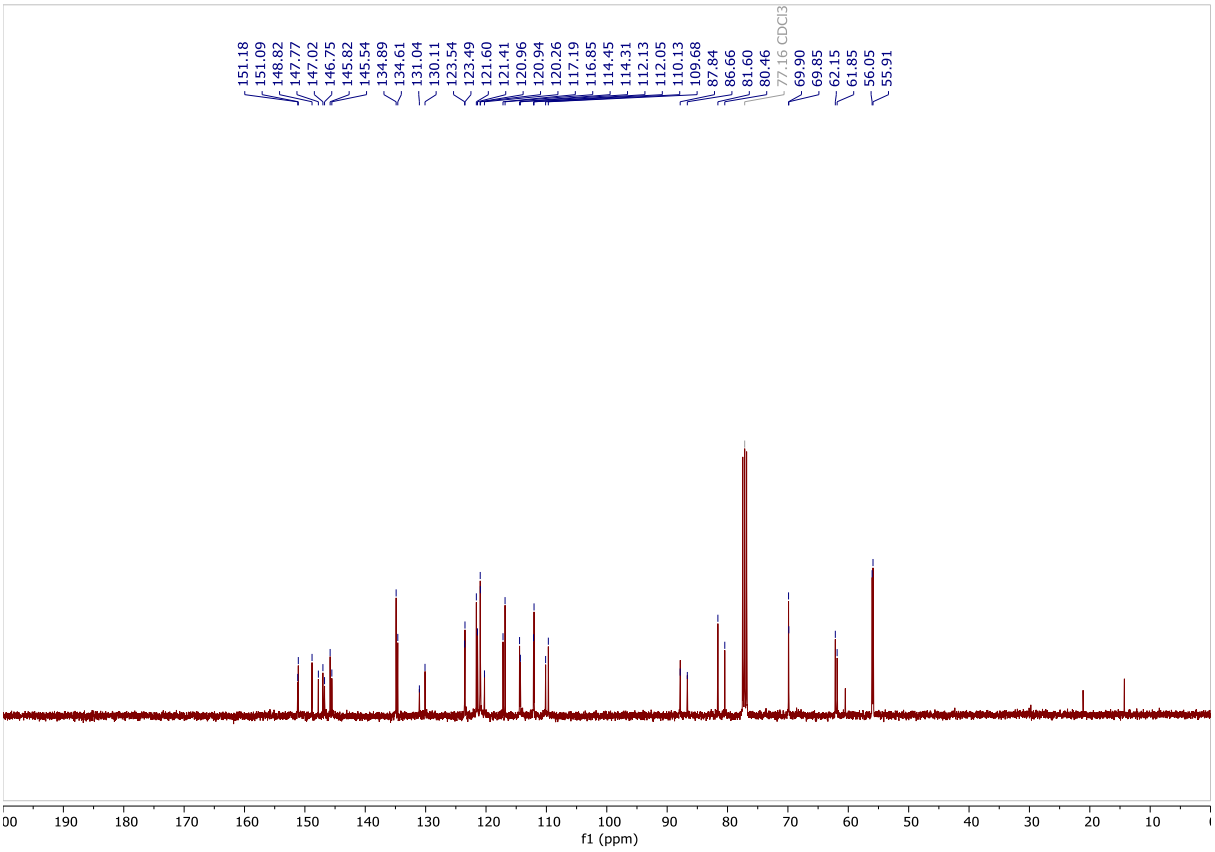
134.59
128.35
105.18
79.80
77.16 CDCl3
74.77
72.00
56.96
56.42
f1 (ppm)

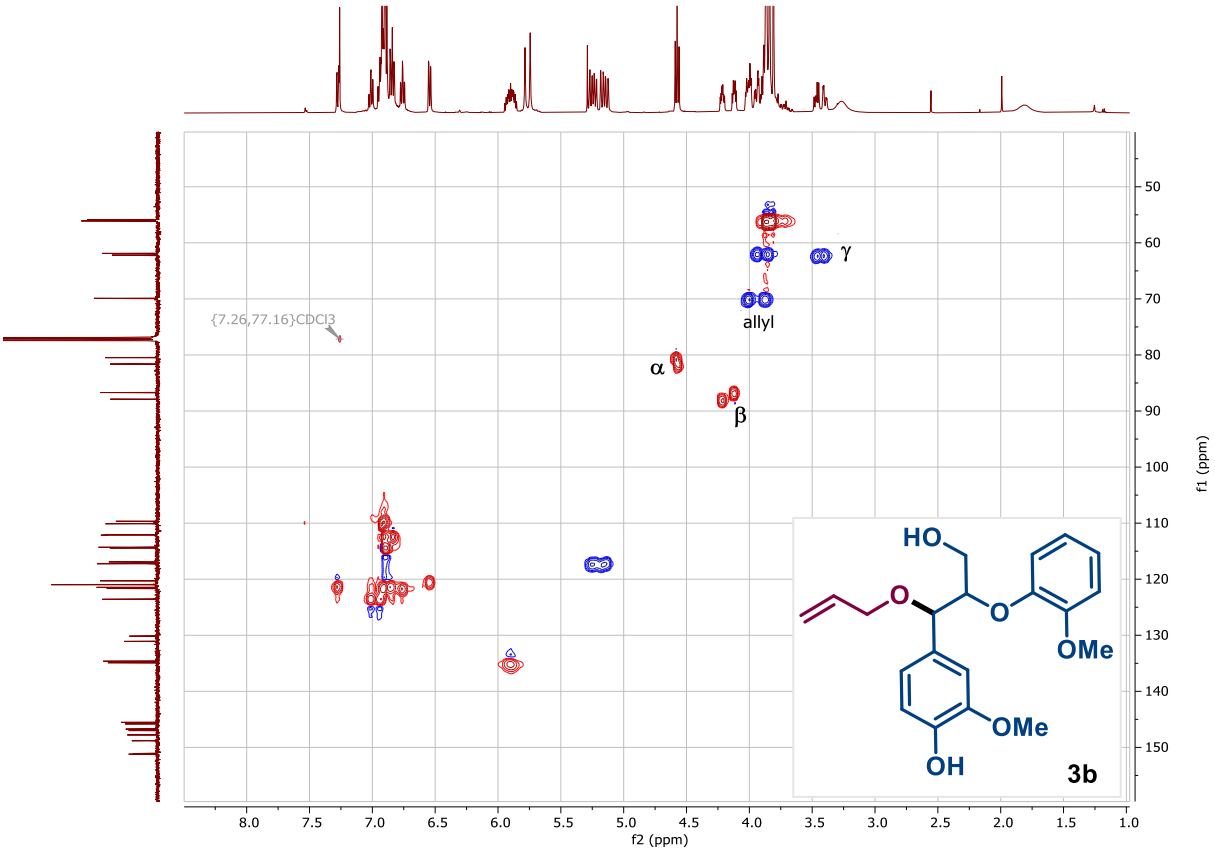

7.31
7.29
7.29
7.29
7.28
7.27
7.27
7.26 CDCl3
7.24
7.24
7.23
7.23
7.22
7.22
7.21
6.85
6.84
6.84
6.83
6.82
4.47
3.87
3.84
3.70
3.68
3.67
2.95
2.93
2.91
Ph
O
MeO
OMe
3o
6.15
3.00
2.00
3.45
3.12
2.00
2.01
f1 (ppm)


149.13
148.63
139.15
131.09
129.06
128.44
126.29
120.21
111.02
110.96
77.16 CDCl3
72.95
71.05
56.04
55.90
36.49
f1 (ppm)

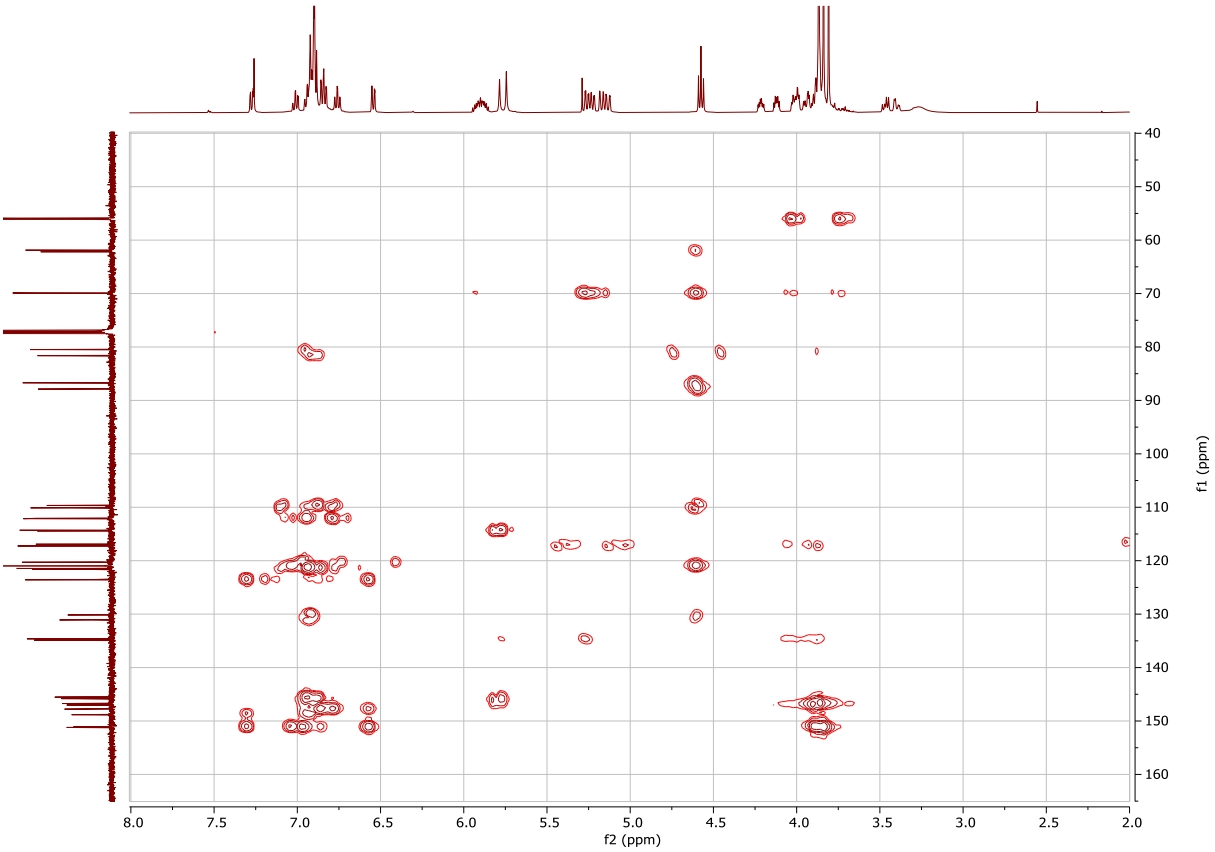

HO
O
O
OMe
OMe
OH
3b
f1 (ppm)

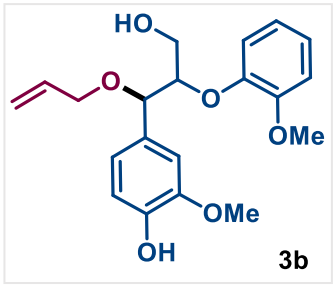

f1 (ppm)

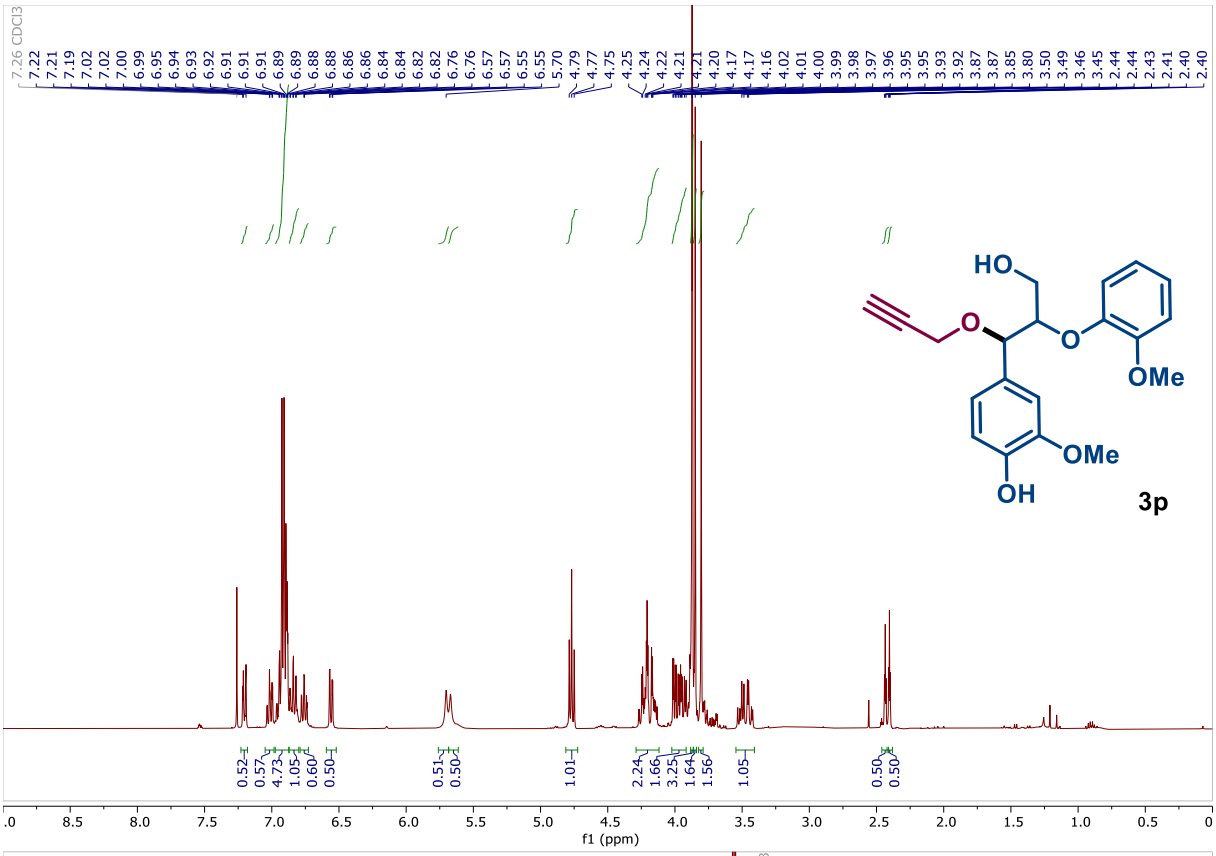
HSQC

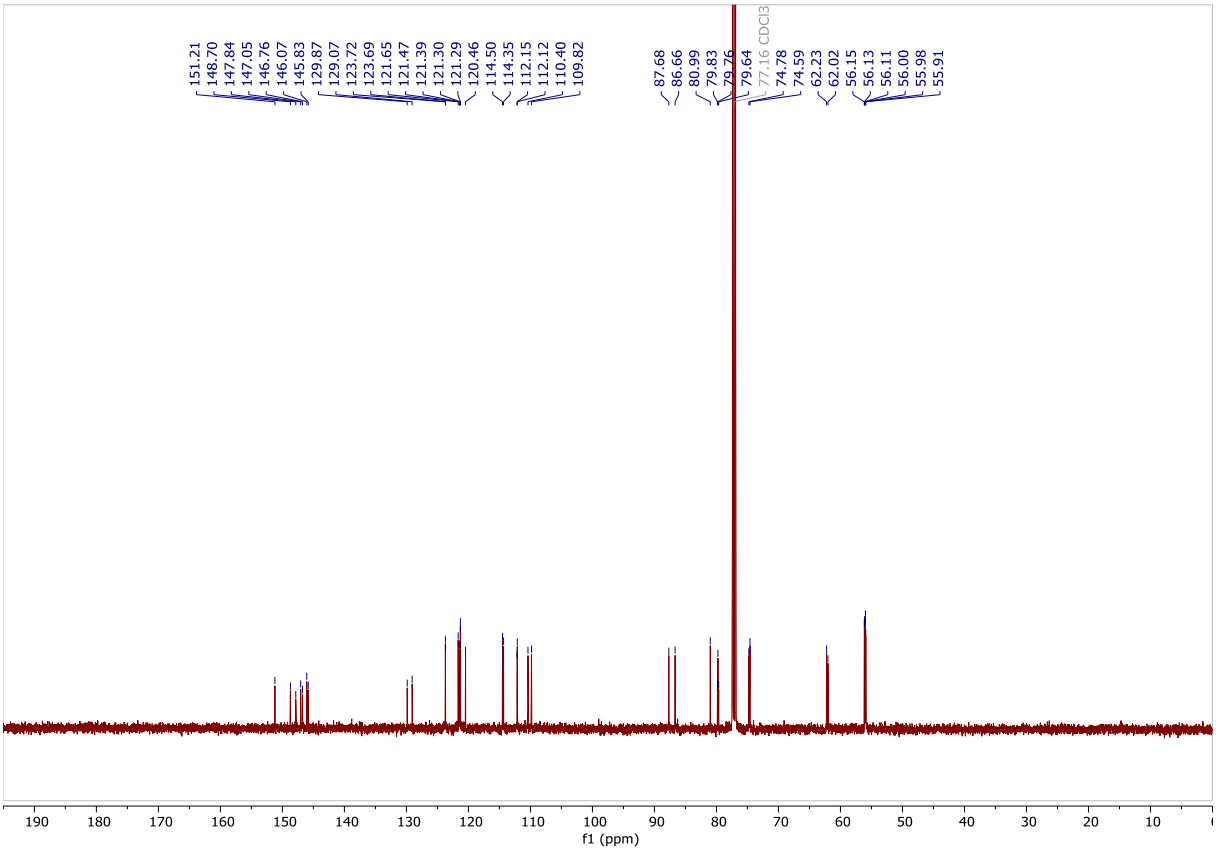


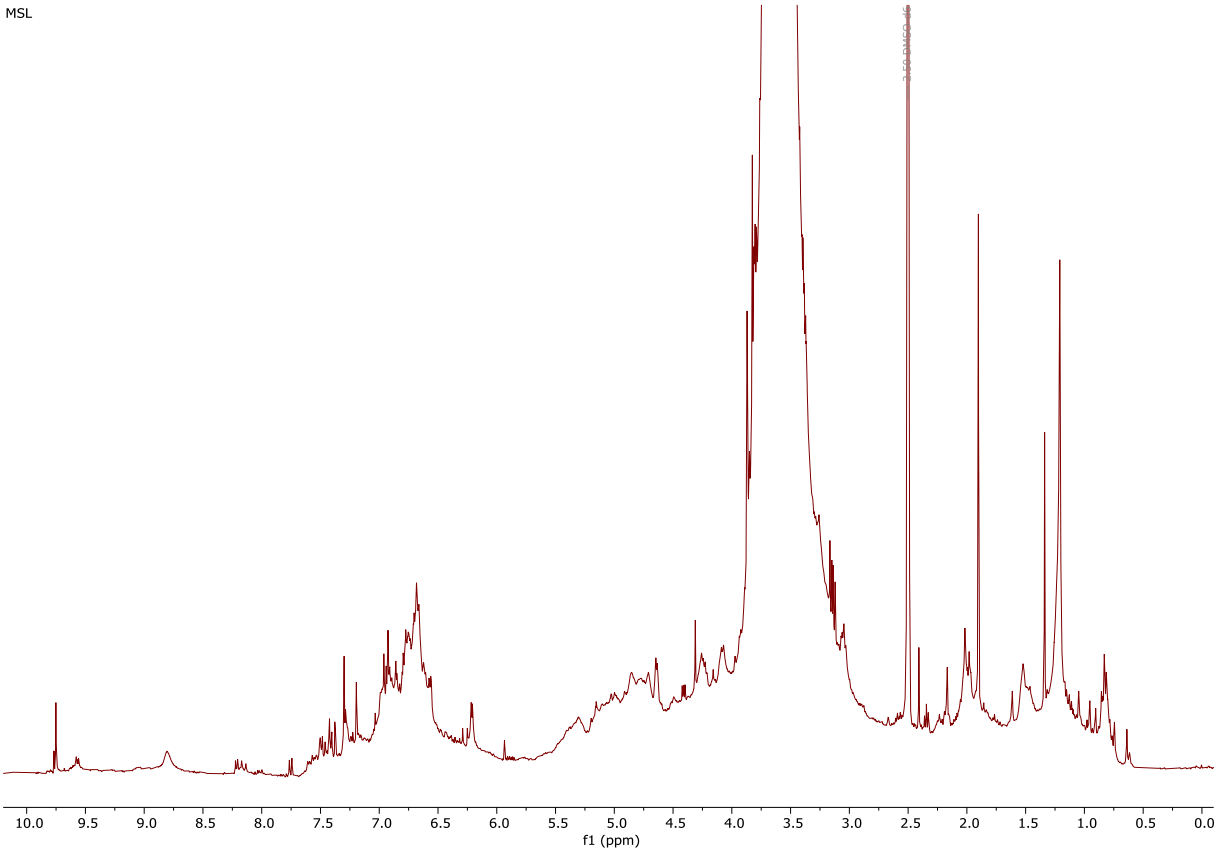
HMBC

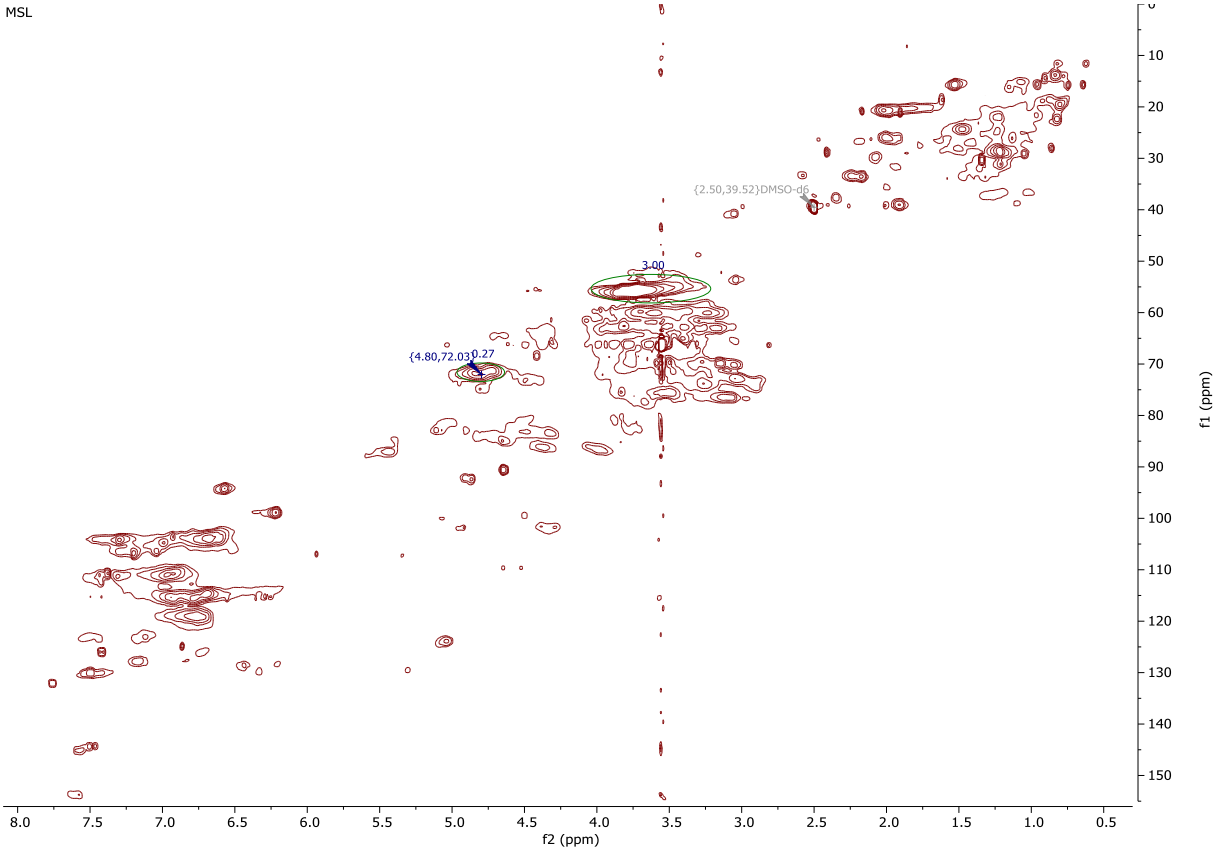

8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
f2 (ppm)
40
50
60
70
80
90
100
110
120
130
140
150
160
f1 (ppm)

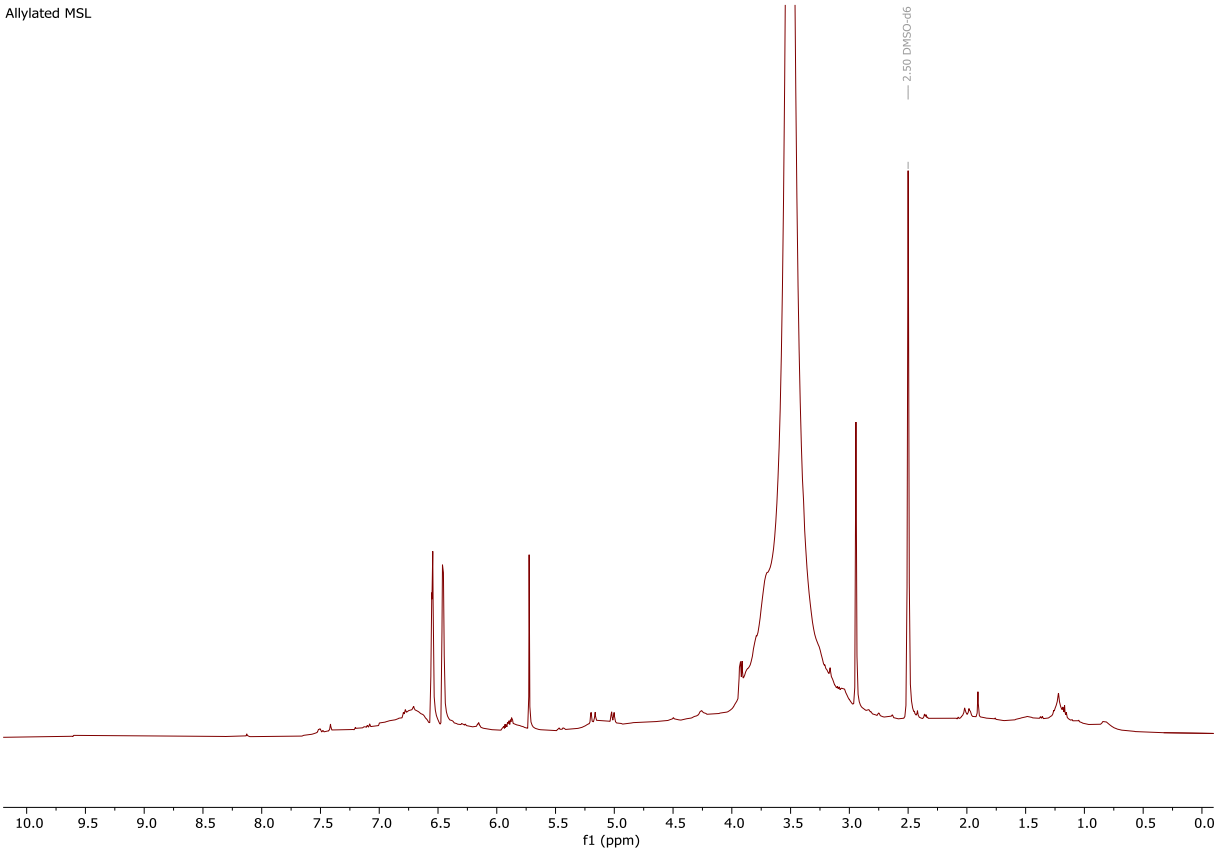

HO
O
O
OMe
OMe
OH
3b

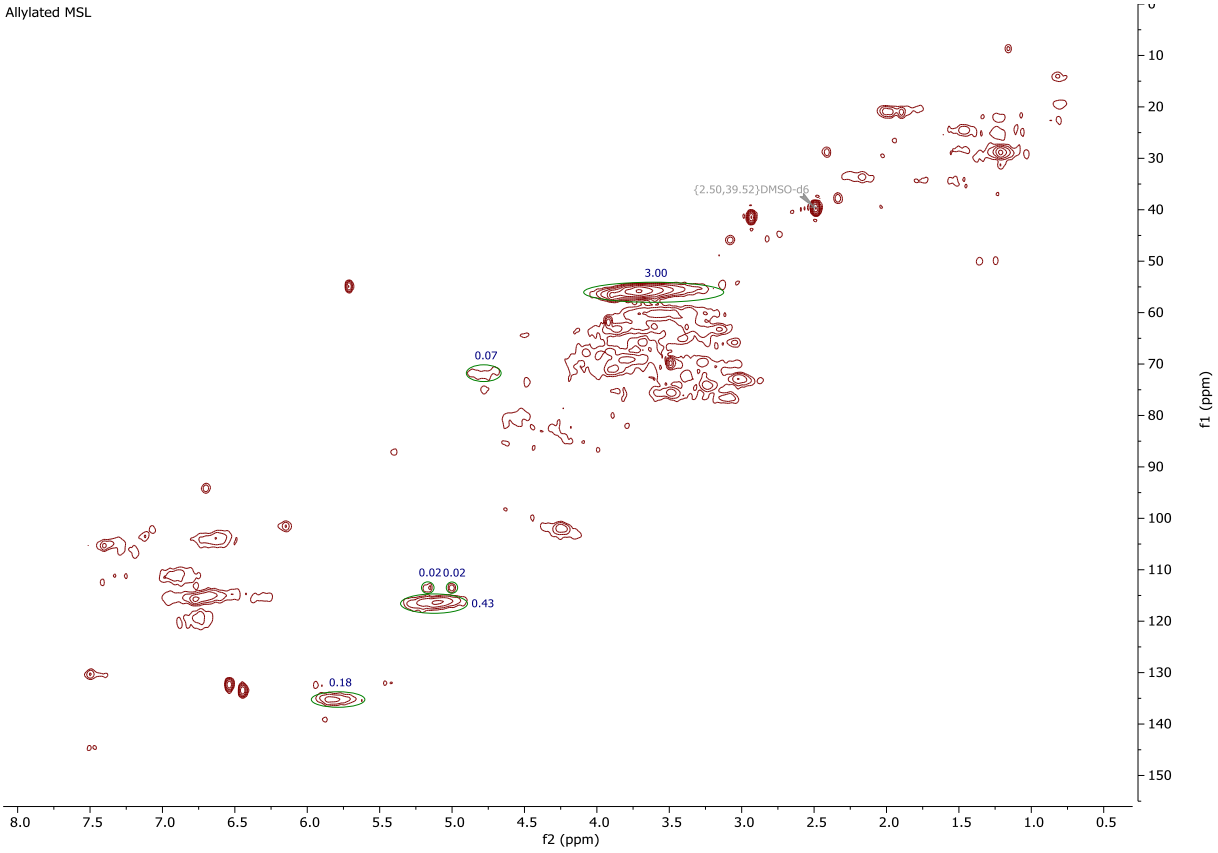

7.26 CDCl3
HO
O
O
OMe
OMe
OH
3p
f1 (ppm)

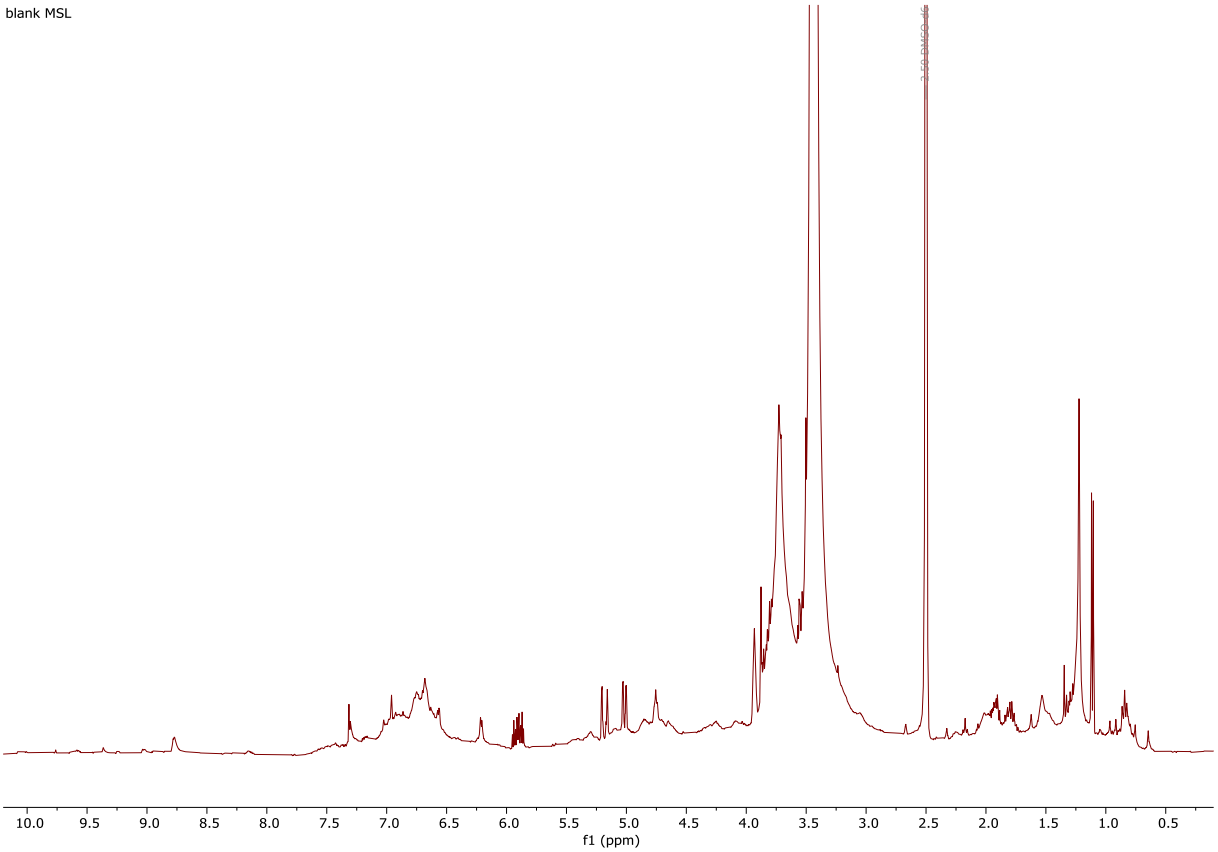

77.16 CDCl3
f1 (ppm)

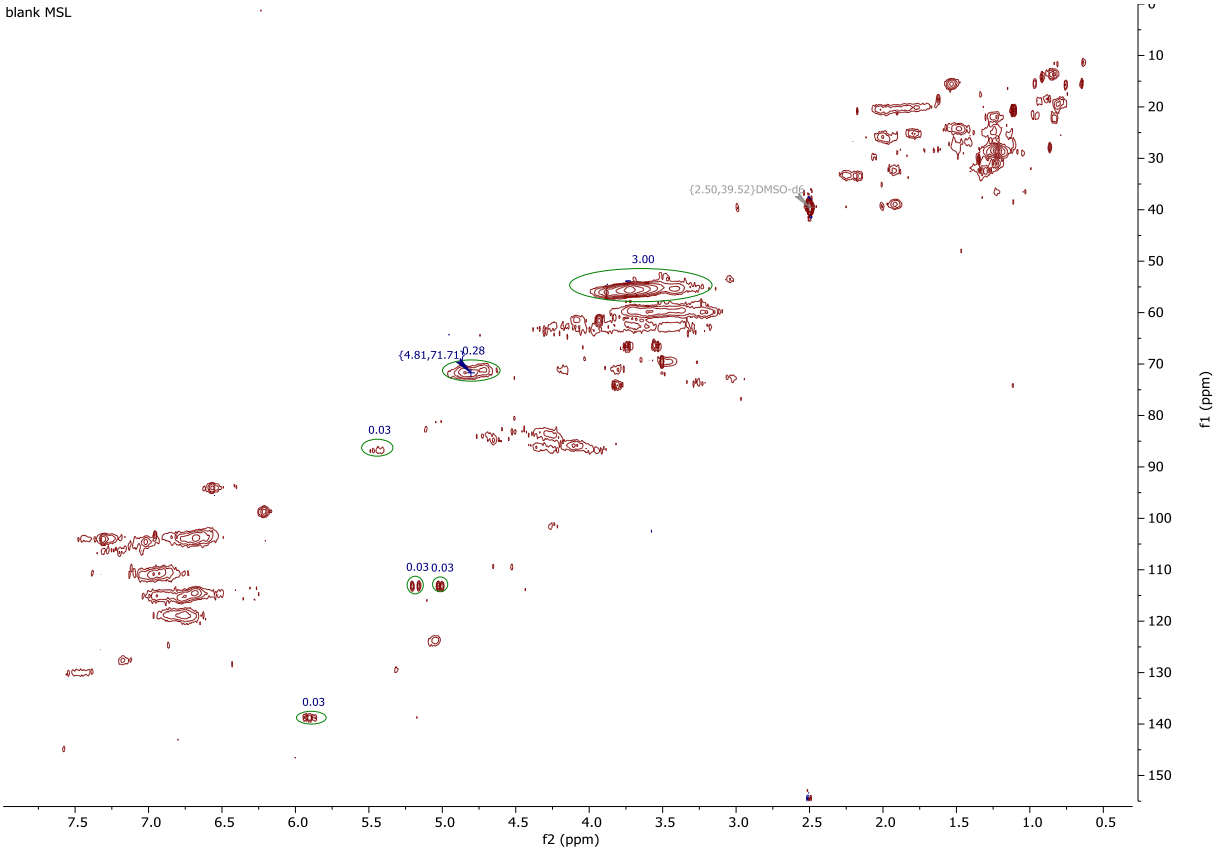

MSL
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)


MSL
{2.50,39.52}DMSO-d6
3.00
{4.80,72.03}0.27
8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5
f2 (ppm)
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
f1 (ppm)


Allylated MSL
2.50 DMSO-d6
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)


Allylated MSL
{2.50,39.52}DMSO-d6
3.00
0.07
0.02 0.02
0.43
0.18
8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5
f2 (ppm)
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
f1 (ppm)


blank MSL
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5
f1 (ppm)


blank MSL
{2.50,39.52}DMSO-d6
3.00
{4.81,71.71}
0.28
0.03
0.03
0.03
0.03
7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5
f2 (ppm)
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
f1 (ppm)

8. References

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