**Supplemental Information for "Study of the kinetics and equilibria of the oligomerization reactions of 2-methylglyceric acid"**

**A. W. Birdsall, C. A. Zentner, and M. J. Elrod**

Department of Chemistry and Biochemistry, Oberlin College, Oberlin, Ohio, USA

Correspondence to: M. J. Elrod (mjelrod@oberlin.edu)

## S1. Additional NMR Data

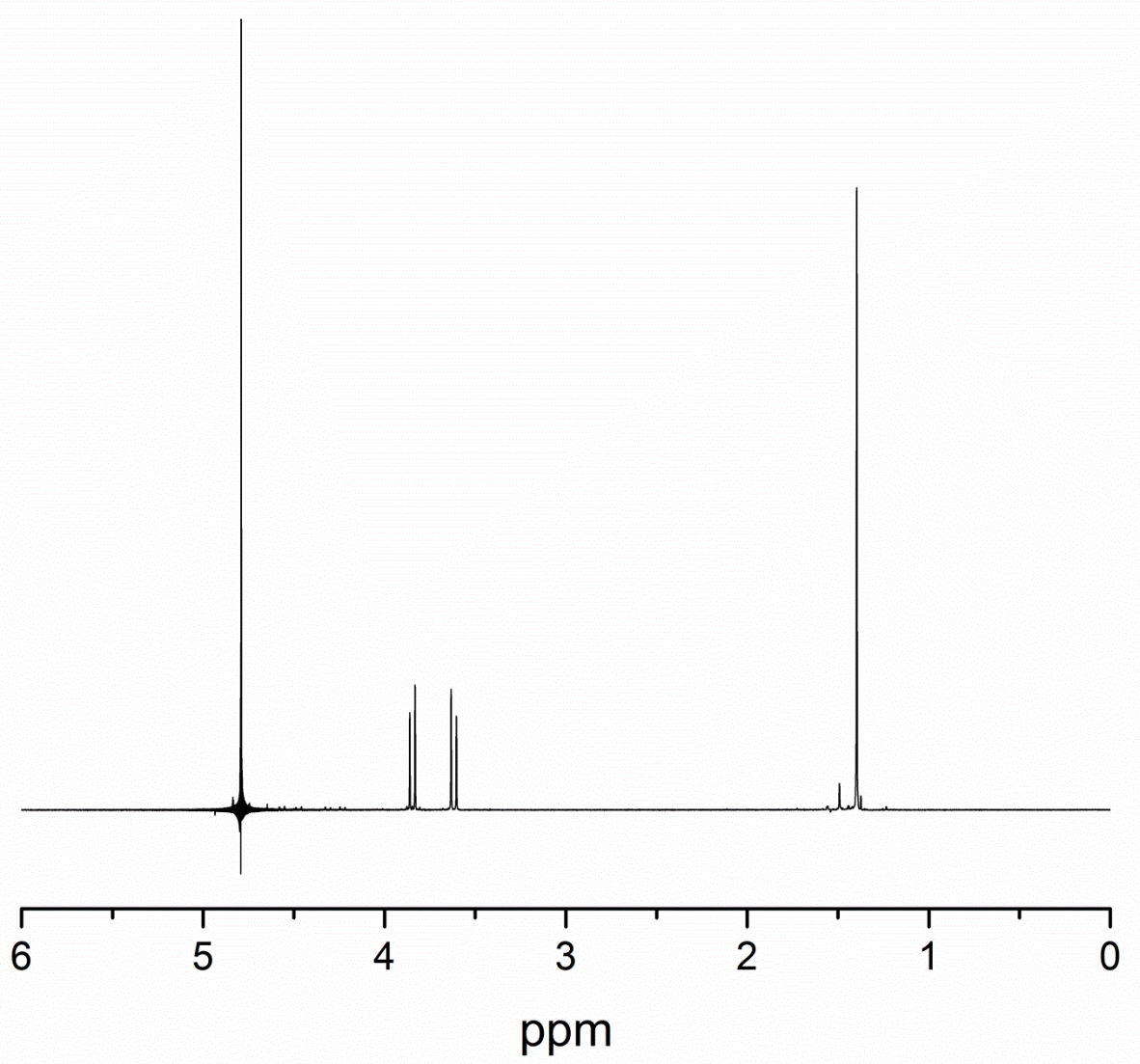


**Fig. S1.** $^{1}$H NMR spectrum of 2-methylglyceric acid (2-MG) in $D_2O$, calibrated to solvent HDO peak of 4.79 ppm.

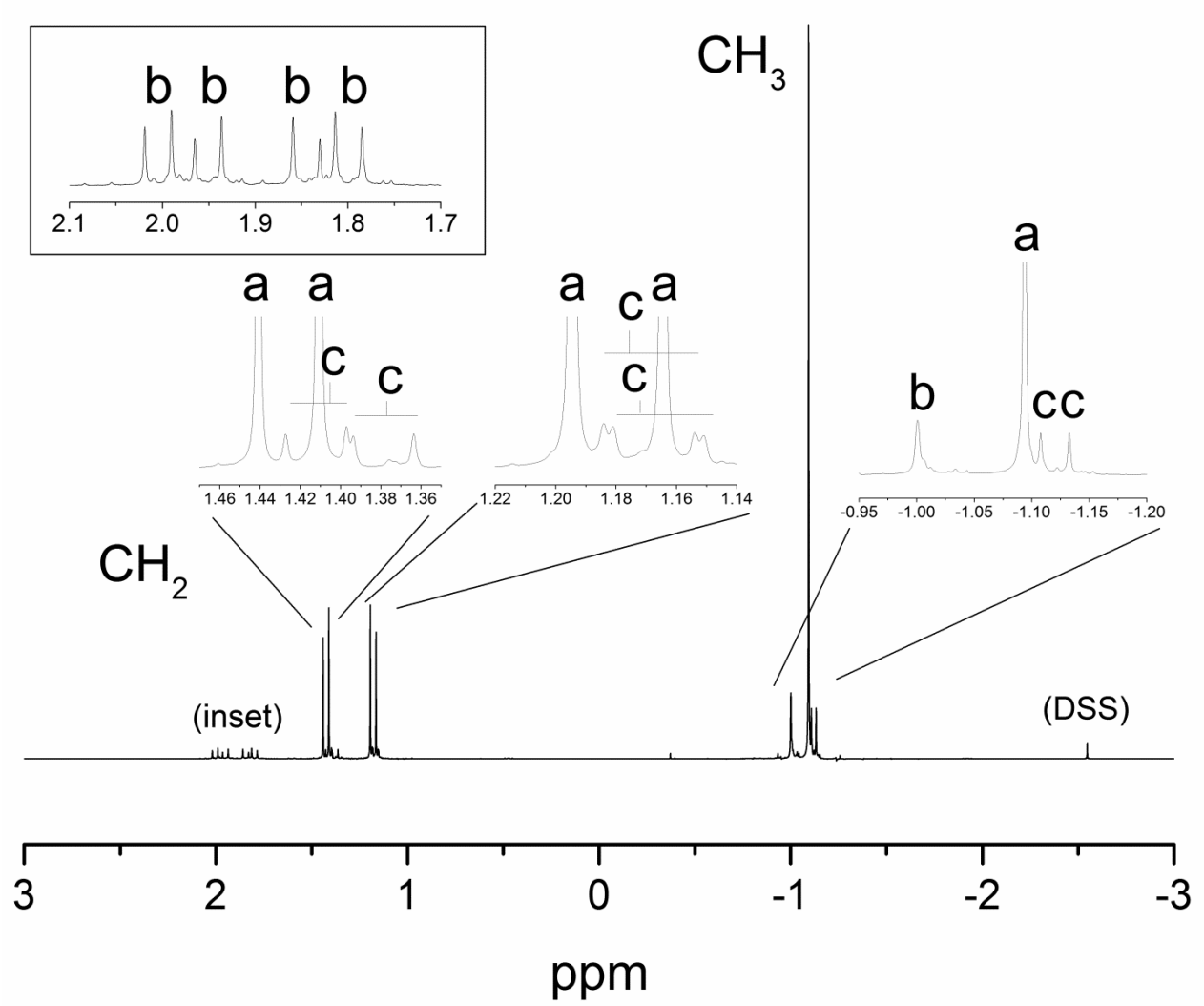


**Fig. S2.** $^{1}$H NMR spectrum of 2-MG and 2-MG diester (Solution 1), calibrated to solvent HDO peak of 4.79 ppm. 2-MG peaks are shifted upfield from Fig. S1 due to high acidity of solution. See Fig. 3 for key to labels. As discussed in Sect. S2.1, due to the presence both isotactic (DD/LL) and syndiotactic (DL/LD) diastereomers of the diester, two sets of peaks are observed for **b** and **c** units of the diester. It was not determined which of the **b** and **c** peaks in each region corresponded to which diastereomer.

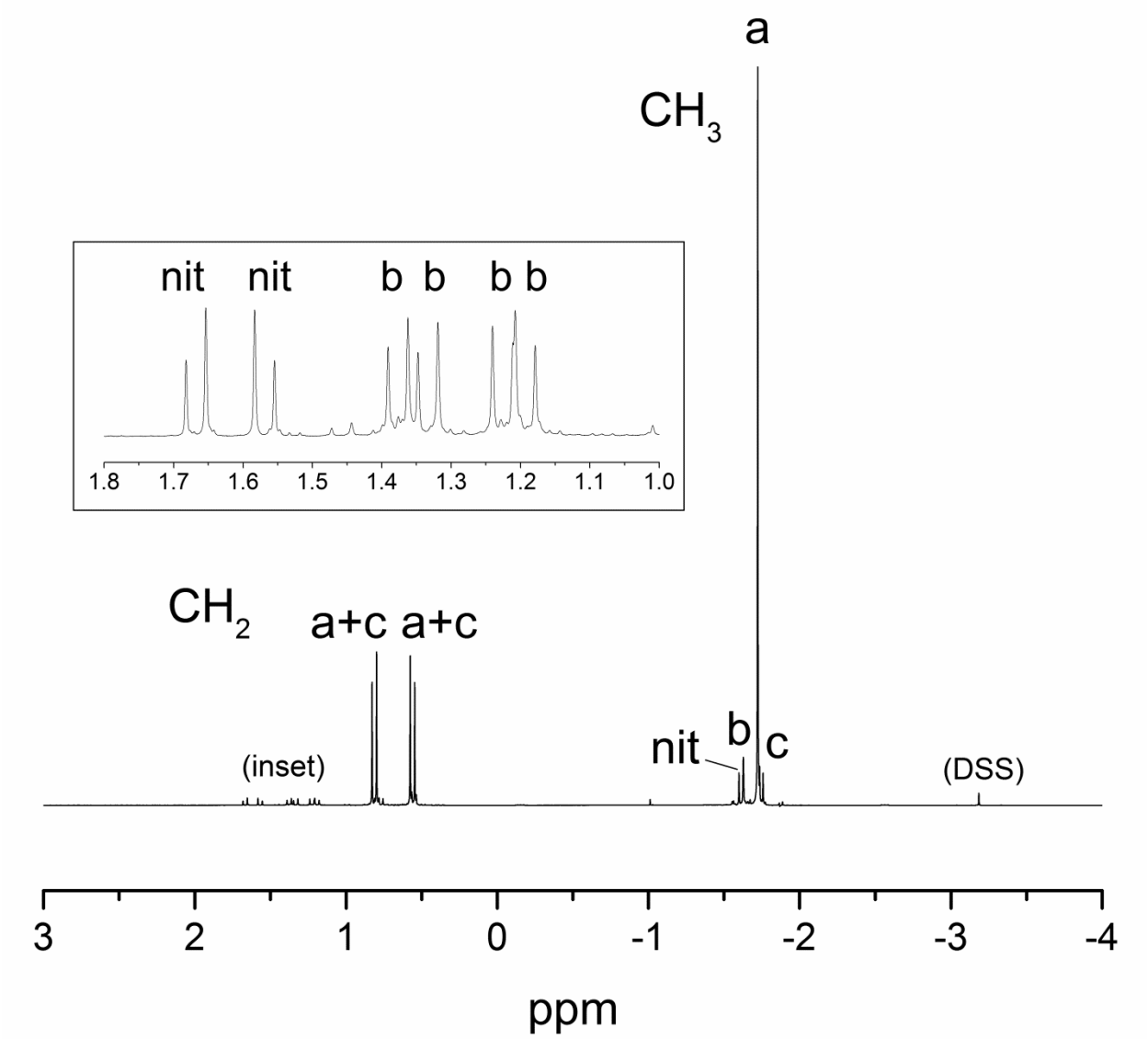


**Fig. S3.** $^{1}$H NMR spectrum of 2-MG, 2-MG diester and nitrate ester (Solution 14), calibrated to solvent HDO peak of 4.79 ppm. 2-MG peaks are shifted upfield from Fig. S1 due to high acidity of solution. See Fig. 3 for key to labels.

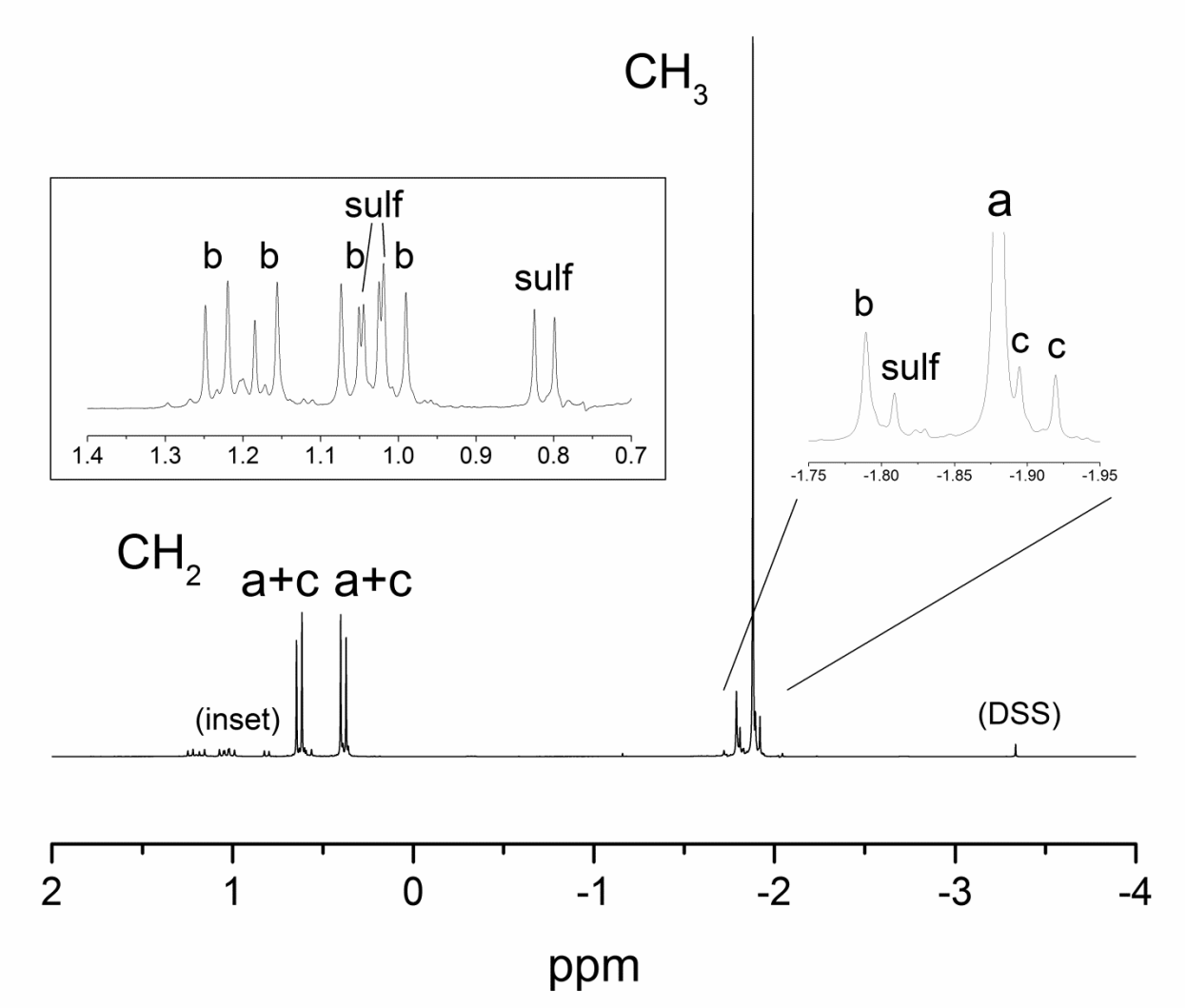


**Fig. S4.** $^{1}$H NMR spectrum of 2-MG, 2-MG diester and sulfate ester (Solution 12), calibrated to solvent HDO peak of 4.79 ppm. 2-MG peaks are shifted upfield from Fig. S1 due to high acidity of solution. See Fig. 3 for key to labels.

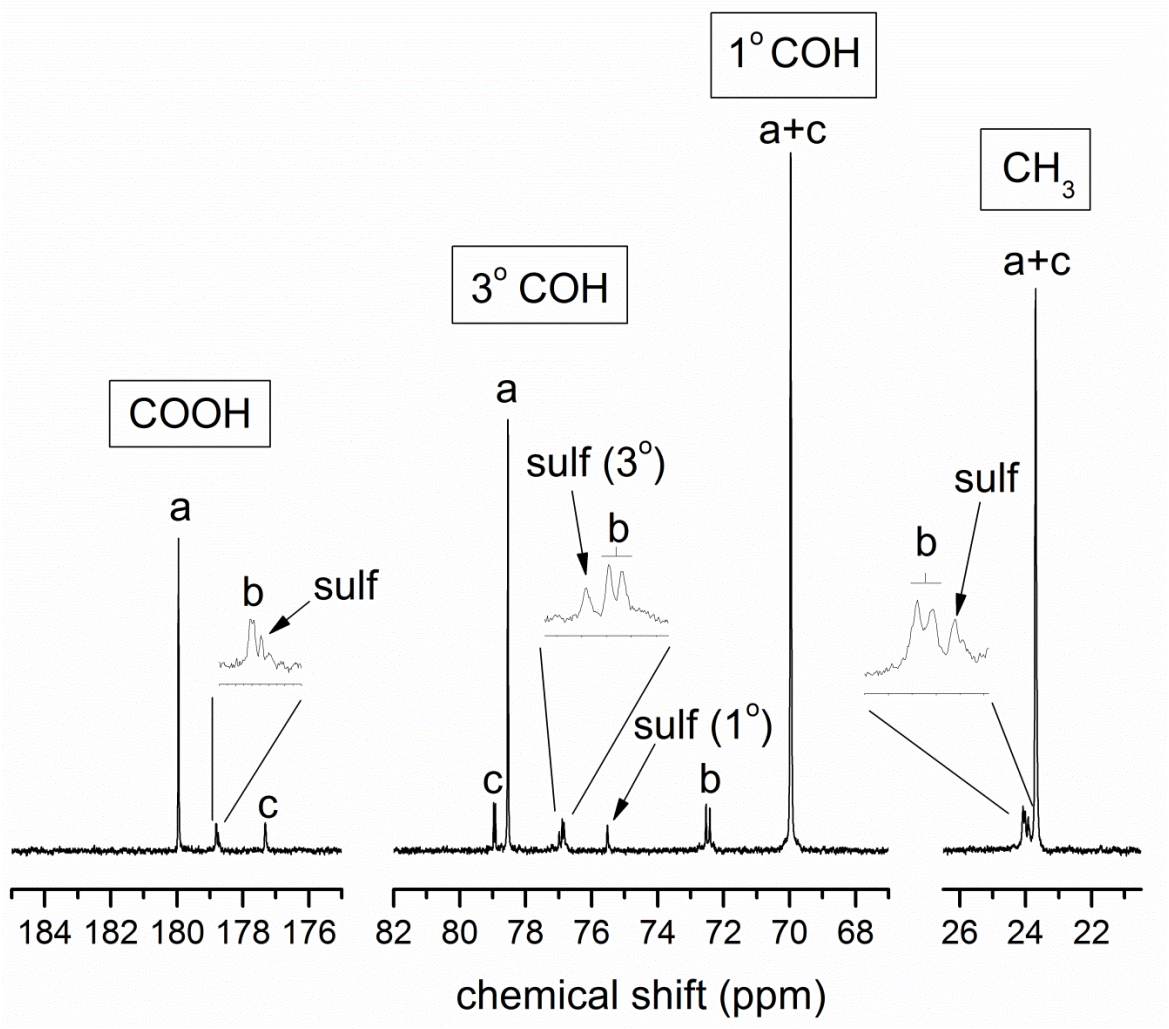


**Fig. S5.** $^{13}$C NMR spectrum of 2-MG, 2-MG diester and sulfate ester (Solution 12). See Fig. 3 for key to labels.

.

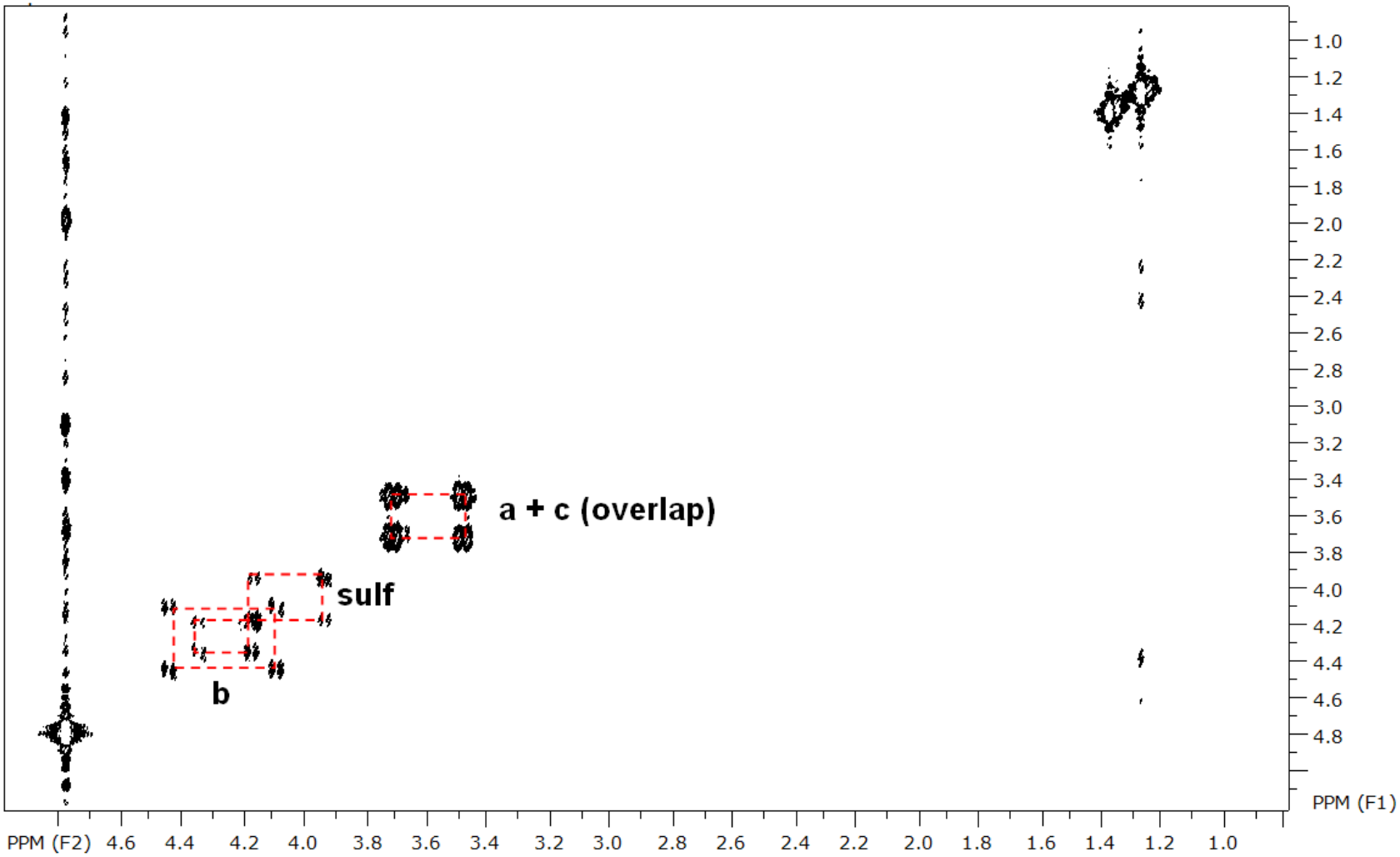


**Fig S6.** COSY spectrum of a dehydration experiment solution (Sect. 2.3) containing 2-MG, 2-MG diester and 2-MG sulfate ester, calibrated to solvent HDO peak of 4.79 ppm. Correlations are observed between non-equivalent geminal protons in the methylene region (3.4–4.4 ppm), aiding with assignments.

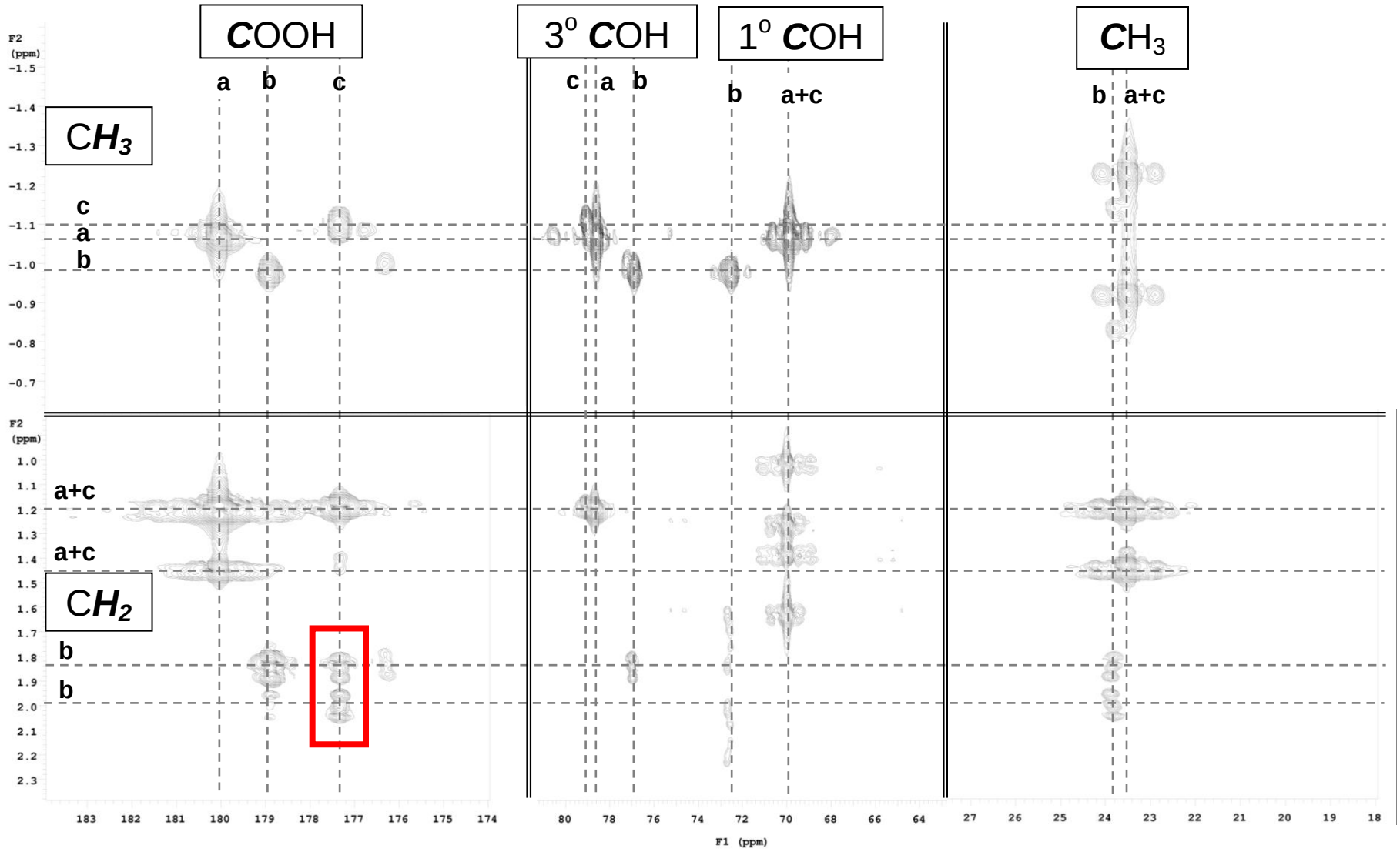


**Fig. S7.** HMBC spectrum of 2-MG and 2-MG diester (Solution 1), showing observed 2- and 3-bond C-H correlations. Dashed lines corresponding to $^{1}H$ and $^{13}C$ peaks are labeled using same nomenclature as Fig. 3 (key), Fig. 4 ($^{13}C$), and Fig. S2 ($^{1}H$). The 3-bond coupling between methylene protons of the **b** unit of the diester and the COOH carbon atom of the **c** unit, critical to the structural determination of the diester, is boxed.

## S2. Extended NMR Discussion (See Sect. 3.1)

### S2.1. 1D $^{1}H$ and $^{13}C$ spectra of 2-MG, diester, and triester

In the following discussion, the same naming convention is used as in the main text: units of 2-MG oligoester species are named as in Espartero et al. (1996) (Fig. 3), and each $^{1}H$ and $^{13}C$ spectrum is divided into several sections: methylene ($CH_2$) and methyl ($CH_3$) regions in $^{1}H$ spectra; carboxyl (COOH), tertiary alcohol ($3^{o}$ COH), primary alcohol ($1^{o}$ COH) and methyl ($CH_3$) regions in $^{13}C$ spectra.

Within each region of each spectrum, the chemical shift of each diester unit peak (**b** and **c**) is expected to be close to that of 2-MG (**a**) for carbon and hydrogen atoms several bonds away from the ester group, because for those atoms the chemical environment is predicted to be similar to that of the analogous 2-MG atom. Atoms closer to the ester group in the diester, alternatively, are expected to have chemical shifts less similar to analogous 2-MG atoms. This general expectation was found to hold true, and agreed with assignments confirmed by 2D NMR (below).

In the methyl region of the $^{1}H$ spectrum of Solution 1 (Fig. S2), the **b** unit was located further downfield than partially overlapping **a** and **c** peaks. Similarly in the methylene region of the $^{1}H$ spectrum, both **b** units were downfield from **a**, while **c** peaks were almost entirely overlapped with **a**. The $^{1}H$ chemical shift assignments for these species are given in Table S1.

In the $^{13}C$ spectrum (Fig. 4), both the methyl region and primary alcohol region showed **a**/**c** overlap while the **b** unit was observed further downfield. In the tertiary alcohol region, the **c** unit was slightly downfield of **a**, while the **b** unit was upfield. In the carboxyl region, the **c** unit was found to be further upfield from the **a** unit than the **b** unit. This assignment of the diester carboxyl carbon atoms is opposite to the one made by Espartero et al. for lactic acid, but is consistent both with our 2D HMBC analysis (below), and with the predicted shift pattern: the chemical environment of the **b** unit carboxyl carbon is expected to be more similar to the equivalent 2-MG carbon than the **c** unit carboxyl, which is part of an ester group. Furthermore, the chemical shift of the carboxyl carbon of an ester tends to be further upfield than its corresponding carboxylic acid (Silverstein et al., 2005).The $^{13}C$ chemical shift assignments for these species are given in Table 3.

When comparing spectra of mixed L,D-lactic acid to those containing a single stereoisomer, Espartero et al. observed additional diester peaks in both the $^{13}C$ and $^{1}H$ spectra, explained as arising from the presence of both isotactic (DD/LL) and syndiotactic (DL/LD) diastereomers of the diester. In their $^{1}H$ spectrum, two sets of peaks were observed for the **b** and **c** units in the C*H* region, and **c** unit in the C$H_3$ region. Only a single $CH_3$ peak for the **b** unit in lactic acid was observed. The same pattern was observed in our 2-MG spectra: two sets of signals were observed for **b** and **c** in the methylene region (i.e., two pairs of doublets, where each doublet corresponds to 1H), and for **c** in the methyl region. Further aligning our results with that of Espartero and colleagues, our 400-MHz instrument did not resolve our **b** peak in the methyl region into more than one peak.

The Espartero et al. study also observed multiple sets of peaks in the $^{13}C$ spectrum of L,D-lactic acid due to stereosensitivity between different diastereomers. Similarly, the resolution of our $^{13}C$

spectra allowed us often, but not always, to discern two sets of diester peaks. Espartero et al. were able to assign peaks in the $^{1}H$ spectrum and the carboxyl region of the $^{13}C$ spectrum to specific diastereomers by comparing the spectra of commercially available L- and L,D-lactic acid, but without a stereoisomerically pure sample of 2-MG, we are not able to make a detailed assignment at this time.

In $^{1}H$ spectra in which triester formation was suspected due to extensive diester formation, small features were observed, clustered in the same range as the **a**, **b** and **c** unit peaks in both the methyl and methylene regions. These small peaks overlapped to such an extent that no specific assignments were possible.

Tentative triester assignments were possible for peaks visible in $^{13}C$ spectra for solutions with considerable diester formation. The clearest separation of peaks was visible in the carboxyl region, in which the same pattern of peaks could be observed as was for lactic acid: of the three triester peaks, one each overlapped with the **b** and **c** units, and the third was located further upfield (see Table 2 for a partial assignment of the triester species).

## S2.2 2D spectral analysis of 2-MG diester and sulfate ester

Collection of 2D COSY and HMBC spectra was necessary to confirm peak assignments made above. H-H correlations from the COSY experiment provided correlations between pairs of peaks in the methylene region corresponding to geminal, non-equivalent $CH_2$ protons in 2-MG, the sulfate ester, and each unit of the diester (Fig. S6). The 2- and 3-bond C-H correlations from the HMBC experiment (Fig. S7) were consistent with the formation of a single 2-MG diester isomer which formed by reaction of the carboxyl group of one 2-MG unit with the primary hydroxyl group of another 2-MG unit ("primary diester"). Specifically, a correlation was observed between the methylene protons of the **b** unit of the diester and the ester carbon of the **c** unit, a 3-bond correlation that only could be observed in the primary diester. The alternative "tertiary diester" (i.e., the isomer in which the tertiary hydroxyl group of a 2-MG molecule reacts) has no characteristic 2- or 3-bond C-H correlation expected to be visible in our HMBC spectrum; however, the presence of this species seems unlikely because a full assignment of peaks in the $^{13}C$ and $^{1}H$ spectra was achieved.

## S3. Supplementary Tables

**Table S1.** $^{1}$H NMR assignments for 2-MG and derivatives, in $D_2O$, for $DClO_4$, $D_2SO_4$ and $DNO_3$ experiments. Chemical shifts are given relative to a solvent HDO shift of 4.79 ppm. See Tables 1,2, 6 and 8 for initial and equilibrium solution compositions. *Though a complete assignment of all **b** and **c** units to diastereomeric forms of the diester were not performed, COSY correlations allow for the **b** unit methylene peaks to be paired. Overlap with **a** prevented a similar analysis for the **c** unit.

| Sol'n # | a | | b | | c | | sulfate ester | | nitrate ester | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $CH_2$ | $CH_3$ | $CH_2$* | $CH_3$ | $CH_2$ | $CH_3$ | $CH_2$ | $CH_3$ | $CH_2$ | $CH_3$ |
| 1 | 1.19, 1.44 | -1.11 | 1.81 and 2.02; 1.86 and 1.96 | -1.02 | 1.17, 1.17, 1.38, 1.41 | -1.11, -1.14 | n/a | n/a | n/a | n/a |
| 12 | 0.39, 0.64 | -1.88 | 1.00 and 1.24; 1.06 and 1.17 | -1.79 | 0.38, 0.38, 0.58, 0.62 | -1.89, -1.92 | 0.81, 1.06 | -1.81 | n/a | n/a |
| 14 | 0.56, 0.82 | -1.72 | 1.19 and 1.38; 1.23 and 1.34 | -1.63 | 0.55, 0.55, 0.77, 0.80 | -1.74, -1.76 | n/a | n/a | 1.57, 1.67 | -1.60 |

**Table S2.** Comparison of AIOMFAC-calculated proton activities for perchloric acid controlled composition experiments at equilibrium ($a_{D+}$) to AIOMFAC-calculated proton activities of solutions containing an identical mole fraction of strong acid, but no organic component ($a_{D+}'$). Activities are given on a molality basis.

| Solution # | $a_{D+}$ | $a_{D+}'$ | $a_{D+} / a_{D+}'$ |
|---|---|---|---|
| 1 | 35.3 | 32.2 | 1.1 |
| 2 | 16.1 | 11.6 | 1.4 |
| 3 | 32.6 | 32.2 | 1.0 |
| 4 | 34.6 | 32.9 | 1.1 |
| 5 | 94.8 | 106 | 0.9 |
| 6 | 16.2 | 11.3 | 1.4 |
| 7 | 284 | 478 | 0.6 |

References:

Espartero, J. L., Rashkov, I., Li, S. M., Manolova, N., and Vert, M.: NMR analysis of low molecular weight poly(lactic acid)s, Macromolecules, 29, 3535-3539, 1996.

Silverstein, R. M., Webster, F. X., and Kiemle, D. J.: Spectrometric identification of organic compounds, 7th ed., John Wiley & Sons, Hoboken, NJ, 2005.