Supporting Information for

Unravelling the Enigma of Lignin$^{\text{OX}}$: Can the Oxidation of Lignin be Controlled?

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a Whilst the overall % of oxidised units do not equal the values for un-oxidised units, differences in the NMR relaxation properties of the lignin and lignin\textsuperscript{OX} materials may account for this but remain hard to measure.

b When 1 or more wt. eqvs. of DDQ was used, a plateau was reached and the signal apparently corresponding to the presence of residual native β-O-4 units could be attributed to background noise/other new cross-peaks in the 2D HSQC NMR spectra (see Figure 2C that shows that only trace cross peaks corresponding to native β-O-4 units were present when 3 wt. equivalents of DDQ was used).

c Unexpectedly, the apparent rate of increase of the species corresponding to the dark pink line and the light pink line in Figure 4A were approximately equal under these reaction conditions. It seems likely that the generation of signals corresponding to β-O-4\textsuperscript{α-OX} A(S)\textsuperscript{″} (dark pink) would require population of the β-O-4\textsuperscript{α-OX} A(S)\textsuperscript{′} (light pink) state. Perhaps at 80 °C the rates of generation and consumption of these β-O-4\textsuperscript{α-OX} A(S)\textsuperscript{′} (light pink) state are equally rapid. When this experiment was repeated with the only change being in the reaction temperature (run at room temperature (for 14 hours) rather than 80 °C, Figures S9-S10 and Table S5), our expected outcome was observed. An initial increase in β-O-4\textsuperscript{α-OX} A(S)\textsuperscript{′} (light pink) state (See Figure S10b) was observed after 30 minutes, whilst a lower level of β-O-4\textsuperscript{α-OX} A(S)\textsuperscript{″} (dark pink) was noted. This agrees with the necessity for population of the β-O-4\textsuperscript{α-OX} A(S)\textsuperscript{′} (light pink) state prior to generation of increasing amounts of β-O-4\textsuperscript{α-OX} A(S)\textsuperscript{″} (dark pink) state.

d Whilst S- β-O-4 oxidation occurs fast, analysis of G- β-O-4 oxidation in beech lignin appears to reach its maxima (i.e. as much G- β-O-4\textsuperscript{α-OX} A” that can be generated, has been), in even less time (c.f. Figure 4 and Figures S9-10). This is likely due to the increased rate of oxidation of G-benzylic alcohols over S-benzylic alcohols. To explore this further, time-course analyses were undertaken using S and G β-O-4 model compounds (See SI, Scheme S2, Figures S13-S16). These studies supported this view. The outcome of these studies on oxidation of the β-O-4 unit showed that at any given time point within the initial ten minutes of the reaction at 80 °C, G- β-O-4 model oxidation reached higher conversions than the G- β-O-4 model system to the corresponding benzylic ketone models.
one possibility is that the β-β unit has been converted to the previously proposed pyran-4-one structure (see references 1–3). Additional transformations are possible and are the subject of on-going work in our groups.

Whilst only 40% of the spent DDQ was recovered as DDQ-H₂ (which can be converted back to DDQ using MnO₂ (an excess in Et₂O, stirred at r.t. for 2 hours and collected by filtration and concentration of filtrate to give DDQ in a ca. 54% yield based on two repeats), the residual 60% (~54% recovered as a crude mixture, 43% isolated as DDQ through a CHCl₃ recrystallization of the crude mixture) is recoverable from the diethyl ether precipitation step required to precipitate lignin α-OX through concentration of the filtrate.
**General Information & Procedures**

Relevant $^1$H NMR spectroscopic data and melting point analysis (if required) is provided for literature compounds. Full characterisation data consisting of $^1$H NMR, $^{13}$C NMR, 2D HSQC NMR (where applicable), IR, M.P (if possible) and HRMS are provided for all non-literature compounds.

All materials were used as received unless otherwise stated. Diisopropylamine was distilled prior to use and stored over KOH. n-BuLi was titrated using diphenylacetic acid. Dry solvents were acquired from an MBRAUN (MB-SPS-800) dry solvent purification machine. $^1$H NMR and $^{13}$C NMR was performed on a Bruker Ascend 400 MHz, Bruker Avance 500 MHz, Bruker Avance III 500 with nitrogen cooled broadband probe or Bruker AVANCE III HD 700 5mm $^1$H, $^{13}$C, $^{15}$N triple resonance inverse nitrogen cooled probe (TCI Prodigy) spectrometer with solvent peak used as internal standard. Multiplicities reported as following: s = singlet, d = doublet, t = triplet, q = quartet and m = multiplet and J values are reported in Hz. Column chromatography was conducted using Davisil® silica (40-63 μm, 230-400 mesh) on a Biotage Isolera One Spektra system with ACI. Thin layer chromatography was performed using pre-coated glass plates (Silica gel 60A from Fluorochem) and visualised under UV light (254 nm) or through staining with KMnO$_4$, 4-dinitrophenylhydrazine (aldehydes) and FeCl$_3$ (phenols). IR spectra were obtained on a Shimadzu IRAffinity-1 Fourier Transform IR spectrophotometer as thin films. IR analysis was carried out using IResolution v1.50 with only characteristic peaks reported. Mass spectrometry data was acquired through the University of St Andrews School of Chemistry mass spectrometry service or EPSRC Swansea Mass Spectrometry Service. Reactions at -78 °C were achieved using acetone: dry ice. Any reactions requiring anhydrous conditions were run using oven-dried (140 °C) or flame dried glassware under N$_2$ atmosphere.

**Lignin Dioxasolv Extraction:** as previously described.$^{4,5}$

**DDQ Oxidation of Lignin**

To a stirring solution of lignin (1 wt. eq.) in 1,4-dioxane (100 mg/ 2.33 mL) is added DDQ (varying wt. eq.). The solution is heated to 80 °C for 2 hours, cooled, filtered through a pad of celite and washed with 1,4-dioxane (1 volume). The filtrate is added dropwise to Et$_2$O (10
volumes) and the resulting precipitate is filtered and washed with excess Et₂O. Ligninα-OX is dried to constant weight in a vacuum oven at 40 °C for 24 hours prior to analysis.

β-O-4 model compounds S1-S2: Synthesised as previously described.⁴,⁵

2D HSQC NMR Acquisition
Oven-dried lignin samples (70 mg) are dissolved in 0.6 mL of d₆-DMSO in a 1.5 mL eppendorf tube and subjected to sonication for 10 minutes at 30 °C. Samples are centrifuged at 6000 RPM for 5 minutes. Supernatant is filtered through a 0.45 μM syringe filter into an over dried NMR tube. 2D HSQC NMR spectra were acquired on a Bruker Avance III 500 with nitrogen cooled broadband probe or Bruker AVANCE III HD 700 5mm ¹H, 13C, 15N triple resonance inverse nitrogen cooled probe (TCI Prodigy) spectrometer. The central DMSO solvent peak was used as internal reference (δC 39.5, δH 2.49 ppm). The 1H, 13C-HSQC experiment was acquired using standard Bruker pulse sequence ‘hsqcetgosp.2’ (phase-sensitive gradient-edited-2D HSQC using adiabatic pulses for inversion and refocusing). Composite pulse sequence ‘garp4’ was used for broadband decoupling during acquisition. 2048 data points was acquired over 12 ppm spectral width (acquisition time 170 ms) in F2 dimension using 24 scans with 1 s interscan delay and the δ4 delay was set to 1.8 ms (1/4J, J = 140 Hz). A spectral width of 86 ppm (47-133 ppm) and 128 increments were acquired in F1 dimension (acquisition time 5.9 ms). The spectrum was processed using squared cosinebell in both dimensions and LPfc linear prediction (32 coefficients) in F1. Volume integration of cross peaks in the HSQC spectra was carried out using MestReNova 11.0 for Mac software and figures were prepared using Adobe Illustrator CS6 for Mac for spectral annotation.
Scheme S1: Westwood group methodology for one-pot lignin depolymerisation. Lignin is initially oxidised selectively using a catalytic DDQ system followed by a stoichiometric zinc mediated reductive cleavage of the C-O-aryl ether bond. The reductive cleavage of the C-O-aryl bond leads to the generation of a lignin-bound keto-alcohol, a monomeric keto-alcohol and a free phenol end-group on a lignin chain.
**Figure S1a**: Representative structure and reactivity of a hardwood dioxasolv lignin that has been selectively oxidised at the benzylic position of the β-O-4 unit. An example of a 2D HSQC NMR spectrum (selected region in insert) is shown to illustrate the key cross-peaks that are used to assess the structures within lignin and how different β-O-4α-OX units are assigned. Cross peaks are assigned based on comparison of the chemical shifts with those of model compounds.1,5

*Highlighted in red are the key structural features that influence the chemical shift of the H atoms within the 2D HSQC NMR of lignin. In this scenario, two adjacent α-keto units within two S-β-O-4α-OX structures deshield (reduce electron density) the β-H atom causing a cross-peak in a downfield chemical shift (in this case, A''β-S/G-S). In a scenario where only one S-β-O-4α-OX unit is oxidised and one is not, less deshielding of the β-H atom would be expected. This would cause a cross-peak upfield of the previous one, e.g. A'β-S/G-S.*
**Figure S1b**: A diagram explaining the different scenarios of β-O-4′-OX units present within a lignin polymer which could give rise to an appearance of a cross-peak in the 2D HSQC NMR of lignin β-OX.
Figure S2: An example of a 2D HSQC NMR of lignin\textsuperscript{α-OX} generated using a catalytic AcNH-TEMPO system by Stahl \textit{et al.}\textsuperscript{6} Key changes, circled above, include near complete loss of β-O-4 units (A) (as expected), β-5 (B) (unexplained loss) and β-β (C) (unexplained loss). Reprinted (adapted) with permission from Stahl \textit{et al.} \textit{J. Am. Chem. Soc.}, 2013, 135 (17), pp 6415–6418. Copyright © 2013 American Chemical Society.
Solvent & Temperature Screen for DDQ oxidation of Lignin

Figure S3: 2D HSQC NMR ($d_6$-DMSO) of beech lignin$^{\alpha-OX}$ from the DDQ oxidation of beech lignin at (a) 40 °C; (b) 60 °C; (c) 80 °C and; (d) 100 °C. Reaction conducted with 1.33 wt. eqv. of DDQ in 1,4-dioxane for 2 hours. Spectra acquired using a reduced $^{13}C$ sweep with of 47-133 ppm. For colour coding see Figure S6 or Figure 2 in manuscript.

Table S1: Results from temperature screen of DDQ lignin oxidation

| Temperature | $\beta$-O-4$^{OX}$ in situation (ii) or (iii) above: $\beta$-O-4$^{OX}$ in situation (iv) or (v) above | Note |
|-------------|-------------------------------------------------------------------------------------------------|------|
| 40 °C       | 1: 1.2                                                                                          | -    |
| 60 °C       | 1: 1.6                                                                                          | -    |
| **80 °C**   | **1: 1.8**                                                                                      | Comparable results, therefore 80 °C selected |
| 100 °C      | 1: 1.9                                                                                          |      |

From the temperature screen, the highest amount of the $\beta$-O-4 linkage in situations (iv) or (v) was achieved at 80 °C and 100 °C, both yielding comparable results. 80°C was therefore carried through to all the following reactions.
Figure S4: 2D HSQC NMR (d$_6$-DMSO) of beech lignin$^{\text{a,OX}}$ from the DDQ oxidation of beech lignin when using (a) 1,4-dioxane; (b) MeCN: MeOH (9:1) and; (c) MeCN; as the reaction solvent. Reactions were conducted with 1.33 wt. equiv. DDQ for 2 hours at 80 °C. Spectra acquired using a reduced $^{13}$C sweep with of 47-133 ppm.$^1$ For colour coding see Figure S6 or Figure 2 in manuscript.

Table S2: Results from solvent screen of DDQ lignin oxidation

| Solvent                | $\beta$-O-4$^{\text{OX}}$ in situation (ii) or (iii) above: $\beta$-O-4$^{\text{OX}}$ in situation (iv) or (v) above | Solubility | Note                              |
|------------------------|-----------------------------------------------------------------------------------------------------------|------------|-----------------------------------|
| 1,2-dimethoxyethane    | n/a                                                                                                       | Low        | -                                 |
| MeCN                   | 1: 1.89                                                                                                   | Medium     | -                                 |
| MeCN: MeOH             | 1: 1.23                                                                                                   | High       | Solvent incorporation             |
| 1,4-dioxane            | 1: 2.03                                                                                                   | High       | Highest OSB achieved              |

From the solvent screen (and more solvents in which the beech dioxsolv lignin was insoluble, not shown), 1,4-dioxane was decided on as the optimum solvent. The highest ratio of $\beta$-O-4$^{\text{OX}}$ in situation (iv) or (v) to $\beta$-O-4$^{\text{OX}}$ in situation (ii) or (iii) was obtained in this solvent which
should allow for more monomers to be produced by a C-O cleavage-mediated depolymerisation strategy (e.g. Scheme S1). The choice of non-alcoholic solvents also prevented any chance of incorporation of solvent molecules into the lignin structure.

**Figure S5**: 2D HSQC NMR analysis (700 MHz, d$_6$-DMSO) with integral analysis of beech dioxasolv lignin. For assignment of structures based on colour coding, see Figure S6 or Manuscript Figure 2. Spectra acquired using a reduced $^{13}$C sweep with of 47-133 ppm.$^1$

**Equation 1**: \( \text{No per 100 C9 units} = \frac{\text{unit integral}}{G2 + G20X \text{ integral} + \left( \frac{52.6 + 52.60X \text{ integral}}{2} \right)} \times 100 \)

\( \text{e.g. for} \) $\beta$-O-4 (A). \( \text{No per 100 C9 units} = \frac{170}{100 + 12.3 \text{ integral} + \left( \frac{725.6 + 44.1}{2} \right)} \times 100 \)

\( \text{No per 100} \) $\beta$-O-4 (A) units = 34.2 units (34)
Throughout the course of this study, pre-defined regions were used for all integration on MestReNova 11.0 for Mac.

**MestReNova Integral Regions**

| From(f2) | To(f2)   | From(f1)   | To(f1)   | Unit  |
|---------|----------|------------|----------|-------|
| 5.131600 | 4.632200 | 69.317300  | 74.558200 | Aα    |
| 5.598900 | 5.258300 | 86.078600  | 89.147100 | Bα    |
| 4.836300 | 4.495400 | 83.143500  | 87.729200 | Cα    |
| 4.281800 | 4.001700 | 65.700200  | 69.240800 | LBHKγ |
| 7.534400 | 7.003900 | 104.787600 | 108.773100| S2,6OX|
| 7.207500 | 6.791200 | 109.525500 | 113.813600| G2    |
| 7.044200 | 6.256400 | 101.177700 | 109.218300| S2,6  |
| 5.780600 | 5.423200 | 82.076700  | 85.370600 | A(S)''|
| 5.437300 | 5.110300 | 82.108300  | 85.366500 | A(S)' |
| 6.089900 | 5.769300 | 78.915700  | 82.922900 | A(G)''|
| 5.754900 | 5.459700 | 79.308900  | 82.052100 | A(G)' |
| 4.789500 | 4.579400 | 51.463700  | 54.309100 | D     |
| 10.307300| 9.966600 | 99.567800  | 102.184800| E (when spectrum folded)*|
| 7.718500 | 7.317300 | 109.752800 | 114.106700| G2OX  |
| 10.254300| 9.970400 | 184.673000 | 189.368000| E (when spectrum is unfolded)§|

*Spectrum acquired using a reduced $^{13}$C sweep width of 47-133 ppm

§ Spectrum acquired using $^{13}$C sweep width of 0-170 ppm, o2p spectral centre moved to 125 ppm from 85 ppm.
**Table S3**: Integral data from 2D HSQC NMR analysis of beech lignin DDQ oxidations (varied weight equivalents). In the first grouping of values ($S_{2,6}$, $S_{2,6}^{OX}$, $G_2$ (integral set arbitrarily to 100 units), $G_2^{OX}$), a value is obtained (in triplicate) for the total aromatic integral obtained from 2D HSQC NMR analysis using the integral regions described below Figure S5. The second grouping ($\beta$-O-4 native, $\beta$-O-4$^{OX}$ A(S’), $\beta$-O-4$^{OX}$ A(S’’), $\beta$-\beta resinal native, $\beta$-\beta derived alcohol, $\beta$-\beta derived aldehyde, LBHK, $\beta$-O-4$^{OX}$ A(G’ and $\beta$-O-4$^{OX}$ A(G’’)) is reported as a per 100 C9 value obtained from using Equation 1 as is the norm. Raw integral values for the latter part of the table were omitted for clarity (can be back-calculated from Equation 1).

| DDQ Eqv. | 0.0 | 0.16 | 0.33 | 0.5 | 0.66 | 1 | 1.16 | 1.33 | 1.66 | 2 | 2.33 | 2.66 | 3 |
|----------|-----|------|------|-----|------|---|-----|-----|-----|---|-----|-----|---|
| **S_{2,6}** |     |      |      |     |      |   |     |     |     |   |     |     |   |
| REPEAT 1 | 362.8 | 301.1 | 319.6 | 348.2 | 310.9 | 233.6 | 281.0 | 253.0 | 263.5 | 228.9 | 258.0 | 232.5 | 226.1 | 246.6 |
| REPEAT 2 | 279.9 | 327.5 | 315.1 | 295.7 | 222.3 | 257.8 | 214.9 | 247.0 | 229.5 | 240.7 | 225.5 | 224.1 | 213.9 |
| REPEAT 3 | 306.1 | 372.3 | 341.3 | 266.2 | 250.9 | 224.5 | 236.2 | 227.7 | 222.9 | 210.6 | 231.7 | 252.1 | 241.6 |
| STDEV    | 13.9 | 28.4 | 17.5 | 22.7 | 14.4 | 28.4 | 19.1 | 17.9 | 3.7 | 24.0 | 3.8 | 15.6 | 17.6 |
| ST.ERROR | 8.0 | 16.4 | 10.1 | 13.1 | 8.3 | 16.4 | 11.0 | 10.3 | 2.1 | 13.9 | 2.2 | 9.0 | 10.2 |
| **S_{2,6}^{OX}** |     |      |      |     |      |   |     |     |     |   |     |     |   |
| REPEAT 1 | 22.0 | 56.7 | 103.0 | 213.0 | 294.3 | 323.5 | 339.5 | 341.9 | 299.8 | 463.8 | 529.9 | 517.7 | 497.6 | 534.9 |
| REPEAT 2 | 52.2 | 107.3 | 165.0 | 289.8 | 303.1 | 400.1 | 388.3 | 463.4 | 420.2 | 537.1 | 489.4 | 543.1 | 484.2 |
| REPEAT 3 | 59.5 | 115.1 | 183.9 | 310.4 | 356.8 | 380.6 | 444.2 | 429.7 | 444.5 | 492.6 | 490.8 | 630.1 | 565.2 |
| STDEV    | 3.7 | 6.1 | 24.2 | 10.8 | 27.1 | 30.9 | 51.2 | 86.4 | 21.8 | 23.9 | 15.9 | 67.3 | 40.9 |
| ST.ERROR | 2.1 | 3.5 | 14.0 | 6.3 | 15.7 | 17.9 | 29.6 | 49.9 | 12.6 | 13.8 | 9.2 | 38.9 | 23.6 |
| **G_2** |     |      |      |     |      |   |     |     |     |   |     |     |   |
| REPEAT 1 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| REPEAT 2 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| REPEAT 3 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| **G_2^{OX}** |     |      |      |     |      |   |     |     |     |   |     |     |   |
| REPEAT 1 | 12.3 | 23.2 | 55.9 | 98.6 | 106.5 | 116.0 | 132.3 | 145.4 | 111.9 | 159.6 | 181.9 | 167.8 | 171.1 | 173.9 |
| REPEAT 2 | 16.7 | 48.3 | 70.0 | 106.2 | 124.4 | 147.2 | 139.3 | 164.9 | 139.3 | 186.0 | 151.2 | 194.9 | 155.3 |
| REPEAT | 23.6 | 54.4 | 76.7 | 122.0 | 135.5 | 130.6 | 152.3 | 152.1 | 150.9 | 163.3 | 164.9 | 202.9 | 171.3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STDEV | 3.9 | 4.0 | 15.0 | 9.0 | 9.8 | 9.2 | 6.5 | 27.7 | 10.2 | 12.1 | 8.9 | 16.5 | 10.1 |
| ST. ERROR | 2.2 | 2.3 | 8.6 | 5.2 | 5.7 | 5.3 | 3.8 | 16.0 | 5.9 | 7.0 | 5.1 | 9.5 | 5.8 |
| Total Aromatics | | | | | | | | | | | | | |
| REPEAT 1 | 497.1 | 481.0 | 578.5 | 773.0 | 811.7 | 759.8 | 811.7 | 773.0 | 952.3 | 1069.8 | 1017.9 | 994.8 | 1055.4 |
| REPEAT 2 | 448.8 | 583.0 | 650.1 | 749.8 | 905.1 | 842.5 | 975.3 | 889.0 | 1063.8 | 966.1 | 1062.1 | 953.3 | |
| REPEAT 3 | 489.2 | 641.7 | 701.8 | 798.5 | 843.2 | 835.7 | 932.7 | 909.5 | 918.2 | 966.5 | 987.3 | 1185.1 | 1078.1 |
| β-O-4 native | | | | | | | | | | | | | |
| REPEAT 1 | 34.2 | 35.6 | 29.8 | 19.7 | 12.0 | 10.0 | 6.0 | 7.8 | 14.8 | 5.6 | 6.3 | 4.0 | 6.5 | 6.2 |
| REPEAT 2 | 36.8 | 29.6 | 23.4 | 14.5 | 10.9 | 6.8 | 7.3 | 5.8 | 9.4 | 6.6 | 7.7 | 4.8 | 5.1 |
| REPEAT 3 | 35.9 | 30.0 | 22.2 | 12.6 | 9.3 | 9.2 | 5.6 | 6.4 | 5.6 | 8.1 | 5.8 | 6.3 | 6.6 |
| AVG | 34.2 | 30.0 | 22.2 | 12.6 | 9.3 | 9.2 | 5.6 | 6.4 | 5.6 | 8.1 | 5.8 | 6.3 | 6.6 |
| STDEV | 0.6 | 0.2 | 1.9 | 1.3 | 0.8 | 1.7 | 1.1 | 5.0 | 2.2 | 1.0 | 1.8 | 1.0 | 0.8 |
| ST. ERROR | 0.4 | 0.1 | 1.1 | 0.8 | 0.5 | 1.0 | 0.7 | 2.9 | 1.3 | 0.6 | 1.0 | 0.6 | 0.5 |
| β-O-4ox A(S)’ | | | | | | | | | | | | | |
| REPEAT 1 | 2.3 | 5.3 | 9.4 | 12.7 | 13.1 | 11.7 | 11.5 | 12.4 | 11.9 | 9.9 | 9.5 | 10.3 | 9.4 | 9.6 |
| REPEAT 2 | 6.2 | 11.0 | 12.7 | 13.0 | 11.5 | 10.9 | 10.3 | 9.6 | 10.6 | 10.2 | 10.0 | 9.8 | 9.0 |
| REPEAT 3 | 6.1 | 10.0 | 13.0 | 13.3 | 11.7 | 11.6 | 10.0 | 10.7 | 10.8 | 10.9 | 9.8 | 8.0 | 9.4 |
| AVG | 2.3 | 10.1 | 12.8 | 13.1 | 11.6 | 11.3 | 10.9 | 10.7 | 10.5 | 10.2 | 10.0 | 9.0 | 9.3 |
| STDEV | 0.5 | 0.8 | 0.2 | 0.1 | 0.1 | 0.4 | 1.3 | 0.5 | 0.7 | 0.3 | 0.9 | 0.3 |
| ST. ERROR | 0.3 | 0.5 | 0.1 | 0.1 | 0.2 | 0.7 | 0.7 | 0.3 | 0.4 | 0.1 | 0.5 | 0.2 |
| β-O-4ox A(S)” | | | | | | | | | | | | | |
| REPEAT 1 | 0.4 | 1.1 | 2.3 | 9.3 | 13.5 | 17.5 | 19.4 | 20.6 | 15.6 | 22.4 | 24.3 | 24.1 | 23.3 | 23.8 |
| REPEAT 2 | 0.1 | 3.0 | 7.1 | 14.7 | 17.0 | 19.1 | 21.1 | 22.1 | 22.4 | 24.1 | 24.0 | 25.2 | 24.6 |
| REPEAT 3 | 0.9 | 2.8 | 7.5 | 15.7 | 19.1 | 20.2 | 22.1 | 22.1 | 23.3 | 25.2 | 24.0 | 25.0 | 24.7 |
| AVG | 0.4 | 2.7 | 8.0 | 14.6 | 17.9 | 19.6 | 21.3 | 19.9 | 22.7 | 24.5 | 24.0 | 24.5 | 24.4 |
| STDEV | 0.5 | 0.3 | 1.1 | 1.1 | 1.1 | 0.5 | 0.8 | 3.8 | 0.5 | 0.6 | 0.0 | 1.0 | 0.5 |
|                | ST.ERROR | 0.3 | 0.2 | 0.7 | 0.6 | 0.6 | 0.3 | 0.4 | 2.2 | 0.3 | 0.3 | 0.0 | 0.6 | 0.3 |
|----------------|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **β-β resinol native** |           |     |     |     |     |     |     |     |     |     |     |     |     |     |
| REPEAT 1       |           | 9.4 | 6.9 | 4.2 | 4.0 | 3.7 | 2.3 | 2.3 | 1.8 | 2.5 | 1.3 | 1.8 | 1.7 | 1.7 |
| REPEAT 2       |           | 6.8 | 5.0 | 5.3 | 3.1 | 2.3 | 1.3 | 1.8 | 1.4 | 2.2 | 2.0 | 1.4 | 2.1 | 2.2 |
| REPEAT 3       |           | 7.1 | 5.9 | 4.5 | 3.3 | 2.4 | 2.3 | 1.7 | 1.5 | 1.9 | 1.8 | 1.8 | 1.6 | 1.9 |
| AVG            |           | 9.4 | 7.0 | 5.9 | 4.6 | 3.4 | 2.3 | 2.0 | 1.8 | 1.8 | 1.8 | 1.6 | 1.8 | 1.9 |
| STDEV          |           | 0.2 | 0.9 | 0.7 | 0.3 | 0.1 | 0.6 | 0.0 | 0.6 | 0.5 | 0.1 | 0.2 | 0.3 | 0.3 |
| ST.ERROR       |           | 0.1 | 0.5 | 0.4 | 0.2 | 0.0 | 0.3 | 0.0 | 0.4 | 0.3 | 0.1 | 0.1 | 0.2 | 0.2 |
| **β-β derived alcohol** |         |     |     |     |     |     |     |     |     |     |     |     |     |     |
| REPEAT 1       |           | -0.2| 0.6 | 1.1 | 3.0 | 4.1 | 3.1 | 4.8 | 4.0 | 2.4 | 2.8 | 1.9 | 1.8 | 1.6 |
| REPEAT 2       |           | 0.1 | 1.1 | 2.3 | 4.5 | 4.5 | 5.6 | 6.2 | 3.5 | 3.4 | 2.4 | 2.7 | 1.0 | 1.5 |
| REPEAT 3       |           | 0.2 | 1.5 | 2.3 | 4.4 | 5.2 | 6.0 | 4.6 | 4.0 | 3.2 | 3.6 | 1.8 | 0.9 | 1.2 |
| AVG            |           | -0.2| 0.1 | 0.6 | 1.3 | 2.2 | 2.3 | 2.8 | 2.0 | 1.6 | 1.4 | 1.4 | 0.8 | 0.7 |
| STDEV          |           | 0.2 | 0.3 | 0.4 | 0.2 | 1.3 | 0.8 | 0.5 | 0.8 | 0.4 | 0.8 | 0.5 | 0.4 | 0.1 |
| ST.ERROR       |           | 0.1 | 0.2 | 0.2 | 0.1 | 0.8 | 0.4 | 0.3 | 0.5 | 0.2 | 0.5 | 0.3 | 0.2 | 0.0 |
| **β-β derived aldehyde** |       |     |     |     |     |     |     |     |     |     |     |     |     |     |
| REPEAT 1       |           | -0.1| 0.0 | 0.3 | 0.8 | 0.3 | 1.3 | 2.0 | 3.3 | 1.1 | 2.2 | 2.5 | 4.0 | 3.4 |
| REPEAT 2       |           | -0.3| 0.1 | 0.1 | 0.6 | 0.7 | 1.8 | 2.1 | 2.1 | 2.3 | 2.1 | 2.9 | 3.0 | 3.0 |
| REPEAT 3       |           | 0.2 | 0.1 | 0.7 | 0.5 | 0.8 | 1.1 | 1.8 | 2.5 | 2.3 | 2.5 | 3.2 | 3.0 | 2.4 |
| AVG            |           | -0.1| 0.0 | 0.2 | 0.5 | 0.5 | 0.9 | 1.6 | 2.4 | 1.9 | 2.3 | 2.3 | 3.4 | 3.1 |
| STDEV          |           | 0.3 | 0.1 | 0.4 | 0.2 | 0.4 | 0.5 | 0.8 | 0.7 | 0.1 | 0.2 | 0.5 | 0.2 | 0.3 |
| ST.ERROR       |           | 0.2 | 0.1 | 0.2 | 0.1 | 0.2 | 0.3 | 0.5 | 0.4 | 0.0 | 0.1 | 0.3 | 0.1 | 0.2 |
| **LBHK**       |           |     |     |     |     |     |     |     |     |     |     |     |     |     |
| REPEAT 1       |           | 8.4 | 7.2 | 8.7 | 9.6 | 6.7 | 7.9 | 6.4 | 6.0 | 9.2 | 6.1 | 6.3 | 5.0 | 8.0 |
| REPEAT 2       |           | 7.9 | 8.3 | 8.9 | 8.3 | 8.1 | 5.5 | 5.5 | 6.2 | 6.2 | 5.4 | 5.3 | 5.1 | 4.1 |
| REPEAT 3       |           | 8.3 | 8.6 | 8.1 | 9.0 | 7.7 | 7.2 | 5.6 | 6.1 | 6.0 | 5.7 | 4.9 | 5.0 | 4.8 |
|       | AVG  | STDEV | ST.ERROR |
|-------|------|-------|----------|
|       | 8.4  | 0.5   | 0.3      |
|       | 7.8  | 0.2   | 0.1      |
|       | 8.5  | 0.7   | 0.4      |
|       | 8.9  | 1.1   | 0.7      |
|       | 8.0  | 0.2   | 0.1      |
|       | 7.9  | 0.8   | 0.5      |
|       | 6.4  | 0.3   | 0.2      |
|       | 5.7  | 1.7   | 1.0      |
|       | 7.2  | 0.1   | 0.1      |
|       | 6.1  | 0.5   | 0.3      |
|       | 5.8  | 0.2   | 0.1      |
|       | 5.1  | 1.7   | 0.1      |
|       | 6.0  | 0.2   | 0.1      |
|       | 4.9  | 0.9   | 0.5      |

| β-O-4ox A(G)' | REPEAT 1 | | REPEAT 2 | | REPEAT 3 | | AVG | | STDEV | | ST.ERROR |
|---------------|----------|---|----------|---|----------|---|------|---|------|---|
|               | 0.9      | | 2.3      | | 1.4      | | 0.9  | | 0.6   | | 0.4    |
|               | 1.1      | | 2.3      | | 2.3      | | 1.6  | | 0.0   | | 0.0    |
|               | 2.5      | | 3.4      | | 2.5      | | 2.3  | | 0.5   | | 0.3    |
|               | 3.2      | | 3.0      | | 2.8      | | 2.8  | | 0.2   | | 0.1    |
|               | 3.2      | | 2.5      | | 2.9      | | 2.9  | | 0.3   | | 0.2    |
|               | 3.3      | | 2.8      | | 2.3      | | 2.8  | | 0.5   | | 0.3    |
|               | 2.3      | | 3.0      | | 2.6      | | 2.6  | | 0.4   | | 0.4    |
|               | 3.4      | | 2.8      | | 3.2      | | 3.2  | | 0.6   | | 0.0    |
|               | 4.0      | | 3.0      | | 2.6      | | 2.6  | | 0.7   | | 0.1    |
|               | 2.6      | | 2.7      | | 3.3      | | 3.3  | | 0.7   | | 0.7    |
|               | 2.9      | | 2.7      | | 2.6      | | 3.0  | | 0.1   | | 0.3    |
|               | 2.4      | | 3.7      | | 2.8      | | 2.8  | | 0.4   | | 0.4    |
|               | 2.5      | | 3.2      | | 3.0      | | 3.0  | | 0.3   | | 0.2    |

| β-O-4ox A(G)" | REPEAT 1 | | REPEAT 2 | | REPEAT 3 | | AVG | | STDEV | | ST.ERROR |
|---------------|----------|---|----------|---|----------|---|------|---|------|---|
|               | 0.8      | | 0.8      | | 0.2      | | 0.8  | | 0.4   | | 0.2    |
|               | 0.8      | | 1.3      | | 0.5      | | 1.3  | | 0.7   | | 0.4    |
|               | 1.9      | | 1.8      | | 2.1      | | 1.8  | | 0.2   | | 0.1    |
|               | 2.2      | | 4.3      | | 4.4      | | 4.3  | | 0.6   | | 0.0    |
|               | 4.3      | | 4.3      | | 4.4      | | 4.3  | | 0.5   | | 0.5    |
|               | 6.4      | | 5.5      | | 5.8      | | 5.5  | | 0.5   | | 0.5    |
|               | 4.1      | | 5.2      | | 6.2      | | 5.2  | | 1.0   | | 0.5    |
|               | 4.5      | | 4.7      | | 6.0      | | 4.7  | | 0.9   | | 0.7    |
|               | 5.0      | | 6.0      | | 6.3      | | 6.0  | | 0.7   | | 0.2    |
|               | 7.0      | | 6.7      | | 7.0      | | 6.7  | | 0.6   | | 0.6    |
|               | 7.0      | | 6.5      | | 7.0      | | 6.5  | | 0.5   | | 0.5    |
|               | 7.7      | | 6.9      | | 7.7      | | 6.9  | | 0.4   | | 0.4    |
|               | 6.5      | | 7.2      | | 6.7      | | 7.2  | | 0.4   | | 0.1    |
|               | 7.4      | | 7.2      | | 7.3      | | 7.2  | | 0.1   | | 0.1    |

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Figure S6: 2D HSQC NMR analysis (700 MHz, $d_6$-DMSO) of beech dioxasolv lignin (A) and beech lignin$^{\text{a-OX}}$ (B-N) from DDQ weight equivalents study. An example spectrum from each wt. eqv. of DDQ (B-N) is shown. Spectra acquired using a reduced $^{13}$C sweep with of 47-133 ppm. Dark green units in the aromatic region refer to oxidised G aromatic units (e.g. G'/G$''$); dark blue refer to non-oxidised S aromatic units (e.g. S) and dark red refer to oxidised S aromatic units (e.g. S'/S$''$).
**S-G/G-G-β-O-4 Oxidation Discussion**

In general, in the 2D HSQC spectra we obtained, the cross peaks corresponding to the S-S\(^{α-OX}\) or G-S\(^{α-OX}\) containing β-O-4\(^{α-OX}\) linkages were dominant compared with the G-G\(^{α-OX}\) or S-G\(^{α-OX}\) signals (Figure S7a-b). This results from the fact that the S:G ratio was 3.3:1 for the batch of dioxasolv beech lignin (from semi-quantitative 2D HSQC NMR analysis) that was isolated for this study though this will vary depending on the extraction method. This assumes that S:G ratio in the β-O-4 units mirrors the overall S:G ratio (which may well not be the case). Despite the complexities, Figure S7b clearly demonstrates how much smaller the signals corresponding to the G-G/S-G β-O-4\(^{α-OX}\) linkages are compared to those corresponding to the S-S/G-S β-O-4\(^{α-OX}\) linkages. Given the low percentage of all unit content that the G-G/S-G β-O-4 units correspond to, it is unsurprising that the signals are not always observed by 2D HSQC NMR (c.f. Figure S6B-N).
Figure S7b: 2D HSQC NMR (700 MHz, d6-DMSO) analysis of the β-O-4α-OX β-proton region of A) the starting beech dioxasolv lignin; B) Beech ligninα-OX (0.66 wt. eqv. DDQ) and; C) Beech ligninα-OX (3 wt. eqv. DDQ).
Examining S-G and G-G β-O-4 oxidation (see Manuscript for discussion of G-S or S-S β-O-4 unit oxidation)

Figure S8: Beech Lignin DDQ oxidation study: A) Proposed reactivity of G- β-O-4 units within lignin including possible oxidized stages within lignin \(\alpha^{+}\text{OX} \) of the G- β-O-4 unit. The chemical shifts of the highlighted H atoms are reliant on the substituents on the aromatic ring connected via the aryl-ether linkage (Figure S1); B) Graph displaying G-β-O-4 \(\alpha-\text{OX} \) units per 100 C9 units against DDQ weight equivalents; Highlighted H atoms (and their corresponding cross-peaks within 2D HSQC analysis) were used for semi-quantification of units within lignin. Data repeated in triplicate, for standard error analysis, see Table S3. Native β-O-4 not shown for clarity.

This discussion is based on the data presented in Figure 3 in the manuscript and reproduced in Figure S8 above for ease of understanding this section. An initial increase in the quantity of oxidised β-O-4 units in the situations shown in Figures S8A(ii) or A(iii) in the lignin was observed \(\text{A(G')}(\text{OSA})\) (Fig. S8B light green bar increases on going from 0 – 0.5 wt. eqv. of DDQ (1 to 3 units per 100 C9 units). This was followed by a steady plateau in the size of the light green bar. Fully oxidised G-β-O-4 \(\text{A(G)}'(\text{OSB})\) (in the situations shown in Figures S8A(iv) or A(v), dark green section of the bars in Figure S8B) was found to increase in quantity from 0 – 3 wt. eqv. of DDQ (see Manuscript Figure 2C for result at 3 wt. eqv. and Figure S6). Interestingly, unlike the situation for the β-O-4(S) units (light pink A(S)' signal), no decrease in the light green bar \(\text{A(G')}(\text{OSA})\) was seen as the dark green bar \(\text{A(G)}'(\text{OSB})\) was increasing (c.f. Figure 3B changes in light pink and dark pink bars). A key observation noticed for most weight equivalents of DDQ used was that the dark green bar \(\text{A(G)}'(\text{OSB})\) was larger than the light green bar \(\text{A(G')}(\text{OSA})\). This led us to become interested in whether there were differences in reactivity for the G-G\(\_\text{G-S-G}\) when compared to the S-S/G-S units. For this reason, we conducted time course analyses for the beech lignin oxidation at 80 °C and room temperature (S-S/G-S units discussed in manuscript).
G-G/S-G \( \beta\)-O-4 Results from the Time-course Study (S-S/G-S \( \beta\)-O-4 results discussed in manuscript)

**Figure S9**: G-G/S-G \( \beta\)-O-4 time-course analysis of beech lignin oxidation at: (a) 80 °C and; (b) room temperature. Data plotted as time vs. no per 100 C9 units, see full data in Tables S4 and S5.

Consumption of \( \beta\)-O-4 units have been omitted from Figure S9. The purpose of this time-course study was to examine differences in rates of S- and G-\( \beta\)-O-4 oxidation within beech lignin (for more discussion of S-\( \beta\)-O-4 oxidation, see manuscript). At 80 °C (Figure S9 (a)), within 10 minutes, almost equal amounts of A(\( \text{G} \))' (light green) and A(\( \text{G} \))” (dark green) units were observed (analogous to A(\( \text{S} \))’ and A(\( \text{S} \))”, Figure S10(a)(i)). By 20 minutes, a plateau of oxidation for G-\( \beta\)-O-4 units has been reached and no more A(\( \text{G} \))” is observed. This was not the same for S-\( \beta\)-O-4 oxidation at 20 minutes as a gradual increase of A(\( \text{S} \))” and corresponding decrease in A(\( \text{S} \))’ is still observed (Figure S10(a)(i)) over the next 80 minutes of the reaction. This provides further evidence that either (a) G-\( \beta\)-O-4 oxidation is faster than S-\( \beta\)-O-4 using these conditions or; (b) S-\( \beta\)-O-4 units could more often be found adjacent to other oxidizable units which are comparatively slower to be oxidised than \( \beta\)-O-4 units (for example, as is observed with the rapid loss of \( \beta\)-\( \beta\) resinol native units and slow increase in \( \beta\)-\( \beta\) derived alcohol and aldehyde units, Manuscript Figure 4 and Figure S10). To examine this in more detail, a competitive DDQ oxidation of model compounds \textbf{S1} and \textbf{S2} was conducted (Scheme S2).
Time Course Analysis of DDQ Oxidation of Beech lignin

Figure S10: Graphical representations of a time-course analysis of DDQ oxidation of beech lignin at: (a) 80 °C; (i) β-O-4 oxidation; (ii) β-β oxidation; and; (b) room temperature; (i) β-O-4 oxidation; (ii) β-β oxidation. Data plotted as time vs. no per 100 C9 units, see full data in Table S4 and S5.
Table S4: Integral data from 2D HSQC NMR analysis of beech lignin DDQ oxidations (time-course study at 80 °C). In the first grouping of values ($S_{2,6}$, $S_{2,6}^{OX}$, $G_2$ (integral set arbitrarily to 100 units), $G_2^{OX}$), a value is obtained (in triplicate) for the total aromatic integral obtained from 2D HSQC NMR analysis using the integral regions described below Figure S5. The second grouping ($\beta$-O-4 native, $\beta$-O-4$^{OX}$ A(S)’, $\beta$-O-4$^{OX}$ A(S)”’, $\beta$-$\beta$ resinol native, $\beta$-$\beta$ derived alcohol, $\beta$-$\beta$ derived aldehyde, LBHK, $\beta$-O-4$^{OX}$ A(G)’ and $\beta$-O-4$^{OX}$ A(G)”’) is reported as raw integrals and a per 100 C9 value obtained from using Equation 1 as is the norm.

| Time / minutes | 0   | 5   | 10  | 20  | 40  | 60  | 80  | 100 |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| $S_{2,6}$      | 362.8 | 328.0 | 220.7 | 203.8 | 215.1 | 199.2 | 197.0 | 188.9 |
| $S_{2,6}^{OX}$ | 22.0  | 212.6 | 358.6 | 404.3 | 471.5 | 485.8 | 523.7 | 538.6 |
| $G_2$          | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| $G_2^{OX}$     | 12.3  | 103.5 | 178.5 | 192.2 | 220.6 | 226.3 | 236.9 | 237.1 |
| Total Aromatics| 497.1 | 744.1 | 857.8 | 900.3 | 1007.1| 1011.3| 1057.6| 1064.6|
| Raw integral   | 34.2 | 12.8 | 8.5  | 7.1  | 7.0  | 6.3  | 5.7  | 6.0  |
| per 100 C9     | 94.9 | 72.9 | 64.4 | 70.5 | 63.8 | 60.0 | 63.9 |

| Raw integral   | 2.3 | 11.0 | 12.1 | 11.4 | 10.5 | 10.0 | 9.5  | 8.8  |
| per 100 C9     | 81.7 | 104.0 | 102.3 | 106.2 | 101.4 | 100.6 | 93.6 |

| Raw integral   | 0.4 | 10.5 | 23.6 | 24.7 | 26.8 | 27.4 | 28.6 | 29.2 |
| per 100 C9     | 78.4 | 202.2 | 222.6 | 270.0 | 277.4 | 302.1 | 310.7 |

| Raw integral   | 9.4 | 3.4  | 2.0  | 2.1  | 2.1  | 1.9  | 1.5  | 1.8  |
| per 100 C9     | 25.5 | 17.3  | 18.9  | 20.7  | 19.7  | 15.8  | 18.8 |

| Raw integral   | 7.7 | 20.0 | 17.4 | 15.8 | 14.5 | 11.4 | 9.3  |
| per 100 C9     | 20.0 | 17.4 | 15.8 | 14.5 | 11.4 | 9.3  | 7.7  |
| per 100 C9 | 0.0 | 1.0 | 2.3 | 1.9 | 1.6 | 1.4 | 1.1 | 0.9 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|
| **β-β derived aldehyde** | |
| Raw integral | 2.2 | 16.2 | 18.4 | 31.3 | 31.8 | 40.0 | 48.6 |
| per 100 C9 | 0.0 | 0.3 | 1.9 | 2.0 | 3.1 | 3.1 | 3.8 | 4.6 |
| |
| **LBHK** | |
| Raw integral | 59.8 | 42.8 | 40.1 | 45.0 | 38.9 | 38.7 | 38.7 |
| per 100 C9 | 8.4 | 8.0 | 5.0 | 4.5 | 4.5 | 3.8 | 3.7 | 3.6 |
| |
| **β-O-4\textsuperscript{0x} A(G)'** | |
| Raw integral | 31.9 | 26.0 | 25.3 | 27.0 | 26.2 | 31.7 | 28.8 |
| per 100 C9 | 0.9 | 4.3 | 3.0 | 2.8 | 2.7 | 2.6 | 3.0 | 2.7 |
| |
| **β-O-4\textsuperscript{0x} A(G)''** | |
| Raw integral | 28.0 | 50.8 | 65.6 | 72.9 | 79.7 | 81.5 | 82.9 |
| per 100 C9 | 0.8 | 3.8 | 5.9 | 7.3 | 7.2 | 7.9 | 7.7 | 7.8 |
Table S5: Integral data from 2D HSQC NMR analysis of beech lignin DDQ oxidations (time-course study at room temperature). In the first grouping of values ($S_{2,6}$, $S_{2,6}^{\text{OX}}$, $G_{2}$ (integral set arbitrarily to 100 units), $G_{2}^{\text{OX}}$), a value is obtained for the total aromatic integral obtained from 2D HSQC NMR analysis using the integral regions described below Figure S5. The second grouping ($\beta$-O-4 native, $\beta$-O-4$^{\text{OX}}$ A($S'$), $\beta$-O-4$^{\text{OX}}$ A($S''$), $\beta$-$\beta$ resinol native, $\beta$-$\beta$ derived alcohol, $\beta$-$\beta$ derived aldehyde, LBHK, $\beta$-O-4$^{\text{OX}}$ A(G)$'$ and $\beta$-O-4$^{\text{OX}}$ A(G)$''$) is reported as raw integrals and a per 100 C9 value obtained from using Equation 1 as is the norm.

| Time / hours | 0    | 0.5  | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 14   |
|-------------|------|------|------|------|------|------|------|------|------|------|------|
| $S_{2,6}$   | 438.8| 326.4| 318.6| 284.5| 265.9| 309.3| 259.7| 287.5| 268.0| 258.0| 257.8|
| $S_{2,6}^{\text{OX}}$ | 13.3 | 141.5| 142.6| 176.8| 226.8| 263.3| 261.3| 279.5| 297.7| 298.7| 315.5|
| $G_{2}$     | 100.0| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0| 100.0|
| $G_{2}^{\text{OX}}$ | 10.7 | 83.0 | 72.4 | 81.7 | 98.7 | 107.5| 110.4| 109.1| 123.1| 115.2| 123.0|
| Total Aromatics | 562.7| 650.9| 633.7| 642.9| 691.3| 780.1| 731.3| 776.1| 788.8| 771.8| 796.2|

| $\beta$-O-4 native |
|-------------------|
| Raw integral  |
| per 100 C9      |
| 171.2            | 166.8          | 142.7          | 130.8          | 109.7          | 129.1          | 104.8          | 101.6          | 102.8          | 102.7          | 84.6            |
| **30.4**          | **25.6**        | **22.5**        | **20.4**        | **15.9**        | **16.6**        | **14.3**        | **13.1**        | **13.0**        | **13.3**        | **10.6**        |

| $\beta$-O-4$^{\text{OX}}$ A($S'$) |
|-----------------------------|
| Raw integral  |
| per 100 C9      |
| 7.2             | 68.1            | 64.0            | 69.4            | 75.1            | 86.6            | 82.5            | 88.9            | 86.8            | 88.3            | 88.5            |
| **1.3**          | **10.5**         | **10.1**         | **10.8**         | **10.9**         | **11.1**         | **11.3**         | **11.5**         | **11.0**         | **11.4**         | **11.1**         |

| $\beta$-O-4$^{\text{OX}}$ A($S''$) |
|-----------------------------|
| Raw integral  |
| per 100 C9      |
| 2.1             | 36.6            | 36.4            | 59.1            | 88.8            | 102.9           | 113.4           | 118.5           | 137.0           | 138.2           | 140.2           |
| **0.4**          | **5.6**          | **5.7**          | **9.2**          | **12.8**         | **13.2**         | **15.5**         | **15.3**         | **17.4**         | **17.9**         | **17.6**         |

| $\beta$-$\beta$ native |
|------------------------|
| Raw integral  |
| per 100 C9      |
| 45.8           | 34.8            | 32.0            | 26.6            | 24.0            | 24.0            | 20.3            | 19.6            | 23.2            | 21.9            | 18.3            |
| **8.1**          | **5.4**          | **5.0**          | **4.1**          | **3.5**          | **3.1**          | **2.8**          | **2.5**          | **2.9**          | **2.8**          | **2.3**          |

| $\beta$-$\beta$ derived alcohol |
|-------------------------------|
| Raw integral  |
| 1.1              | 3.3              | 3.4              | 5.4              | 4.2              | 6.4              | 5.2              | 5.9              | 8.6              | 9.3              | 10.7              |
|                  | per 100 C9 | 0.2 | 0.5 | 0.5 | 0.8 | 0.6 | 0.8 | 0.7 | 0.8 | 1.1 | 1.2 | 1.3 |
|------------------|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **β-β derived aldehyde** |            |     |     |     |     |     |     |     |     |     |     |     |
| Raw integral per 100 C9 | 0.2 | 2.0 | 1.0 | 2.8 | 2.6 | 2.9 | 3.8 | 2.0 | 4.3 | 2.8 | 6.7 |     |
|                  | 0.0 | 0.3 | 0.2 | 0.4 | 0.4 | 0.4 | 0.5 | 0.3 | 0.5 | 0.4 | 0.8 |     |
|                  |     |     |     |     |     |     |     |     |     |     |     |     |
| **LBHK**         |            |     |     |     |     |     |     |     |     |     |     |     |
| Raw integral per 100 C9 | 40.2 | 60.3 | 49.9 | 47.8 | 67.2 | 73.9 | 70.1 | 70.1 | 71.7 | 64.9 | 70.9 |     |
|                  | 7.1 | 9.3 | 7.9 | 7.4 | 9.7 | 9.5 | 9.6 | 9.0 | 9.1 | 8.4 | 8.9 |     |
|                  |     |     |     |     |     |     |     |     |     |     |     |     |
| **β-O-4^\text{OX} A(G)'** |            |     |     |     |     |     |     |     |     |     |     |     |
| Raw integral per 100 C9 | 0.9 | 20.8 | 20.2 | 17.0 | 26.5 | 28.9 | 23.9 | 24.9 | 22.7 | 28.9 | 25.2 |     |
|                  | 0.2 | 3.2 | 3.2 | 2.6 | 3.8 | 3.7 | 3.3 | 3.2 | 2.9 | 3.7 | 3.2 |     |
|                  |     |     |     |     |     |     |     |     |     |     |     |     |
| **β-O-4^\text{OX} A(G)''** |            |     |     |     |     |     |     |     |     |     |     |     |
| Raw integral per 100 C9 | 0.0 | 16.0 | 15.0 | 18.2 | 31.2 | 31.5 | 38.2 | 36.0 | 38.8 | 38.7 | 44.8 |     |
|                  | 0.0 | 2.5 | 2.4 | 2.8 | 4.5 | 4.0 | 5.2 | 4.6 | 4.9 | 5.0 | 5.6 |     |
**Figure S11:** 2D HSQC NMR analysis (700 MHz, $d_6$-DMSO) of beech dioxasolv lignin (A-H, 0 - 100 minutes) during time course analysis at 80 °C. Reaction conducted using 3 wt. eqv. of DDQ. For coloured contour assignment, see Figure S6.
Figure S12: 2D HSQC NMR analysis (700 MHz, $d_6$-DMSO) of beech dioxasolv lignin during time course analysis of DDQ oxidation at room temperature. For coloured contour assignment, see Figure S6.
G- vs. S- β-O-4 Competitive Oxidation of Model Compounds

To examine whether G-G or S-S β-O-4 units convert faster under our reaction conditions, a competitive model study with G-G and S-S β-O-4 models S1 and S2 was conducted. A mixture of 1: 2.5 of S1 and S2 (25.0 mg and 75.0 mg respectively representing a ~1: 2.5 mixture) were prepared and subjected to the following conditions: DDQ (60 mg, 1 eqv.), 1,4-dioxane (4 mL, 25 mg/mL), 80 °C. 400 µL aliquots were taken over an 8-minute period and each aliquot quenched through addition of 200 µL NaHCO3 (saturated solution). Samples were transferred to a GeneVac® EZ-2 and concentrated under reduced pressure. To each sample was added 1000 µL of an internal standard solution in CDCl3 (I.S: Sesamol >99%, 52.6 mg accurately weighed out into 50 mL of CDCl3 in a volumetric flask), vortexed to homogenise the solution and centrifuged at 5000 rpm for 5 minutes. Samples were transferred to NMR tubes and analysed by quantitative 1H NMR using the standard pulse sequence from the Bruker library (zg) with an interscan delay (D1) of 30 seconds.

NB. Whilst a 1: 2.5 mixture of S1 to S2 does not represent the exact S:G ratio found in the hardwood lignin we were using, enough of S1 was needed to ensure signal was acquired by NMR.

Scheme S2: Competitive DDQ oxidation of β-O-4 models S1 and S2. (a) DDQ (1.0 eqv.), 1,4-dioxane (25 mg/mL), 80 °C, 8 minutes.
**Figure S13**: $^1$H NMR spectra (CDCl$_3$) of models S1-S4 (a)-(d).

**Figure S14**: Example of $^1$H NMR data from DDQ model reaction of S1 and S2 at 80 °C. Peak at 6.25 ppm corresponds to one of the signals in the internal standard, Sesamol.
Figure S15: DDQ oxidation of S1 and S2 leads to proposed intermediate carbocations S1a and S2a.

Figure S16: Graphical representation of DDQ oxidation of models S1 and S2 to yield S3 (green line) and S4 (pink line) as shown in Scheme S2.

From the competitive DDQ oxidation reaction with models S1 and S2 (Scheme S2), it would be predicted that at any given time point, the conversion of S1, the G-G β-O-4 model, would be higher due to better stability of the intermediate carbocation (S1a vs. S2a, Figure S15), than S2, the S-S β-O-4 model. From the time-course analysis data (Figure S16), it is observable that at any time point, the oxidation of model S1 to model S3 (green line) reaches higher conversion than model S2 to S4 (pink line). This evidence supports the observation that G-β-O-4 oxidation is faster than S-β-O-4 with much lower conversions observed over time. A low rate of S-β-O-4 oxidation may also be impacted by the rapid consumption of DDQ from G-β-O-4 oxidation.
Study of LBHK model compounds with DDQ

For synthesis of Models 1a and 1b see Reference 7

Scheme S3: Reactivity of LBHK model 1a/b when subjected to DDQ oxidation conditions analogous to beech ligninα-Ox generation.

General reaction procedure: To a vial is added model compound 1a/b (25 mg) in 1,4-dioxane (1 mL) is added DDQ (X equiv.) and heated to 80 °C for 2 hours. The reaction is cooled, filtered through celite and concentrated in vacuo to give a crude product for NMR analysis.

Figure S17a: S-LBHK DDQ model study: 1H NMR spectra from A) LBHK model 1a (S-LBHK); and crude reaction mixture with B) 1 eqv. DDQ; C) 3 eqv. DDQ and; D) 5 eqv. DDQ.
From analysis of S-LBHK 1a reactions (Figure S17a), decomposition of 1a with increasing numbers of equivalents of DDQ does appear to be occurring but to no single product.

**Figure S17b**: G-LBHK DDQ model study: $^1$H NMR spectra from A) LBHK model 1b (G-LBHK); and crude reaction mixture with B) 1 equiv. DDQ; C) 3 equiv. DDQ and; D) 5 equiv. DDQ. *Proposed structure

From analysis of G-LBHK 1b reactions (Figure S17b), the reaction with 1 equiv. of DDQ (Figure S17b: B), no/very little conversion of 1b is observed. With increasing numbers of DDQ (3-5 equiv.) (Figure S17b: C-D), full conversion of 1b is observed to one major species. Attempts to purify the material generated here (silica/alumina chromatography) led to decomposition of the product and any additional work-up steps caused decomposition (e.g. quenching of excess DDQ with NaHCO$_3$). Crude analysis of the mixture generated from 3 equiv. of DDQ led us to a proposed structure shown in Figure S17b: C.
Figure S17c: $^1$H NMR analysis of crude reaction mixture from the reaction of 1b with 3 eqv. of DDQ yielding proposed 8-membered ring structure 2b.

From the $^1$H NMR (Figure S17c) (and COSY analysis, not shown) it was found that H4/4' and H8/8' are found on the same carbon with high geminal J values of 20 Hz. There is one major set of signals present suggesting the molecule is C2 symmetric (possibly only one diastereoisomer present). 2D multiplicity-edited HSQC NMR analysis (Figure S17d) confirms that the singlet peak at 6.15 ppm is a CH and the doublets at 4.68 and 4.59 ppm is a CH$_2$. The $^{13}$C NMR (Figure S17e) confirms a carbonyl is still present at 204.7 ppm (similar to the starting material$^7$) and corresponding HMBC analysis (Figure S17f) confirms that this carbonyl still observes H4/8 and H2/6 (and H4/8 and H2/6 observe each other) suggesting no change in the backbone to this structure. H2/6 still observes 3J coupling to C13/22 and C17/18 again confirming no change. Strong de-shielding of H2/6 by ca. 2 ppm could be explained by it now being bound to an oxygen atom and adjacency to a ketone. The effect of the macrocycle may also be influencing the chemical shifts of these H-atoms.
**Figure S17d:** $^{13}$C NMR analysis of crude reaction mixture from the reaction of 1b with 3 eqv. of DDQ yielding proposed 8-membered ring structure 2b.

**Figure S17e:** 2D HSQC NMR analysis of crude reaction mixture from the reaction of 1b with 3 eqv. of DDQ yielding proposed 8-membered ring structure 2b.
**Figure S17f:** 2D HSQC NMR analysis of crude reaction mixture from the reaction of 1b with 3 eqv. of DDQ yielding proposed 8-membered ring structure 2b.

HRMS analysis led to the following: **HRMS (ESI+) m/z [M + 2H⁺]** calcd. for C_{22}H_{26}O_{8}^{2+} 209.0808, found 209.0809. A possible DDQ mechanism involving formation of a benzylic cation via H-abstraction followed by intermolecular trapping with the primary alcohol of another molecule of 1b (Figure S17g A) examines how 2b could be formed. A possible fragmentation in the MS could have led to the found mass of 209.0809 Da (Figure S17g B). Additional HRMS analysis led to the following result: **HRMS (ASAP+) m/z [M + H⁺]** calcd. for C_{22}H_{25}O_{8}^{+} 417.1550, found 417.1549.

IR analysis led to the following result: **IR (FTIR) ν max:** 2966, 2939, 1734, 1695, 1681, 1560, 1514, 1442 cm⁻¹; the carbonyl shift is consistent for a carbonyl in an 8-membered ring structure.
**Figure 17g:** A) Proposed mechanism leading to the formation of 2b using DDQ and; B) possible rationale for HRMS result.
**Pseudo-2D DOSY NMR Analysis of Compound 2b**

Initial analysis of 2b led to two possible structures being proposed, a 4-membered ring and an 8-membered ring (Figure S17h). In an attempt to distinguish between the two structures, molecular weight prediction using DOSY NMR (a non-destructive technique) was conducted based on recent work by Morris et al.\(^8\)

![Figure S17h: Two proposed structures of compound 2b.](image)

A known compound, 1b, was analysed by DOSY NMR alongside a doped sample of 1b with a crude mixture of 2b. The crude reaction mixture (containing 10 mg of 2b) was dissolved in 0.7 mL of \(\text{d}_4\)-MeOD and was doped with 1b (10 mg). DOSY measurements were carried out on Bruker Avance III 700 MHz spectrometer equipped with a \(^1\text{H}/^{13}\text{C}/^{15}\text{N}\) TCI cryoprobe (Prodigy) using the \textit{ledbpgp2s} pulse sequence from the Bruker library. Diffusion parameters \(\Delta\) and \(\delta\) were optimised prior to the 2D experiment. 32 magnetic field gradient amplitudes from 5.9 to 57.9 G cm\(^{-1}\) were used and incremented in equal steps. The probe temperature was maintained at 298 K and the sample was left to thermally equilibrate for 15 minutes inside the magnet prior to acquisition. Molecular weights of the solutes were predicted as previously reported by Morris et al.\(^8\)

2D DOSY NMR analysis (Figure S17i) of model 1b (highlighted in green) yielded a predicted molecular weight of 188.9 g mol\(^{-1}\) (actual \(M_W\) of 210.2 g mol\(^{-1}\)). 2D DOSY NMR analysis of model 2b (Figure S17i, highlighted in red) doped with 1b (green) showed a major difference in predicted molecular weights of 1b and 2b. Compound 2b was predicted to have a molecular weight of 384.2 g mol\(^{-1}\) (actual \(M_W\) of 416.4 g mol\(^{-1}\)). This result suggests the 8-membered ring is more likely to be present in solution than the 4-membered ring. Unfortunately, due to the instability of the compound, further analysis (e.g. X-ray crystallographic analysis) at this time is not possible.
Figure S17: Pseudo-2D DOSY NMR analysis of G-LBHK model (1b) (diffusion coefficient highlighted in green) and compound 2b (diffusion coefficient highlighted in red). * highlighted position on model 1b refers to the signal in the ¹H NMR spectrum used to acquire the diffusion coefficient of that molecule. Only one peak was selected on 1b due to overlap of other peaks.
Synthesis of β-O-4-LBHK advanced model compounds

Scheme S4: Synthesis of β-O-4-LBHK model compounds 3 and 4. Reaction conditions: (a) CSA, 1,2-ethanediol, toluene, reflux, 2h; (b) ethyl bromoacetate, K₂CO₃, acetone, reflux, 1h; (c) TBS-Cl, imidazole, DMAP, dry DCM, r.t. 16h; (d) LDA, dry THF, 3,4-dimethoxybenzaldehyde (for S13), 3,4,5-trimethoxybenzaldehyde (for S14), -78 °C, 2h; (e) NaBH₄, EtOH, MeOH, r.t., 16h; (f) DDQ, DCM, r.t. 16h; (g) I₂, acetone, r.t. 16h. R² = CO₂Et.
ethyl 2-{4-((2-((tert-butyldimethylsilyl)oxy)methyl)-1,3-dioxolan-2-yl)methyl}-2-methoxyphenoxy)acetate (S11)

To a stirred solution of S5 (0.356 g, 1.81 mmol) in toluene (20 mL) is added campher-10-sulfonic acid (0.021 g, 0.05 eqv.) and ethylene glycol (0.50 mL, 5.00 eqv.) and heated at reflux for 2 hours. Upon completion, mixture is cooled and quenched with H2O, washed with brine, dried over MgSO4 and concentrated in vacuo to give crude S7. To a solution of crude S7 (0.436 g, 1.81 mmol) in acetone (30 mL) is added K2CO3 (0.301 g, 1.20 eqv.) and ethyl bromoacetate (0.24 mL, 1.2 eqv.) and heated to reflux for 1 hour. Upon completion, mixture is filtered through celite and concentrated in vacuo to yield crude S9 as a yellow oil. To a solution of crude S9 (0.592 g, 1.81 mmol) in DCM (10 mL) is added imidazole (0.247 g, 2.00 eqv.), DMAP (0.011 g, 0.05 eqv.) and TBS-Cl (0.348 g, 1.30 eqv.) and stirred for 16 hours. Upon completion, reaction is quenched with NH4Cl (saturated solution), washed with H2O, brine, dried over MgSO4 and concentrated in vacuo. Crude S11 is purified by flash column chromatography (10-30% ethyl acetate in petroleum ether) to give pure S11 as a colourless oil (0.399 g, 50% over 3 steps).

IR (FTIR) νmax: 2954, 1761 1734, 1606, 1514, 1463 cm⁻¹; HRMS (NSI⁺) m/z [M + NH4⁺] calcd. for C22H40O7Si⁺ 458.2569, found 458.2558; ¹H NMR (700 MHz, Chloroform-d) δ = 6.89 (d, J=1.9, 1H), 6.78 (dd, J=8.3, 1.9, 1H), 6.73 (d, J=8.2, 1H), 4.65 (s, 2H), 4.25 (q, J=7.1, 2H), 3.88 – 3.84 (m, 5H), 3.65 – 3.61 (m, 2H), 2.89 (s, 2H), 1.28 (t, J=7.1, 3H), 0.91 (s, 9H), 0.07 (s, 6H). ¹³C NMR (176 MHz, CDCl₃) δ 169.29, 149.08, 145.99, 130.87, 122.92, 114.75, 113.88, 110.25, 66.83, 66.21, 65.60, 61.36, 56.02, 40.59, 26.08, 14.32, -5.19.
ethyl 2-((2-(((tert-butyldimethylsilyl)oxy)methyl)-1,3-dioxolan-2-yl)methyl)-2,6-dimethoxyphenoxy)acetate (S12)

To a stirred solution of S6 (0.235 g, 1.03 mmol) in toluene (20 mL) is added campher-10-sulfonic acid (0.014 g, 0.05 eqv.) and ethylene glycol (0.29 mL, 5.00 eqv.) heated at reflux for 2 hours. Upon completion, mixture is cooled and quenched with H₂O, washed with brine, dried over MgSO₄ and concentrated in vacuo. To a solution of crude S8 (0.201 g, 0.74 mmol) in acetone (20 mL) is added K₂CO₃ (0.123 g, 1.20 eqv) and ethyl bromoacetate (0.1 mL, 1.20 eqv.) and heated to reflux for 1 hour. Upon completion, mixture is filtered through celite and concentrated in vacuo to yield crude S10 as a yellow oil. To a solution of crude S10 (0.265 g, 0.74 mmol) in DCM (10 mL) is added imidazole (0.102 g, 2.00 eqv.), DMAP (0.005 g, 0.05 eqv.) and TBS-Cl (0.14 g, 1.25 eqv.) and stirred for 16 hours. Upon completion, reaction is quenched with NH₄Cl (saturated solution), washed with H₂O, brine, dried over MgSO₄ and concentrated in vacuo. Crude S12 is purified by column chromatography (10-30% ethyl acetate in petroleum ether) to give pure S12 as a colourless oil (0.206 g, 42% over 3 steps).

IR (FTIR)ν_max: 2950, 2354, 1975, 1759, 1593, 1506 cm⁻¹; HRMS (NSI+) m/z [M + H⁺] calcd. for C₂₃H₃₉O₈Si 471.2409, found 471.2397; ¹H NMR (500 MHz, CDCl₃) δ = 6.53 (s, 2H), 4.59 (s, 2H), 4.26 (q, J=7.1, 2H), 3.90 – 3.84 (m, 2H), 3.82 (s, 6H), 3.67 – 3.62 (m, 2H), 3.50 (s, 2H), 2.88 (s, 2H), 1.30 (t, J=7.1, 3H), 0.91 (s, 9H), 0.07 (s, 6H). ¹³C NMR (126 MHz, CDCl₃) δ 169.79, 152.19, 134.97, 132.53, 110.23, 107.91, 69.92, 66.24, 65.61, 61.02, 56.24, 41.27, 26.07, 18.52, 14.40, 1.16, -5.22.
ethyl 2-(4-((2-(((tert-butyldimethylsilyl)oxy)methyl)-1,3-dioxolan-2-yl)methyl)-2-methoxyphenoxy)-3-(3,4-dimethoxyphenyl)-3-hydroxypropanoate (S13)

General procedure from Reference 5. S11 (0.372 g, 0.84 mmol, 1.00 eqv.), 3,4-dimethoxybenzaldehyde (0.147 g, 0.88 mmol, 1.05 eqv.), THF (5 mL), LDA in THF (6 mL): n-BuLi (0.45 mL of 2.30 M, 1.20 eqv.); Diisopropylamine (0.15 mL, 1.30 eqv.). Reaction left at -78 °C for 2 hours. Product obtained as a viscous oil after column chromatography (10-40% ethyl acetate in petroleum ether) to give S13 (0.209 g, 41%) as a mixture of diastereoisomers (d.r. 2.57:1, measured by integration of peak at 5.13 ppm (dd) for major diastereoisomer and peak at 5.04 ppm (dd) for minor diasteroisomer).

IR (FTIR)ν max: 2968, 2358, 1749, 1739, 1683, 1261 cm⁻¹; HRMS (NSI+) m/z [M + NH₄⁺] calcd. for C₃₁H₅₀O₁₀Si⁺ 624.3198, found 624.3209; ¹H NMR (700 MHz, CDCl₃) δ = 7.05 (d, J=2.1, 0.72H, H₂ major), 6.97 (m, 1H, H₆ major/minor), 6.95 – 6.74 (m, 5H), 5.13 (dd, J=6.2, 4.8, 0.72H, Hα major), 5.04 (dd, J=7.4, 2.6, 0.28H, Hα minor), 4.71 (d, J=4.8, 0.72H, Hβ major), 4.43 (d, J=7.3, 0.28H, Hβ minor), 4.13 (q, J=7.1, 1.44H, OCH₂CH₃ major), 4.09 – 4.00 (m, 0.56H, OCH₂CH₃ minor), 3.88- 3.85 (m, 11H, 3 x OMe major/minor, 1 x O-CH₂CH₂-O major/minor), 3.66 – 3.62 (m, 0.56H, 1 x O-CH₂CH₂-O minor), 3.64 – 3.59 (m, 1.44H, 1 x O-CH₂CH₂-O major), 3.49 (s, 0.56H, Hγ' minor), 3.48 (s, 1.44H, Hγ' major), 2.89 (s, 0.56H, Hα' minor), 2.89 (s, 1.44H, Hα' major), 1.15 (t, J=7.1, 2.16H, OCH₂CH₃ major), 1.06 (t, J=7.1, 0.84H, OCH₂CH₃ minor), 0.91 (m, 9H, Si-(CH₃)₂(CH₂)₃m major/minor), 0.07 (m, 6H, Si-(CH₃)₂(CH₂)₃, major/minor). ¹³C NMR (176 MHz, CDCl₃) δ 169.62 (CO₂Et minor), 169.50 (CO₂Et major), 150.05, 149.82, 149.20, 149.05, 148.86, 148.81, 146.03, 145.94, 132.58, 132.55, 131.81, 130.64, 123.46, 123.36, 119.78, 119.40, 118.65, 117.94, 114.88, 114.86, 110.82, 110.79, 110.22, 110.20, 110.08, 86.05 (Cβ minor), 84.43 (Cβ major), 75.04 (Cα minor), 73.92 (Cα major), 66.15 (Cγ' major), 66.07
ethyl 2-(4-(((tert-butyldimethylsilyl)oxy)methyl)-1,3-dioxolan-2-yl)methyl)-2,6-dimethoxyphenoxy)-3-hydroxy-3-(3,4,5-trimethoxyphenyl)propanoate (S14)

General procedure from Reference 5. S12 (0.236 g, 0.50 mmol, 1.00 eqv.), 3,4,5-trimethoxybenzaldehyde (0.101 g, 0.52 mmol, 1.05 eqv.), THF (4 mL). LDA in THF (5 mL): n-BuLi (0.26 mL of 2.3 M, 1.20 eqv.); Diisopropylamine (0.09 mL, 1.30 eqv.). Reaction left at -78 °C for 2 hours. Product obtained as a viscous oil after column chromatography (20-40% ethyl acetate in petroleum ether) to give S13 (0.229 g, 69%) as a mixture of diastereoisomers (d.r. 4.1:1, measured by integration of peak at 4.67 ppm (d) for major diastereoisomer and peak at 4.01 ppm (d) for minor diastereoisomer).

IR (FTIR)νmax: 2975, 2358, 1975, 1749, 1734, 1506, 1458 cm⁻¹; HRMS (NSI+) m/z [M + NH₄⁺] calcd. for C₃₃H₅₀NO₁₂Si⁺ 684.3410, found 684.3410; ¹H NMR (700 MHz, CDCl₃) δ = 6.67 (s, 1.6H, H₂,6 major), 6.61 (s, 0.4H, H₂,6 minor), 6.58 (s, 1.6H, H₂,6' major), 6.56 (s, 0.4H, H₂,6 minor), 4.94 – 4.89 (m, 1H, Hα major/minor), 4.71 (d, J=7.9, 0.8H, α-OH major), 4.67 (d, J=3.9, 0.8H, Hβ major), 4.15 – 3.98 (m, 2H, OCH₂CH₃ major/minor), 4.01 (d, J=8.5, 0.2H, Hβ minor), 3.89 – 3.79 (m, 17H, 5 x OMe, 1 x O-CH₂CH₂O major/minor), 3.68 – 3.60 (m, 2H, 1 x O-CH₂CH₂O major/minor), 3.51 (m, 2H, Hγ' major/minor), 2.95 – 2.86 (m, 2H, Hα' major/minor), 1.07 (t, J=7.1, 2.4H, OCH₂CH₃ major), 1.04 (t, J=7.1, 0.6H, OCH₂CH₃ minor), 0.92 (s, 9H, Si-(CH₃)₂(CH₃)₃ major/minor), 0.08 (s, 6H, Si-(CH₃)₂(CH₃)₃ major/minor). ¹³C NMR (176 MHz, CDCl₃) δ 169.67 (CO₂Et minor), 168.90 (CO₂Et major), 153.52, 153.25, 153.07, 151.95,
151.68, 137.59, 136.73, 135.79, 134.80, 133.24, 110.19 (Cβ'), 107.90 (2C, S2',6' major), 107.69 (2C, S2',6' minor), 103.92 (C2,6 major), 103.89 (C2,6 minor), 89.88 (Cβ minor), 75.98 (Cα minor), 73.93 (Cγ minor), 66.25 (Cg', major/minor), 66.07 (Cg minor), 65.62 (2C, O-CH₂CH₂-O), 61.01 (p-OMe minor), 60.94 (p-OMe major), 60.87 (OCH₂CH₃ major), 60.69 (OCH₂CH₃ minor), 56.26, 56.23, 56.15, 41.34 (Cα major/minor).

To a stirred solution of S13 (0.196 g, 0.32 mmol, 1.00 eqv) in EtOH (5 mL) is added NaBH₄ (0.061 g, 5.00 eqv.) followed by the slow addition of MeOH (0.2 mL, 15.00 eqv.) and stirred for 16 hours. Upon completion, mixture is quenched with NH₄Cl (saturated solution), extracted with ethyl acetate (3 x), washed with water, brine, dried and concentrated in vacuo to give pure S15 (0.117 g, 64%), as a colourless oil, with no need for purification and as a mixture of diastereoisomers (d.r. 3:1 measured by integration of peak at 4.13 ppm (ddd) for major diastereoisomer and peak at 3.98 ppm (dt) for minor diastereoisomer).

IR (FTIR)νmax: 2985, 2900, 2358, 1558, 1516, 1456 cm⁻¹; HRMS (NSI+) m/z [M + NH₄⁺] calcd. for C₂₉H₄₈NO₉Si' 582.3098, found 582.3104; ¹H NMR (700 MHz, CDCl₃) δ = 7.03 – 6.82 (m, 6H), 4.99 – 4.96 (m, 1H, Hα major/minor), 4.13 (ddd, J=8.0, 5.1, 3.5, 0.75H, Hβ major), 3.98 (dt, J=7.9, 3.4, 0.25H, Hβ minor), 3.93 – 3.87 (m, 3H, O-CH₂CH₂-O, 1 x Hγ major), 3.89 – 3.86 (m, 10H, 3 x OMe, 1 x Hγ minor), 3.66 (m, 2H, O-CH₂CH₂-O), 3.62 (ddd, J=11.9, 7.9, 3.5, 0.75H, 1 x Hγ major), 3.51 – 3.49 (m, 2H, Hγ' major/minor), 3.45 (ddd, J=12.3, 8.6, 3.7, 0.25H, Hγ minor),
2.92 (m, 2H, Hα’ major/minor), 2.76 – 2.72 (m, 0.25H, γ-OH minor), 2.72 (dd, J=8.0, 5.3, 0.75H, γ-OH major), 0.92 (s, 9H, Si-(CH3)2(CH3)3, major/minor), 0.11 – 0.03 (m, 6H, Si-(CH3)2(CH3)3, major/minor). \(^{13}\)C NMR (176 MHz, CDCl3) δ 151.13, 150.79, 149.20, 149.15, 149.01, 148.55, 146.07, 145.33, 133.02, 132.42, 132.19, 124.09, 124.05, 120.70, 119.79, 118.42, 114.77, 111.11, 110.23 (Cβ’), 109.96, 109.18, 89.83 (Cβ minor), 87.75 (Cβ major), 74.05 (Cα minor), 72.70 (Cα major), 66.03 (Cγ’ major/minor), 65.58 (2C, O-CH2CH2-O), 61.08 (Cg minor), 60.80 (Cg major), 56.06 (OMe), 40.71 (Cα’ major), 40.68 (Cα’ minor), 26.07 (Si-(CH3)2(CH3)3, major/minor), -5.18 (Si-(CH3)2(CH3)3, major/minor).

2-(4-(((tert-butyldimethylsilyloxy)methyl)-1,3-dioxolan-2-yl)methyl)-2,6-dimethoxyphenoxy)-1-(3,4,5-trimethoxyphenyl)propane-1,3-diol (S16)

![Chemical structure of S16](image)

To a stirred solution of S14 (0.212 g, 0.32 mmol, 1.00 eqv) in EtOH (5 mL) is added NaBH₄ (0.060 g, 5.00 eqv.) followed by the slow addition of MeOH (0.19 mL, 15.00 eqv.) and stirred for 16 hours. Upon completion, mixture is quenched with NH₄Cl (saturated solution), extracted with ethyl acetate (3 x), washed with water, brine, dried and concentrated in vacuo to give pure S16 (0.139 g, 70%), as a colourless oil, with no need for purification and as a mixture of diastereoisomers (d.r. 5.6:1 measured by integration of peak at 5.00 ppm (t) for major diastereoisomer and peak at 5.02 ppm (d) for minor diastereoisomer).

IR (FTIR)νmax: 2968, 2885, 2355, 1558, 1521, 1456 cm⁻¹; HRMS (NSI+) m/z [M + NH₄⁺] calcd. for C₃₁H₅₂NO₁₁Si⁺ 642.3304, found 642.3299; \(^{1}H\) NMR (700 MHz, CDCl₃) δ = 6.70 (s, 0.3H, H₂,6 minor), 6.63 (s, 1.7H, H₂’,6’ major), 6.61 (s, 0.3H minor, H₂’,6’ minor), 6.57 (s, 1.7H, H₂,6 major), 5.02 (d, J=8.8, 0.15H, Hα minor), 5.00 (t, J=3.4, 0.85H, Hα major), 4.18 (d, J=3.1, 0.85H, α-OH major), 4.14 – 4.10 (m, 1H, Hβ major), 3.91 (m, 2H, O-CH₂CH₂-O major/minor), 3.89 (m,
1H, 1 x H\text{\gamma} major), 3.87 (s, 5.1H, 2 x OMe major), 3.87 (s, 0.9H 2 x OMe minor), 3.85 (s, 5.1H, 2 x OMe major), 3.83 (s, 0.45H, p-OMe minor), 3.82 (s, 2.55H, p-OMe major), 3.75 – 3.70 (m, 2H, O-CH\text{2}CH\text{2}-O major/minor), 3.70 – 3.67 (m, 0.3H, O-CH\text{2}CH\text{2}-O minor), 3.58 (dt, J=12.5, 3.4, 0.15H, 1 x H\text{\gamma} minor), 3.52 (s, 1.7H, H\text{\gamma}' major), 3.51 (s, 0.3H, H\text{\gamma}' minor), 3.46 (ddd, J=11.6, 8.4, 2.7, 1H, 1 x H\text{\gamma} major), 3.41 (dd, J=9.8, 3.8, 0.15H, γ'-OH minor), 3.34 (ddd, J=12.4, 9.8, 2.5, 0.15H, 1 x H\text{\gamma} minor), 3.18 (dd, J=8.5, 3.6, 1H, γ-OH major), 2.97 – 2.91 (m, 2H, Ha' major/minor), 0.93 (s, 9H, Si-(CH\text{3})\text{2}(CH\text{3})\text{3}, major/minor), 0.08 (s, 6H, Si-(CH\text{3})\text{2}(CH\text{3})\text{3}, major/minor).

13C NMR (176 MHz, CDCl\text{3}) δ 153.39 (2C, C\text{3}/C\text{5}), 153.32 (2C, C\text{3}/C\text{5}), 152.80 (C\text{4}), 152.44 (C\text{4}), 137.18, 135.13, 133.45, 133.39, 110.25 (C\text{b}'), 107.95 (C\text{2'}/C\text{6'} major), 107.85 (C\text{2'}/C\text{6'} minor), 104.34 (C\text{2}/C\text{6} minor), 102.80 (C\text{2}/C\text{6} major), 89.00 (C\text{β} minor), 87.15 (C\text{β} major), 74.55 (C\text{α} minor), 72.78 (C\text{α} major), 66.03 (C\text{γ}’ minor), 65.89 (C\text{γ}’ major), 65.60 (O-CH\text{2}CH\text{2}-O major/minor), 61.01 (p-OMe major), 60.98 (p-OMe minor), 60.76 (C\text{γ} major), 60.67 (C\text{γ} minor), 56.29 (o-OMe major/minor), 41.33 (C\text{α}’ major), 41.28 (C\text{α}’ minor), 26.07 (Si-(CH\text{3})\text{2}(CH\text{3})\text{3}, major/minor), -5.16 (Si-(CH\text{3})\text{2}(CH\text{3})\text{3}, major/minor).

2-(4-((2-(((tert-butyldimethylsilyl)oxy)methyl)-1,3-dioxolan-2-yl)methyl)-2-methoxyphenoxy)-1-(3,4-dimethoxyphenyl)-3-hydroxypropan-1-one (S17)

To a stirred solution of S15 (0.102 g, 0.18 mmol, 1.00 equiv.) in DCM (5 mL) is added DDQ (0.049 g, 1.20 equiv.) and stirred for 16 hours. Upon completion, mixture is quenched with NaHCO\text{3} (saturated solution), extracted with DCM (3x), washed with NaHCO\text{3} (sat. solution), brine, dried over Na\text{2}SO\text{4}, concentrated in vacuo to give S17 (0.101 g, 100%) as a colourless oil.

IR (FTIR) ν\text{max}: 2972, 2357, 1683, 1558, 1508, 1456 cm\text{−1}; HRMS (NSI+) m/z [M + H\text{+}] calcd. for C\text{29}H\text{43}O\text{9}Si\text{+} 563.2676, found 563.2674; \text{1}H NMR (700 MHz, Chloroform-d) δ = 7.74 (dd, J=8.5,
2.0, 1H, H6), 7.60 (d, J=2.0, 1H, H2), 6.90 – 6.87 (m, 2H, H2′,H5), 6.79 (d, J=8.2, 1H, H5′), 6.74 (dd, J=8.2, 1.9, 1H, H6′), 5.38 (t, J=5.2, 1H, Hβ), 4.06 (d, J=5.2, 2H, Hγ), 3.95 (s, 3H, OMe), 3.92 (s, 3H OMe), 3.86 – 3.83 (m, 5H, 1 x OMe, 1 x O-CH2CH2O), 3.64 – 3.58 (m, 2H, 1 x O-CH2CH2-O), 3.48 (s, 2H, Hγ′), 2.88 (s, 2H, Hα′), 0.91 (s, 9H, Si-(CH3)2(CH3)3), 0.96 (s, 6H, Si-(CH3)2(CH3)3).

13C NMR (176 MHz, CDCl3) δ 195.24 (Cα), 154.04, 149.95, 149.31, 145.51, 132.28, 128.17, 123.80, 123.48, 118.11, 114.91, 111.04, 110.18, 84.74 (Cγ), 66.12 (Cγ′), 65.57 (O-CH2CH2-O), 63.78, (Cγ), 56.62 (OMe), 56.14 (OMe), 55.97 (OMe), 40.63 (Cβ), 26.06 (Si-(CH3)2(CH3)3), 5.19 (Si-(CH3)2(CH3)3).

IR (FTIR) νmax: 2987, 2900, 2358, 1687, 1558, 1506, 1456 cm⁻¹; HRMS (NSI+) m/z [M + H⁺] calcd. for C31H47O11Si+ 623.2888, found 623.3893; 1H NMR (700 MHz, CDCl3) δ = 7.38 (s, 2H, H2, 6), 6.56 (s, 2H, H2′,6′), 5.08 (dd, J=7.2, 3.1, 1H, Hβ)), 4.00 (dd, J=12.3, 7.3, 1H, Hγ), 3.92 (s, 3H, OMe), 3.90 (s, 6H, 2 x OMe), 3.87 (m, 2H, O-CH2CH2-O), 3.85 – 3.80 (m, 1H, Hγ), 3.73 (s, 6H, 2 x OMe), 3.70 – 3.61 (m, 2H, O-CH2CH2-O), 3.50 (s, 2H, Hγ′), 2.94 – 2.85 (m, 2H, Hα′), 0.92 (s, 9H, Si-(CH3)2(CH3)3), 0.07 (s, 6H, Si-(CH3)2(CH3)3). 13C NMR (176 MHz, CDCl3) δ 195.68 (Cα), 153.12, 152.00, 142.82, 134.84, 133.20, 130.92, 110.19, 107.88, 106.54, 87.41 (Cα), 66.10

To a stirred solution of S16 (0.131 g, 0.21 mmol, 1.00 equiv.) in DCM (5 mL) is added DDQ (0.050 g, 1.05 equiv.) and stirred for 16 hours. Upon completion, mixture is quenched with NaHCO₃ (saturated solution), extracted with DCM (3x), washed with NaHCO₃ (sat. solution), brine, dried over Na₂SO₄, concentrated in vacuo to give S17 (0.110 g, 84%) as a colourless oil.

IR (FTIR) νmax: 2987, 2900, 2358, 1687, 1558, 1506, 1456 cm⁻¹; HRMS (NSI+) m/z [M + H⁺] calcd. for C31H47O11Si+ 623.2888, found 623.3893; 1H NMR (700 MHz, CDCl3) δ = 7.38 (s, 2H, H2, 6), 6.56 (s, 2H, H2′,6′), 5.08 (dd, J=7.2, 3.1, 1H, Hβ)), 4.00 (dd, J=12.3, 7.3, 1H, Hγ), 3.92 (s, 3H, OMe), 3.90 (s, 6H, 2 x OMe), 3.87 (m, 2H, O-CH2CH2-O), 3.85 – 3.80 (m, 1H, Hγ), 3.73 (s, 6H, 2 x OMe), 3.70 – 3.61 (m, 2H, O-CH2CH2-O), 3.50 (s, 2H, Hγ′), 2.94 – 2.85 (m, 2H, Hα′), 0.92 (s, 9H, Si-(CH3)2(CH3)3), 0.07 (s, 6H, Si-(CH3)2(CH3)3). 13C NMR (176 MHz, CDCl3) δ 195.68 (Cα), 153.12, 152.00, 142.82, 134.84, 133.20, 130.92, 110.19, 107.88, 106.54, 87.41 (Cα), 66.10
(Cγ'), 65.59 (O-CH₂CH₂-O), 63.44 (Cγ), 61.10 (p-OMe), 56.47 (2C, 2 x OMe), 56.11 (2C, 2 x OMe), 41.28 (Cα'), 26.06 (Si-(CH₃)₂(CH₃)₃, -5.18 (Si-(CH₃)₂(CH₃)₃).

1-(3,4-dimethoxyphenyl)-3-hydroxy-2-(4-(3-hydroxy-2-oxopropyl)-2-methoxyphenoxy)propan-1-one (3)

To a stirred solution of S17 (0.101 g, 0.18 mmol) in acetone (5 mL) is added I₂ (0.009 g, 0.20 eqv.) and stirred for 16 hours. Upon completion, mixture is quenched with Na₂S₂O₃ (sat. solution), extracted with ethyl acetate (3x), washed with Na₂S₂O₃ (sat. solution), brine, dried over Na₂SO₄ and concentrated _in vacuo_. Product obtained as a viscous oil after column chromatography (0-5% MeOH in DCM) to give 2 (0.068 g, 94%).

**IR (FTIR)_ν_{max}:** 2985, 2900, 1734, 1716, 1683, 1593, 1508 cm⁻¹; **HRMS (NSI+) m/z [M+H⁺] calcd. for C₂₁H₂₅O₈⁺ 405.1549, found 405.1550;**

**¹H NMR (700 MHz, CDCl₃) δ = 7.73 (dd, J=8.4, 2.0, 1H, H6), 7.60 (d, J=2.0, 1H, H2), 6.89 (d, J=8.4, 1H, H5), 6.84 (d, J=8.1, 1H, H5'), 6.75 (d, J=2.0, 1H, H2'), 6.66 (dd, J=8.1, 2.0, 1H, H6'), 5.40 (dd, J=6.0, 4.6, 1H, Hβ'), 4.28 (d, J=4.7, 2H, Hγ'), 4.07 (dd, J=7.5, 4.5, 2H, Hγ), 3.95 (s, 3H, OMe), 3.92 (s, 3H, OMe), 3.85 (s, 3H, OMe), 3.65 (s, 2H, Hα'), 2.97 (t, J=4.8, 1H, γ'-OH), 2.90 (dd, J=7.5, 5.8, 1H, γ'-OH). **¹³C NMR (176 MHz, CDCl₃) δ 207.35 (Cβ'), 194.83 (Cα), 154.15, 150.78, 149.39, 146.48, 128.10, 128.04, 123.74, 121.98, 118.69, 113.28, 110.98, 110.23, 84.51 (Cβ'), 67.74 (Cγ'), 63.89 (Cγ), 56.30 (OMe), 56.15 (OMe), 56.03 (OMe), 45.47 (Cα').

**¹H NMR (700 MHz, DMSO-d₆) δ = 7.80 (dd, J=8.5, 2.0, 1H, H6), 7.52 (d, J=2.0, 1H, H2), 7.08 (d, J=8.5, 1H, H5), 6.80 (d, J=1.9, 1H, H2'), 6.67 (d, J=8.2, 1H, H5'), 6.58 (dd, J=8.2, 1.9, 1H, H6'), 5.60 (t, J=5.0, 1H, Hβ), 5.18 (t, J=5.8, 1H, γ'-OH), 5.12 (t, J=5.9, 1H, γ'-OH), 4.12 (d, J=5.8, 2H, Hγ'), 3.87 (t, J=6.0, 2H, Hγ), 3.85 (s, 3H, OMe), 3.79 (s, 3H, OMe), 3.72 (s, 3H, OMe), 3.61 (s,
2H, Hα'). $^{13}$C NMR (176 MHz, DMSO-d$_6$) δ 208.44 (Ωβ’), 195.21 (Ωα), 153.46, 148.85, 148.57, 145.63, 127.90, 127.81, 123.33 (Ω6), 121.49 (Ω6’), 114.30 (Ω5’), 114.05 (Ω2’), 110.93 (Ω5), 110.68 (Ω2), 81.35 (Ωb), 67.19 (Ωg’), 62.54 (Ωg), 55.80 (OMe), 55.52 (OMe), 55.45 (OMe), 44.02 (Ωa’).

3-hydroxy-2-(4-(3-hydroxy-2-oxopropyl)-2,6-dimethoxyphenoxy)-1-(3,4,5-trimethoxyphenyl)propan-1-one (4)

To a stirred solution of S18 (0.101 g, 0.16 mmol) in acetone (5 mL) is added I$_2$ (0.008 g, 0.20 eqv.) and stirred for 16 hours. Upon completion, mixture is quenched with Na$_2$S$_2$O$_3$ (sat. solution), extracted with ethyl acetate (3x), washed with Na$_2$S$_2$O$_3$ (sat. solution), brine, dried over Na$_2$SO$_4$ and concentrated in vacuo. Product obtained as a viscous oil after column chromatography (0-5% MeOH in DCM) to give 3 (0.037 g, 49%).

IR (FTIR)$\nu_{max}$: 2965, 2904, 1737, 1720, 1683, 1583, 1504 cm$^{-1}$; HRMS (NSI+) $m/z$ [M + H$^+$] calcd. for C$_{23}$H$_{29}$O$_{10}$ $^+$ 465.1761, found 465.1762; $^1$H NMR (700 MHz, CDCl$_3$) δ = 7.35 (s, 2H, H$_2$,6), 6.43 (s, 2H, H$_2'$,6’), 5.08 (dd, J=7.4, 2.7, 1H, Hβ), 4.32 (d, J=4.8, 2H, Hγ'), 3.99 (ddd, J=10.3, 7.5, 3.1, 1H, 1 x Hγ), 3.93 (s, 3H, OMe), 3.90 (s, 6H, 2 x OMe), 3.86 – 3.80 (m, 1H, 1 x Hγ), 3.74 (s, 6H, 2 x OMe), 3.67 (s, 2H, Hα’), 2.98 (t, J=4.8, 1H, γ’-OH). $^{13}$C NMR (176 MHz, CDCl$_3$) δ 207.02 (Ωβ’), 195.27 (Ωα), 153.16 (2C, Ω3, Ω5), 152.85 (2C, Ω3’,Ω5’), 142.92 (Ω4), 135.78 (Ω4’), 130.73 (Ω1), 129.20 (Ω1’), 106.45 (4C, Ω2, Ω6 & Ω2’, Ω6’), 87.44 (Ωβ), 67.82 (Ωγ’), 63.52 (Ωγ), 61.11 (OMe), 56.48 (2C, OMe), 56.22 (2C, OMe), 45.98 (Ωα’).

$^1$H NMR (700 MHz, DMSO-d$_6$) δ = 7.31 (s, 2H, H$_2$, 6), 6.51 (s, 2H, H$_2'$, 6’), 5.23 (dd, J=6.6, 5.2, 1H, Hβ), 5.15 (s, 1H, OH), 4.72 (s, 1H, OH), 4.16 (s, 2H, Hγ’), 3.78 (m, 11H, 2 x Hγ, 3 x OMe), 3.66 (s, 2H, Hα’), 3.62 (s, 6H, 2 x OMe). $^{13}$C NMR (176 MHz, DMSO-d$_6$) δ 208.20 (Ωβ’), 195.75
(ςα), 152.58, 151.99, 141.81, 134.44, 131.21, 130.26, 106.90 (ς2',6'), 106.17 (ς2, 6), 83.36 (ςβ'), 67.26 (ςγ'), 62.07 (ςγ), 60.18 (OМe), 56.02 (2 x OМe), 55.83 (2 x OМe), 44.71 (ςα').
Comparison of Ligninα-OX Preparation Procedures (Manuscript Table 1)

**Figure S18**: 2D HSQC NMR analysis (700 MHz, d_6-DMSO) of beech ligninα-OX from reactions of beech dioxasolv lignin (A-F) using different oxidation conditions (see Manuscript Table 1). For assignment of peaks see Figure S6.

**Table S6**: Ratio values for units A, A', A" (normalised to 1 for A), and C, D, E (normalised to 1 for C). Values calculated from using semi-quantitative 2D HSQC NMR on data observed in Figure S18.

| Method                        | A   | A'  | A"  | C   | D   | E   |
|-------------------------------|-----|-----|-----|-----|-----|-----|
| **DDQ Stoichiometric, r.t**   |     |     |     |     |     |     |
| 14 hours                      | S   | 1.05| 1.66|     |     |     |
|                               | G   | 1   | 0.3 | 0.53|     |     |
| Total                         |     |     |     | 1.35| 2.19|     |
| **DDQ Stoichiometric 80 °C**  |     |     |     |     |     |     |
| 2 hours                       | S   | 1.33| 4.17|     |     |     |
|                               | G   | 1   | 0.44| 1.29|     |     |
| Total                         |     |     |     | 1.77| 5.46|     |
| **Cat. DDQ 80 °C**            |     |     |     |     |     |     |
| 14 hours                      | S   | 0.36| 0.84|     |     |     |
|                               | G   | 1   | 0.27| 0.38|     |     |
| Total                         |     |     |     | 0.63| 1.22|     |
| **TEMPO-MsOH 70 °C**          |     |     |     |     |     |     |
| 3 hours                       | S   | 1.02| 1.29|     | 1.0 | 0.0 |
|                               | G   | 1   | 0.23| 0.26|     |     |
| Total                         |     |     |     | 0.63| 1.22| 1.0 |
|                | Total |       |       |
|----------------|-------|-------|-------|
| Bobbitt’s Salt. 70 °C |       |       |       |
| 3 hours        |       |       |       |
| S              | 0.83  | 1.53  |       |
| G              | 0.36  | 0.59  | 1.0   |
| Total          | 1.19  | 2.12  | 0.1   |
| B.S. r.t       |       |       |       |
| S              | 1.11  | 1.92  |       |
| G              | 0.27  | 0.51  | 1.0   |
| Total          | 1.38  | 2.43  | 0.1   |
Scope Study on other Hardwood Lignins (Manuscript Figure 7)

Oak, Maple, Hickory, Cherry and Birch lignins were all extracted using a dioxasolv procedure (General procedures). For 2D HSQC NMR spectra and data from Beech oxidation, See Figure S6 and Table S3.

**Figure S19:** 2D HSQC NMR analysis (700 MHz, d$_6$-DMSO) of Oak Lignin and Oak Lignin $^\alpha$-OX, Maple Lignin and Maple Lignin $^\alpha$-OX
**Figure S20:** 2D HSQC NMR analysis (700 MHz, $d_6$-DMSO) of Hickory Lignin and Hickory Lignin $\alpha$-OX, Cherry Lignin and Cherry Lignin $\alpha$-OX.

**Figure S21:** 2D HSQC NMR analysis (700 MHz, $d_6$-DMSO) of Birch Lignin and Birch Lignin $\alpha$-OX.
Table S7: Integral data from 2D HSQC NMR analysis of hardwood lignin DDQ oxidations (scope study on different lignins with varying weight equivalents of DDQ). In the first grouping of values ($S_{2,6}$, $S_{2,6}^{OX}$, $G_2$ (integral set arbitrarily to 100 units), $G_2^{OX}$), a value is obtained for the total aromatic integral obtained from 2D HSQC NMR analysis using the integral regions described below Figure S5. The second grouping ($\beta$-$O$-$4$ native, $\beta$-$O$-$4^{OX}$ A(S)$'$, $\beta$-$O$-$4^{OX}$ A(S)$''$, $\beta$-$\beta$ resinol native, $\beta$-$\beta$ derived alcohol, $\beta$-$\beta$ derived aldehyde, LBHK, $\beta$-$O$-$4^{OX}$ A(G)$'$ and $\beta$-$O$-$4^{OX}$ A(G)$''$) is reported as raw integrals and a per 100 C9 value obtained from using Equation 1 as is the norm.

|          | Beech |          |          |          | Oak      |          |          |          | Maple    |          |          |          |          |
|----------|-------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|          |       | Native   | 0.66     | 1.33     | 3        | Native   | 0.66     | 1.33     | 3        | Native   | 0.66     | 1.33     | 3        |
|         |       |          |          |          |          |          |          |          |          |          |          |          |          |
| $S_{2,6}$ | 362.8 | 310.9    | 263.5    | 246.6    | 335.4    | 286.13   | 178.33   | 107.49   | 301.9    | 258.9    | 206.1    | 198.1    |
| $S_{2,6}^{OX}$ | 22.0   | 294.3    | 299.8    | 534.9    | 33.4     | 254.0    | 343.7    | 266.1    | 24.3     | 189.6    | 321.3    | 414.9    |
| $G_2$    | 100.0 | 100.0    | 100.0    | 100.0    | 100.0    | 100.0    | 100.0    | 100.0    | 100.0    | 100.0    | 100.0    | 100.0    |
| $G_2^{OX}$ | 12.3   | 106.5    | 111.9    | 173.9    | 53.8     | 121.6    | 137.0    | 102.1    | 13.7     | 78.7     | 132.0    | 160.8    |
| Aromatics| 497.1 | 811.7    | 775.2    | 1055.4   | 522.5    | 761.6    | 759.0    | 575.7    | 439.9    | 627.2    | 759.4    | 873.8    |

|          |       |          |          |          |          |          |          |          |          |          |          |          |          |
|----------|-------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|          |       |          |          |          |          |          |          |          |          |          |          |          |          |
| $\beta$-$O$-$4$ native | | | | | | | | | | | | | |
| Raw integral | | | | | | | | | | | | | |
| per 100 C9 | 34.2 | 12       | 14.8     | 6.2      | 32.1     | 16.2     | 8.4      | 12.4     | 30.4     | 15.6     | 7.5      | 6.8      |
| $\beta$-$O$-$4^{OX}$ A(S)$'$ | | | | | | | | | | | | | |
| Raw integral | | | | | | | | | | | | | |
| per 100 C9 | 2.3   | 13.1     | 11.9     | 9.6      | 2.1      | 12.4     | 9.4      | 7.2      | 2.0      | 11.6     | 9.8      | 8.6      |
| $\beta$-$O$-$4^{OX}$ A(S)$''$ | | | | | | | | | | | | | |
| Raw integral | | | | | | | | | | | | | |
| per 100 C9 | 0.4   | 13.5     | 15.6     | 23.8     | 0.4      | 12.7     | 22.1     | 22.8     | 0.3      | 8.7      | 16.3     | 20.3     |
| $\beta$-$\beta$ native | | | | | | | | | | | | | |
| Raw integral | | | | | | | | | | | | | |
| per 100 C9 | 9.4   | 3.7      | 2.5      | 1.6      | 7.1      | 2.9      | 1.7      | 1.9      | 8.7      | 3.8      | 2.2      | 2.0      |
|                    | β-β derived alcohol |                  | β-β derived aldehyde |                  | LBHK |                  | β-O-4\textsuperscript{ox} A(G)' |                  | β-O-4\textsuperscript{ox} A(G)" |                  | β-5 |                  |
|--------------------|---------------------|------------------|----------------------|------------------|------|------------------|---------------------------------|------------------|---------------------------------|------------------|------|------------------|
| Raw integral       |                     |                  |                      |                  |      |                  |                                 |                  |                                 |                  |      |                  |
| per 100 C\textsubscript{9}|                    |                  |                      |                  |      |                  |                                 |                  |                                 |                  |      |                  |
| 0.0  | 14.4  | 14.7  | 2.5  | 0.0  | 10.9  | 14.6  | 10.1 | 2.3  | 4.5  | 16.7  | 24.1  | 0.0  | 5.2  | 18.6  | 37.0 | 0.9  | 22.0  | 19.1  | 15.1  | 3.1  | 17.0  | 21.5  | 22.4 | 3.5  | 1  | 6.7  | 0.9  | 3.8  | 2.3  | 1.3  | 0.8  | 4.0  | 2.1  | 1.6  | 0.9  |
| 0.4  | 0.6  | 2.2  | 4.2  | 0.0  | 0.8  | 2.4  | 4.2  | 8.4  | 6.7  | 9.2  | 5.9  | 9.4  | 9.1  | 6.9  | 4.7  | 9.5  | 8.8  | 6.5  | 5.1  |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 0.9  | 3.2  | 3.4  | 2.5  | 0.7  | 2.9  | 2.5  | 2.6  | 0.7  | 2.7  | 2.8  | 2.6  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 0.8  | 4.3  | 5  | 7.4  | 0.7  | 3.4  | 5.4  | 6.0  | 0.0  | 3.0  | 4.5  | 6.4  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 3.5  | 1  | 6.7  | 0.9  | 3.8  | 2.3  | 1.3  | 0.8  | 4.0  | 2.1  | 1.6  | 0.9  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |

| Hickory | Cherry | Birch |
|---------|--------|-------|
| Native  | 0.66  | 1.33  | 3   | Native  | 0.66  | 1.33  | 3   | Native  | 0.66  | 1.33  | 3.00 |
| S\textsubscript{2,6} | 178.7 | 201.1 | 140.5 | 136.8 | 318.0 | 314.2 | 218.4 | 225.6 | 522.3 | 460.0 | 328.8 | 287.5 |
| S\textsubscript{2,6} | 15.9  | 145.5 | 340.3 | 427.3 | 23.7  | 237.6 | 380.5 | 525.1 | 38.2  | 413.4 | 616.5 | 698.8 |
|                  | G₂ | G₂⁰x | Aromatics |
|------------------|----|------|-----------|
|                  | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
|                  | 16.8 | 121.9 | 209.1 | 254.3 | 15.2 | 100.2 | 134.9 | 190.2 | 12.8 | 109.2 | 143.8 | 154.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
|                  | 311.4 | 568.5 | 789.9 | 918.4 | 456.9 | 752.0 | 833.8 | 1040.9 | 673.3 | 1082.6 | 1189.1 | 1241.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

|                  | β-O-4⁻native | β-O-4₀x A(S)' | β-O-4₀x A(S)'' |
|------------------|--------------|---------------|----------------|
| Raw integral     |              |               |                |
| per 100 C9       | 137.7 | 119.6 | 70.6 | 76.4 | 176.7 | 138.6 | 61.5 | 77.4 | 239.5 | 166.7 | 76.4 | 67.8 |          |
|                  | 44.2 | 21.0 | 8.9 | 8.3 | 38.7 | 18.4 | 7.4 | 7.4 | 35.6 | 15.4 | 6.4 | 5.5 |          |
|                  | 6.9 | 84.9 | 79.4 | 74.6 | 11.0 | 105.9 | 93.4 | 105.9 | 13.3 | 145.6 | 128.7 | 120.1 |          |
| per 100 C9       | 2.2 | 14.9 | 10.0 | 8.1 | 2.4 | 14.1 | 11.2 | 10.2 | 2.0 | 13.4 | 10.8 | 9.7 |          |
|                  | 2.4 | 65.8 | 206.0 | 283.9 | 2.1 | 95.2 | 191.1 | 273.1 | 1.8 | 137.9 | 259.3 | 302.5 |          |
| per 100 C9       | 0.8 | 11.6 | 26.1 | 30.9 | 0.5 | 12.7 | 22.9 | 26.2 | 0.3 | 12.7 | 21.8 | 24.4 |          |

|                  | β-β native | β-β derived alcohol | β-β derived aldehyde |
|------------------|-----------|---------------------|----------------------|
| Raw integral     |           |                     |                      |
| per 100 C9       | 22.9 | 24.5 | 13.4 | 12.5 | 37.1 | 31.0 | 16.7 | 19.4 | 54.9 | 35.1 | 25.3 | 22.7 |          |
|                  | 7.4 | 4.3 | 1.7 | 1.4 | 8.1 | 4.1 | 2.0 | 1.9 | 8.1 | 3.2 | 2.1 | 1.8 |          |
|                  | 0.3 | 6.7 | 15.9 | 5.7 | 0.8 | 11.6 | 14.2 | 10.2 | 1.3 | 19.1 | 21.2 | 10.6 |          |
| per 100 C9       | 0.1 | 1.2 | 2.0 | 0.6 | 0.2 | 1.5 | 1.7 | 1.0 | 0.2 | 1.8 | 1.8 | 0.9 |          |
|                  | 0.5 | 1.6 | 18.8 | 39.9 | 0.0 | 5.2 | 21.1 | 38.2 | 0.6 | 6.2 | 29.7 | 48.9 |          |
| per 100 C9       | 0.1 | 0.3 | 2.4 | 4.3 | 0.0 | 0.7 | 2.5 | 3.7 | 0.1 | 0.6 | 2.5 | 3.9 |          |

|                  | LBHK |                     |                      |
|------------------|------|---------------------|----------------------|
| Raw integral     |       |                     |                      |
| per 100 C9       | 17.2 | 33.2 | 36.2 | 29.2 | 36.0 | 60.7 | 52.5 | 48.7 | 48.1 | 86.7 | 77.0 | 64.9 |          |
|                  | 5.5 | 5.8 | 4.6 | 3.2 | 7.9 | 8.1 | 6.3 | 4.7 | 7.1 | 8.0 | 6.5 | 5.2 |          |
|                  | \(\beta\)-O-4\(^{\text{OX}}\) A(G)' |     |     |     |     |     |     |     |     |     |
|------------------|---------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Raw integral     | 4.2                             | 18.1| 23.2| 23.2| 2.0 | 16.7| 21.3| 25.8| 3.7 | 27.9|
| per 100 C9       | 1.4                             | 3.2 | 2.9 | 2.5 | 0.4 | 2.2 | 2.6 | 2.5 | 0.6 | 2.6 |
|                  | \(\beta\)-O-4\(^{\text{OX}}\) A(G)'' |     |     |     |     |     |     |     |     |     |
| Raw integral     | 0.3                             | 19.7| 60.3| 83.7| 0.8 | 23.9| 47.9| 69.4| 2.3 | 35.6|
| per 100 C9       | 0.1                             | 3.5 | 7.6 | 9.1 | 0.2 | 3.2 | 5.7 | 6.7 | 0.3 | 3.3 |
|                  | \(\beta\)-5                      |     |     |     |     |     |     |     |     |     |
| Raw integral     | 16.3                            | 19.7| 13.0| 10.1| 17.2| 14.0| 12.8| 11.6| 16.2| 13.5|
| per 100 C9       | 5.2                             | 3.5 | 1.6 | 1.1 | 3.8 | 1.9 | 1.5 | 1.1 | 2.4 | 1.2 |
Reproducibility, scalability and depolymerisation of Lignin $^\alpha$-OX

**Figure S22:** Reproducibility of lignin oxidation. 2D HSQC NMR analysis (700 MHz, $d_6$-DMSO) of beech lignin $^\alpha$-OX generated from using 3 wt. eqv of DDQ oxidation. A) Repeat 1; B) Repeat 2 and; C) Repeat 3.

**Figure S23:** 2D HSQC NMR analysis (700 MHz, $d_6$-DMSO) of (A) Small scale oxidation (300 mg scale) and; (B) Large scale oxidation (20 g scale).
**Figure S24**: Recovery of DDQ-H$_2$ using celite packed fritted column. Celite is the bottom layer. DDQ-H$_2$ has deposited above the celite.

**Figure S25**: $^1$H NMR (CDCl$_3$) of the crude reaction mixture from the zinc reductive cleavage of beech lignin$^{n,OX}$. Highlighted are peaks corresponding to the keto-alcohol monomer as previously reported.$^5$
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13C NMR S12
Solvent: CDCl3
125.77 MHz
1H NMR S13
Solvent: CDCl3
700.13 MHz
1H NMR S14
Solvent: CDCl3
700.13 MHz

R (s) 6.67
C (s) 6.61
B (s) 6.58
D (s) 6.56
F (d) 4.71
H (m) 3.84
K (m) 3.64
E (m) 4.93
I (m) 4.01
J (m) 2.90
N (t) 1.04
M (t) 1.07
P (s) 0.08
G (d) 4.67
L (s) 3.51
O (s) 0.92
A (d) 4.01

12.5 12.0 11.5 11.0 10.5 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 -0.5 -1.
13C NMR S14
Solvent: CDCl3
176.07 MHz

S72
1H NMR S15
Solvent: CDCl3
700.13 MHz
1H NMR S16
Solvent: CDCl3
700.13 MHz
13C NMR S16
Solvent: CDCl3
176.07 MHz
1H NMR S17
Solvent: CDCl3
700.13 MHz
13C NMR S17
Solvent: CDCl3
176.07 MHz
1H NMR S18
Solvent: CDCI3
700.13 MHz

B (s) 7.38
C (s) 6.56
A (dd) 5.08
L (s) 3.92
J (h) 3.87
H (m) 3.83
E (s) 3.50
G (s) 3.73
I (dd) 4.00
K (s) 3.90
F (m) 3.66
D (m) 2.91
M (s) 0.92
N (s) 0.07
1H NMR 3
Solvent: CDCl3
700.13 MHz
13C NMR 176.07 MHz
Solvent: CDC3

- 194.83
- 154.15
- 149.39
- 146.48
- 128.14
- 123.74
- 116.69
- 110.98
- 110.23
- 84.51
67.74
63.89
56.03
45.47
1H NMR 3
Solvent: DMSO
700.13 MHz
2D me-HSQC NMR 3
Solvent: DMSO
700.13 MHz
1H NMR 4
Solvent: CDCl3
700.13 MHz

A (s) 7.35
B (s) 6.43
C (dd) 5.08
D (d) 4.32
E (ddd) 3.99
F (t) 2.98
G (s) 3.67
H (s) 3.74
I (s) 3.90
J (s) 3.93
K (m) 3.62
13C NMR
Solvent: CDCl₃
176.07 MHz

S87
1H NMR
Solvent: DMSO
700.13 MHz
2D me-HSQC NMR 4
Solvent: DMSO
700.13 MHz
