Synthesis of isohexide diyne polymers and hydrogenation to their saturated polyethers

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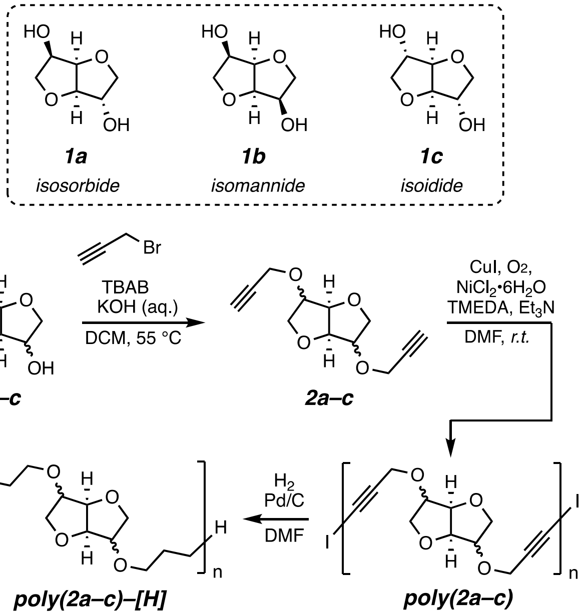
ABSTRACT: The incorporation of renewable feedstocks into polymer backbones is of great importance in modern polymer science. We report the synthesis of 1,3-diyne polymers derived from the *bis*-propargyl ethers of isosorbide, isomannide, and isoidide. The dialkyne monomers can be polymerized through an adaptation of the Glaser-Hay coupling using a nickel (II) cocatalyst. These well-defined diyne polymers bear an iodoalkyne end group, afforded through an unanticipated reductive elimination pathway, and display glass transition temperatures (T_g) from 55 to 64 °C. Fully saturated, analogous polyethers can be prepared from the hydrogenation of the diyne polymers, and these show T_g values between -10 and -2 °C. Both the 1,3-diyne polymers and the saturated analogs display similar trends in their T_g values vis-à-vis the stereochemical features of the isohexide unit within the backbone. This polymerization provided access to two series of isohexide-based polyethers, the thermal properties of which are influenced by the nature of the 2,4-hexadiynyl and hexamethylene linkers as well as the relative configuration of the bicyclic subunit in the backbone. The reported method represents an important step towards accessing well-defined polyethers from renewable feedstocks using readily available catalysts and convenient ambient conditions.

The renewable isohexides isosorbide **1a**, isomannide **1b**, and isoidide **1c** (Scheme 1) have shown promise as step-growth polymer ingredients.[1] These rigid, bicyclic diols are derived from the sequential hydrogenation and double dehydration of their corresponding sugar precursors, *D*-glucose, *D*-mannose, and *L*-idose, respectively. However, the isohexides can be challenging to use in condensation polymerizations due to the limited reactivity of their secondary alcohols,[2] exacerbated by internal hydrogen bonding of the *endo* hydroxyl group in **1a** and **1b**.[3] Step-growth polymers (notably, polyethylene terephthalate and nylon 6,6) are a pivotal class of materials and abound in the commercial marketplace.[4,5] This polymerization strategy capitalizes on the bidirectional chain growth afforded by joining bifunctional monomers in either a homo- or copolymerization. High extent of monomer conversion is essential to obtain high polymer molar mass, requiring efficient and selective coupling chemistry. To this end, considerable research efforts have been devoted to moving the reactive center away from the congested C3/C6 stereocenters of **1a–c** to improve their utility in step-growth polymerization, including advances in isohexide-containing polycarbonates,[6,7] polyesters,[8–10] polyurethanes,[11,12] polyacetals,[13] and poly(thioether)s.[14] In this vein, we hypothesized that the *bis*-propargyl ethers of the isohexides **2a–c** would be suitable substrates for polymerization by Glaser-Hay coupling to 1,3-diyne materials.

The oxidative homocoupling of alkynes to 1,3-diynes is well-studied,[15,16] with the initial report dating back to the late nineteenth century.[17] Hay was first to use this efficient, selective, and robust (highly air and water tolerant) chemistry for polymerization of a dialkyne monomer, *m*-diethynylbenzene, using various Cu(I)-amine complexes.[18] Thereafter, a number of studies have expanded the scope and utility of this polymerization.[19,20]

Scheme 1. Preparation, Glaser-Hay polymerization, and reduction of isohexide bis-propargyl ethers.



However, the marginal solubility properties imposed by limited chain flexibility often make arene-based diyne polymers challenging to manipulate.[21] To date, few recent investigations of non-aromatic Glaser-Hay-type polymerizations of bifunctional alkyne monomers have been reported.

Here, we report (Scheme 1) the synthesis by a modified Glaser-Hay polymerization of the isohexide *bis*-propargyl ethers, **2a**, **2b**, and **2c** to produce three novel 1,3-diyne containing polyethers **poly(2a)**, **poly(2b)**, and **poly(2c)**. These polymers can then be hydrogenated to the corresponding saturated polyethers **poly(2a)–[H]**, **poly(2b)–[H],** and **poly(2c)–[H]**. To our knowledge, this is the first report comparing the thermal properties of a series of diyne polymers to their saturated counterparts. Isosorbide **1a** and isomannide **1b** are commercially available, while **1c** can be prepared from **1b** in two steps.[13] Isohexide *bis*-propargyl ether monomers **2a–c** were previously used by Besset and Drockenmueller to synthesize 1,2,3-triazole-containing polymers using copper-catalyzed azide/alkyne step growth copolymerization.[22] In our hands, the alkylation of **1a–c** was best performed using aqueous potassium hydroxide, propargyl bromide, and a phase-transfer catalyst (tetrabutylammonium bromide) in methylene chloride (Scheme 1). Dialkyne monomers **2a–c** could be easily prepared on gram scale.

After screening many sets of conditions for the Glaser-Hay-type polymerization of **2a–c** (most of which resulted in the premature precipitation of the polymer from the reaction mixture) we were pleased with the results afforded by a protocol adapted from Lei and coworkers.[23] Formation of **poly(2a–c)** could be smoothly accomplished in *N,N*-dimethylformamide (DMF) using copper(I) iodide, nickel(II) dichloride hexahydrate, *N,N,N',N'*-tetramethylethylenediamine (TMEDA), and triethylamine under an atmosphere of oxygen. DMF was the only solvent we found in which these diyne polymers remain solubilized when their respective molar masses exceeded ca. 5 kDa. Polymer isolation and catalyst, ligand, and base removal can be accomplished by precipitation of the reaction mixture into aqueous ammonium chloride, followed by lyophilization of the wet solids. The number and weight average polymer molar masses (M_n and M_w, respectively) and dispersities ($Đ$) were calculated using size exclusion chromatography (DMF mobile phase) equipped with multi-angle light scattering (SEC-MALS), shown in Table 1. The dispersities observed are uncharacteristically low (≤1.5) for polymers synthesized via step-growth processes, likely attributable to fractionation during polymer precipitation.[24]

Table 1. Characterization data for isohexide diyne polymers and saturated polyethers

Polymer	$M_{n,\ ^1\text{H NMR}}$ (kDa)	$M_{n,\text{SEC}}{}^b$ (kDa)	$M_{w,\text{SEC}}{}^b$ (kDa)	$Đ^b$
poly(2a)	*n/a*[a]	12.5	16.3	1.3
poly(2b)	*n/a*[a]	9.1	13.7	1.5
poly(2c)	*n/a*[a]	8.7	13.1	1.5
poly(2a) – [H]	11.4	9.7	15.5	1.6
poly(2b) – [H]	5.7	4.3	5.6	1.3
poly(2c) – [H]	5.0	5.5	9.9	1.8

Polymerization conditions: $[\mathbf{2a–c}]_0$ = 0.5 mol L^{-1} in DMF; CuI (5 mol%), $NiCl_2•6H_2O$ (5 mol%), TMEDA (40 mol%), and Et_3N (3 equiv); O_2 atmosphere; 24 h.

[a] No end groups visible by ^{1}H NMR spectroscopy for M_n estimation. [b] Determined by SEC-MALS (DMF).

The ^{1}H NMR data for monomers **2a–c**, shown in Figure 1, closely matches those reported.[22] The resonances corresponding to the *exo*-propargyl ether methylenes (labeled y) in **2a** and **2c** appear as doublets (J = 2.4 Hz) at ca. 4.2 ppm. Conversely, the *endo*-propargyl ether methylenes (labeled x/x') in **2a** and **2b** appear as a pair of diastereotopic dds (J = 15.8, 2.4 Hz).

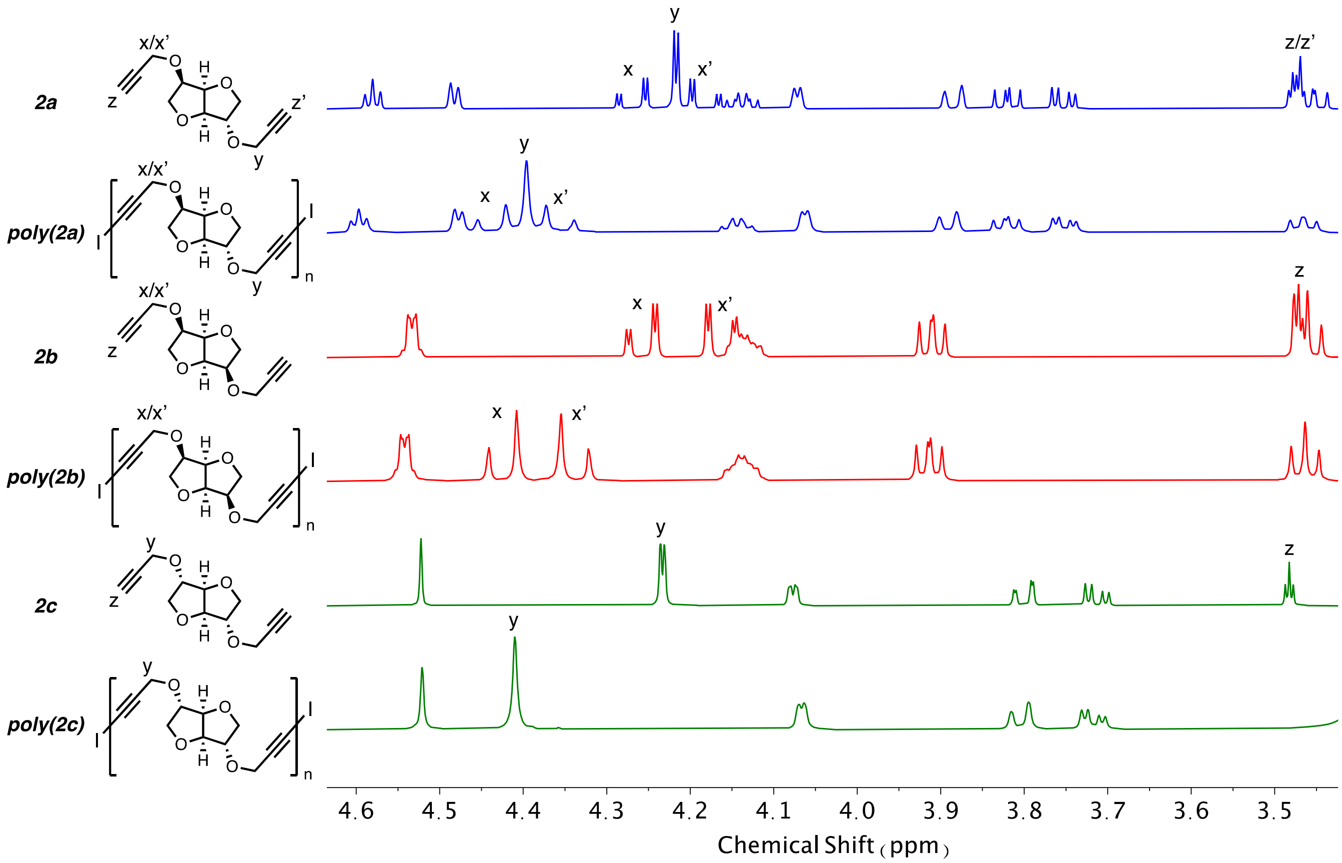


Figure 1. Comparison of ^{1}H NMR spectra (DMSO-d_6, 500 MHz) of isohexide monomers **2a–c** to their counterpart 1,3-diyne polymers **poly(2a–c)**.

Upon polymerization to the corresponding 1,3-diynes in **poly(2a–c)**, the resonances for x/x' and y shift downfield by ca. 0.2 ppm and lack the characteristic J = 2.4 Hz coupling to the alkyne proton, accompanied by the disappearance of the ≡CH alkyne triplets (z/z') at ca. 3.5 ppm. The abnormally deshielded chemical shift for this ≡CH proton is caused by hydrogen bonding to the DMSO-d_6 solvent. Diyne polymers **poly(2a–c)** demonstrated remarkably well-defined spectroscopic behavior. We did not detect any trace of the $OCH_2C{\equiv}C{-}H$ resonances in the ^{1}H NMR spectra of **poly(2a–c)**, which, in theory, would correspond to the alkyne end groups of the diyne polymers. Thus, either the polymers had cyclized or the ≡CH had been converted to a derivative that was not visible by ^{1}H NMR spectroscopy.

During a model homocoupling reaction of the acetate-protected alkyne **3** to diyne **4**, a small quantity of a byproduct, the iodoalkyne **5,** was observed by GC-MS and ^{1}H NMR analyses (Figure 2a). Side product **5** was fully confirmed by alternative synthesis from **3** (*N*-iodosuccinimide and silver nitrate). This unexpected result illumined a reductive elimination pathway, illustrated in Figure 2b, that may be responsible for the formation of iodoalkynes from propargyl ethers under these homocoupling conditions. To our knowledge, this is the first reported example of iodoalkyne formation from a nickel-mediated reductive elimination. In addition, this reactivity can be extended to the step-growth polymerization reaction and provides an explanation for the absence of ≡CH alkyne end groups in **poly(2a–c)**.

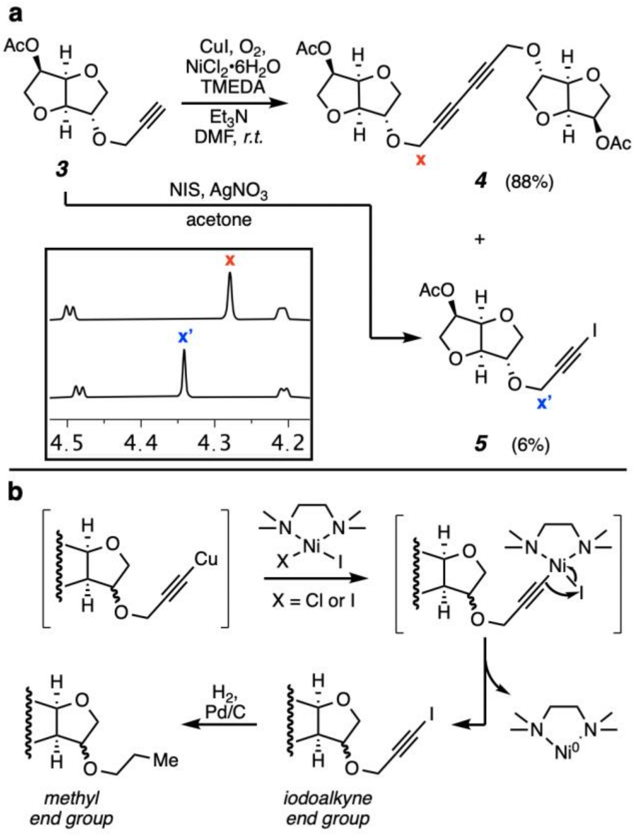


Figure 2. a) Synthesis of iodoalkynes from terminal alkynes and selected ^1H NMR resonances of observed products (500 MHz, $CDCl_3$) **b)** proposed mechanism for reductive elimination to iodoalkyne.

The diyne polymers can be cleanly hydrogenated to their corollary saturated polyethers (**poly(2a–c)–[H]**) under 80 psi H_2 and 20 wt.% loading of Pd/C in DMF. The respective molar mass data for the hydrogenated polymers corresponds reasonably well to that of each parent diyne polymer (Table 1). The ^1H NMR spectra for these polymers showed small methyl triplets at ca. 0.86 ppm, which suggested that each of the saturated polymers was terminated by *n*-propyl ethers. These data support the assertion that the parent diyne polymers were not cyclic, but rather linear, and were terminated by iodoalkyne end groups.

To further investigate this phenomenon, we devised a second model study, wherein we prepared *bis*-iodoalkyne model substrate **6** and subjected it to the same reducing conditions used to hydrogenate the diyne polymers. This hydrogenation yielded **7**, where the propargylic iodoalkynes were smoothly reduced to the corresponding propyl ethers. As shown in Figure 3, the chemical shifts and coupling constants (7.4 Hz) of the methyl group resonances in the sample of **poly(2a)–[H]** align well with those of the analogous methyl groups in the *exo*- vs. *endo*-*n*-propyl groups in model compound **7** ($\Delta\delta$ = 0.004 ppm).

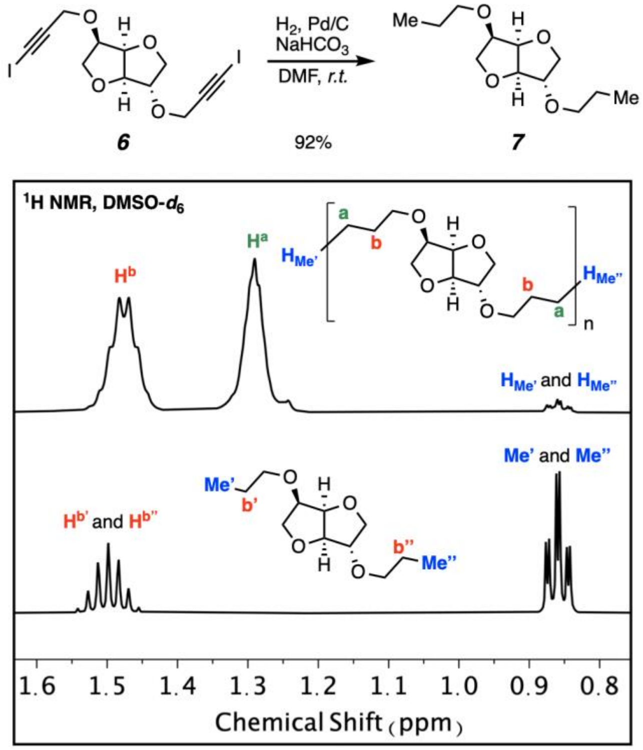
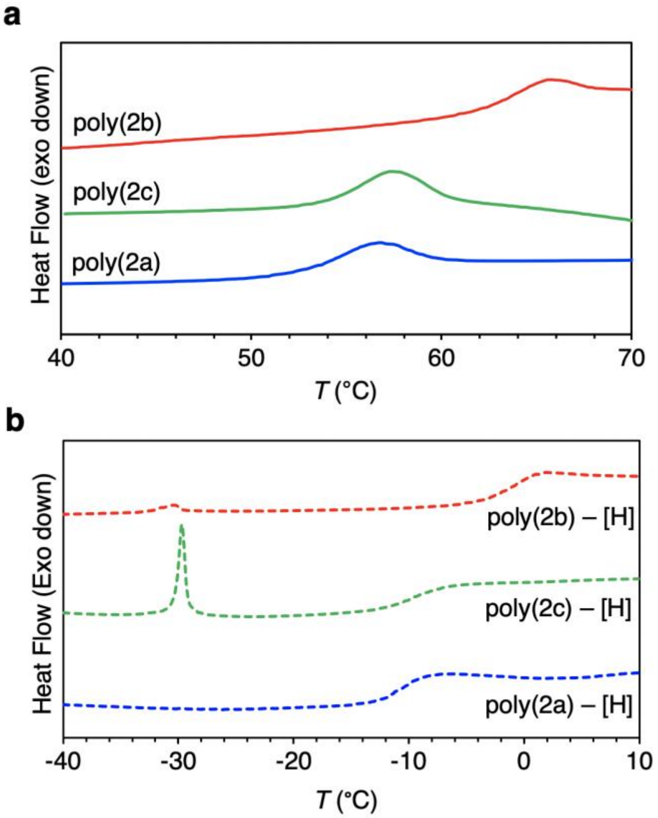


Figure 3. Hydrogenation of bis-iodoalkyne to bis-propyl ether and comparison of ^1H NMR shifts (DMSO-d_6, 500 MHz) of model compound to saturated isohexide polyether.

The thermal properties of the isohexide diyne polymers **poly(2a–c)** and the saturated analogs **poly(2a–c)–[H]** were evaluated using differential scanning calorimetry (DSC, Figure 4a). The diyne polymers **poly(2a–c)** demonstrated a narrow window of T_g values, between 55 and 64 °C, for samples of comparable molar mass. The individual DSC thermograms (**S23–24**) for **poly(2a–c)** display a unique, highly exothermic event at temperatures above the T_g of the polymer, attributed to the aerobic oxidation of the methylene carbons in the 2,4-hexadiynyl ether subunit. This phenomenon may be responsible for the falling baseline in the thermogram for **poly(2c)**. We found that a heating rate of 20 °C/min was necessary to obtain reproducible T_g measurements for **poly(2a–c)**. Further discussion of this oxidation phenomenon is available in the Supporting Information.

The saturated polyethers **poly(2a–c)–[H]**, as expected, exhibit considerably lower T_g values (Figure 4b) than their parent diyne polymers, presumably a reflection of their significantly increased chain flexibility. Glass transitions below -50° C are typical for aliphatic polyethers, but it is not surprising that the rigid isohexide subunit in the backbone of **poly(2a–c)–[H]** raises their observed T_gs. The T_g range for **poly(2a–c)–[H]** is -10 to -2 °C (8 °C window), a range that is very similar to that for **poly(2a–c)** (9 °C window). Saturated polyethers **poly(2b–c)–[H]** display a small, but reproducible, sub-T_g melting feature (T_m) at -30 and -29 °C, respectively. These perhaps correspond to the melting of crystallized propyl ether end groups. This feature is not observed in the thermogram of **poly(2a)–[H]**, which, recall, is terminated by a mixture of both the *exo*- or *endo*-propyl ethers and lacks regioregularity. This less ordered environment may preclude end-unit crystallization under these DSC conditions.



Polymer	T_g (°C)	Polymer	T_g (°C)	T_m (°C)
poly(2a)	55	**poly(2a)–[H]**	-10	*n/a*
poly(2b)	64	**poly(2b)–[H]**	-2	-30
poly(2c)	56	**poly(2c)–[H]**	-9	-29

Figure 4. DSC thermograms of a) isohexide diyne polymers poly(2a–c) 20 °C/min) and b) saturated polyethers poly(2a–c)–[H] (10 °C/min).

The TGA behavior of the two series of polymers (diyne and saturated) was also examined. At least as judged by values of $T_{d5\%}$, **poly(2a)** and **poly(2a)–[H]** showed anomalous behavior from that of the **1b**- and **1c**-derived polymers; the $T_{d5\%}$ was ca. 40-80 °C higher for the **1a**-derived polymers vs. the isomannide or isoidide analogs (see SI). The molecular weights of the **1a** polymers were 30-50% higher than those of the **1b** and **1c** polymers. This suggests that the number of end groups are contributing to the initial mass loss for this class of polyethers.

In conclusion, we report a facile synthesis of 1,3-diyne polymers **poly(2a–c)** from the isohexides (**1a–c**) through a modified Glaser-Hay polymerization of dialkyne monomers **2a–c**. A reductive elimination pathway caps each diyne polymer with iodoalkyne end groups, a process for which we have found no precedent. The corresponding saturated polyethers **poly(2a–c)–[H]** can be prepared from **poly(2a–c)** by catalytic hydrogenation. The diyne vs. saturated polyethers demonstrated parallel trends in their thermal characteristics, displaying T_g values ranging from 55 to 64 °C for the former and -10 to -2 °C for the latter. These polymerization methods allow access to well-defined polyethers incorporating the isohexides using readily available catalysts and convenient, ambient conditions. In addition, both series of polymers illustrate the effects of relative configuration and linker rigidity on T_g values.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Experimental details and characterization data for all monomers, model compounds, and polymers (PDF)

FAIR NMR data, including the primary ^{1}H and ^{13}C NMR FID files for compounds **2a**, **2b**, **2c**, **3**, **4**, **5**, **6**, **7**, **2a–RR**, **poly(2a)**, **poly(2b)**, **poly(2c)**, **poly(2a–RR)**, **poly(2a)–[H]**, **poly(2b)–[H]**, **poly(2c)–[H]**, **S1**, **S2**, **S3**, and **S5**.

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Author Contributions

E.A.G. performed all the experimental work; E.A.G., T.M.R., and T.R.H. interpreted the data and co-wrote the manuscript.

Notes

The authors declare no competing financial interest.

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