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Xanthates as Synthetic Equivalents of Oxyacyl Radicals: Access to Lactones under Tin-Free Conditions

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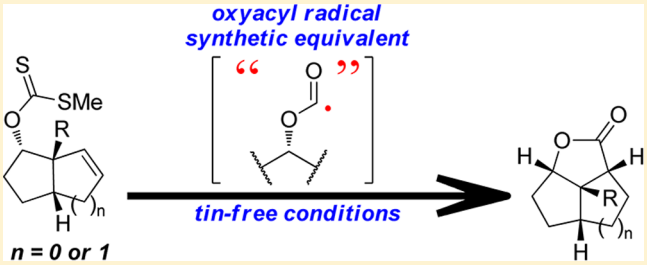
Supporting Information

ABSTRACT: In addition to their utility in Barton–McCombie deoxygenations, xanthates can engage in 5-*exo-trig* radical cyclizations to afford lactones after oxidative workup. In this paper, we describe a tin-free protocol that provides direct access to lactones via hydrolysis of labile thioketal intermediates. Analysis of several systems of varying complexity reveals that the reaction is most applicable for constrained systems in which the reacting center is prepositioned near the radical-accepting alkene.



The iodolactonization reaction[1] provides a powerful method for ring construction, leading to the formation of a new carbon–oxygen bond with excellent control over relative stereochemistry (Figure 1). Since its discovery over 100

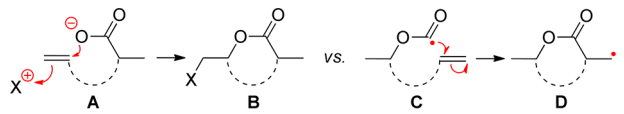


Figure 1. Comparison of an iodolactonization strategy with an oxyacyl radical approach.

years ago,[2] the iodolactonization has been widely used in the synthesis of natural products[3] and other biologically active compounds.[4] This utility has in turn stimulated the development of related reactions, including bromolactonizations,[5] selenolactonizations,[6] tellurolactonizations,[7] and iodolactamizations.[8]

From a strategic perspective, the iodolactonization makes use of an existing carbon–carbon bond to form a new carbon–oxygen bond in the lactone. In principle, the opposite approach, using existing oxygen functionality to form a new carbon–carbon bond, should provide a useful strategic complement. While this alternative strategy could be realized synthetically through the use of oxyacyl radicals (**C**, Figure 1),[9] these species have not been utilized extensively in the synthesis of complex targets,[10] possibly due to the existence of competing decarboxylation pathways for the oxyacyl radicals themselves,[9a,b,11] or difficulties in preparing the required precursors in the presence of other functionality.

O-Alkyl thiocarbonates (xanthates, **E**) represent a potential synthetic equivalent to oxyacyl radicals, in that treatment of these easily prepared substrates with a source of tin radicals leads to the production of stabilized alkyl radicals (**K**, Scheme 1) which can either fragment (resulting in a Barton–McCombie deoxygenation to afford **F**) or cyclize in a 5-*exo-trig* fashion to provide a thionocarbonyl product (**O**) that can in turn be converted under oxidative conditions to afford the corresponding lactone (**G**).[12,13] Despite the potential power of this methodology, xanthate radical cyclizations have been much less widely used in synthesis than have halolactonizations, perhaps because most of the existing reports have described only relatively simple monocyclic and bicyclic products.

In 2005, the Wood group published a reduction of xanthates to the corresponding alkanes using trimethylborane in wet benzene.[14] Because this reaction does not require the use of any tin species and because it proceeds at room temperature, it may be complementary to the traditional Barton–McCombie deoxygenation. The proposed mechanism for this transformation, based on an earlier proposal by Barton,[15] posits the intermediacy of radical **S** (Scheme 1). Hypothesizing that **S** could likewise provide access to lactone products through a 5-*exo-trig* cyclization to initially afford **W**, followed by hydrolytic workup (potentially without the need for an oxidation step) to generate **G**, and mindful of the benefits of developing "greener" synthetic protocols, we sought to develop a tin-free version of the xanthate radical cyclization.

In keeping with our group's interest in the stereocontrolled synthesis of polycyclic scaffolds,[16] we focused our attention primarily on the exploitation of this lactonization strategy for the conversion of readily accessible bicyclo[3.3.0]octenes and bicyclo[3.2.0]heptenes (Schemes 2 and 3) to tricycles. In principle, the oxygen-directed lactonization of pre-existing bicyclic (or higher order) scaffolds could provide a useful entry into a large number of natural product architectures.

These include the picrotoxins,[17] a very large family of cytotoxic natural products. Among several candidate picrotox-

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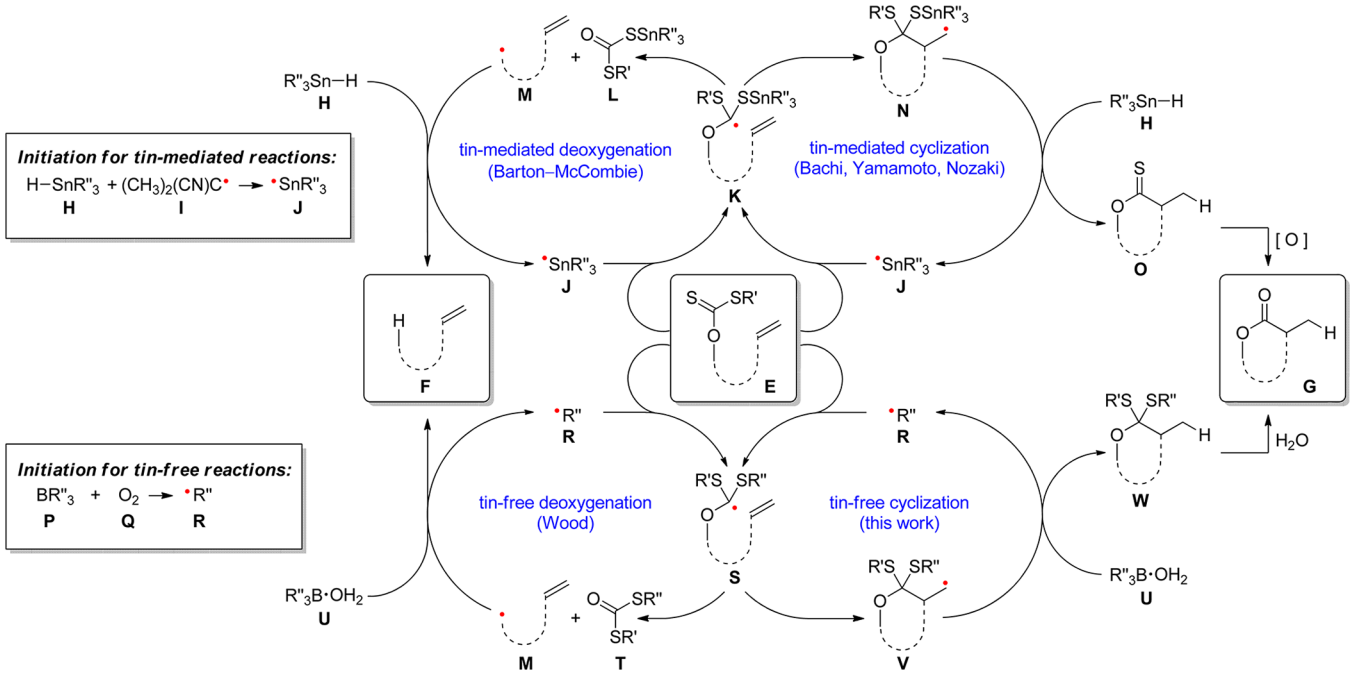
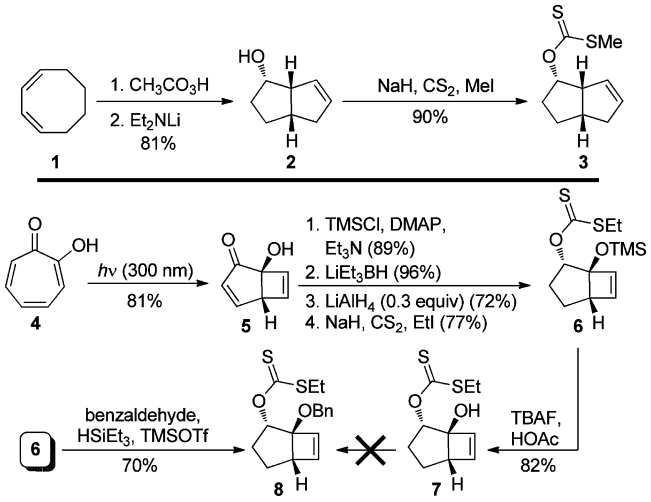
Scheme 1. Proposed Mechanistic Pathways for Tin-Mediated and Tin-Free Radical Reactions[a]

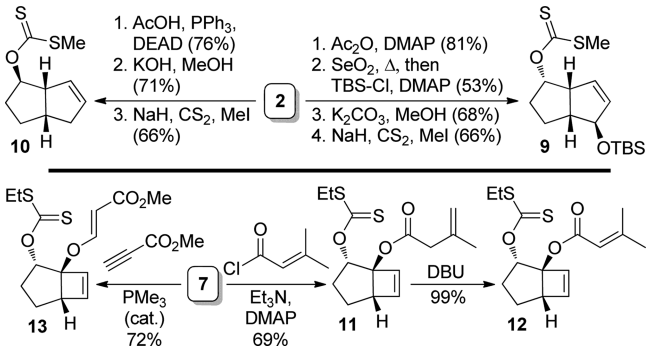


[a]Cyclization is expected to be competitive for fast 5-*exo-trig* additions.

Scheme 2. Synthesis of Bicyclo[3.3.0] and Bicyclo[3.2.0] Substrates



Scheme 3. Synthesis of Substrates Used to Probe the Scope of the Lactonization Reaction



ins, flakinin A[18] presents a particularly compelling example containing two γ-lactones fused to a central bicyclo[4.3.0]-nonane carbon skeleton. The structurally unusual natural product sclerocitrin[19] provides further motivation to develop this methodology, since the core of the molecule (shown in red in Figure 2) could potentially be accessed through oxygen-directed lactonization of a bicyclo[3.3.0]octene precursor not unlike those used as test substrates for this work.

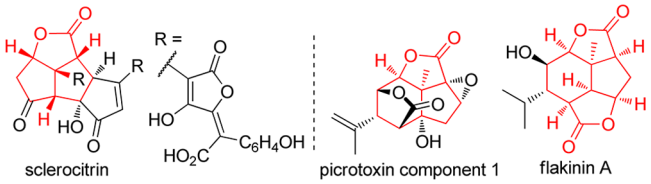


Figure 2. Representative polycyclic lactone targets.

The bicyclo[3.3.0]octenes were accessed from 1,3-cyclooctadiene (**1**) by epoxidation and transannular ring-closure to provide **2** (Scheme 2).[20] Xanthate **3**, the primary target for methodology development, was prepared by deprotonation, reaction with carbon disulfide, and alkylation of the resulting xanthic acid.[21]

Xanthate **3** was dissolved in commercial grade, undried benzene. A solution of triethylborane in THF was added via syringe, after which air was slowly added over several hours with the aid of a syringe pump. Evaporation of the reaction mixture and flash chromatography provided the desired lactone (**14**, Table 1), together with various sulfur-containing products (i.e., **W** and derivatives thereof). Subsequent experimentation revealed that stirring the crude product overnight in a solution of aqueous $CaCO_3$ and I_2 in tetrahydrofuran[22] completed the hydrolysis step (i.e., **W**→**G**, Scheme 1), permitting the isolation of **14** in a 72% yield following purification.

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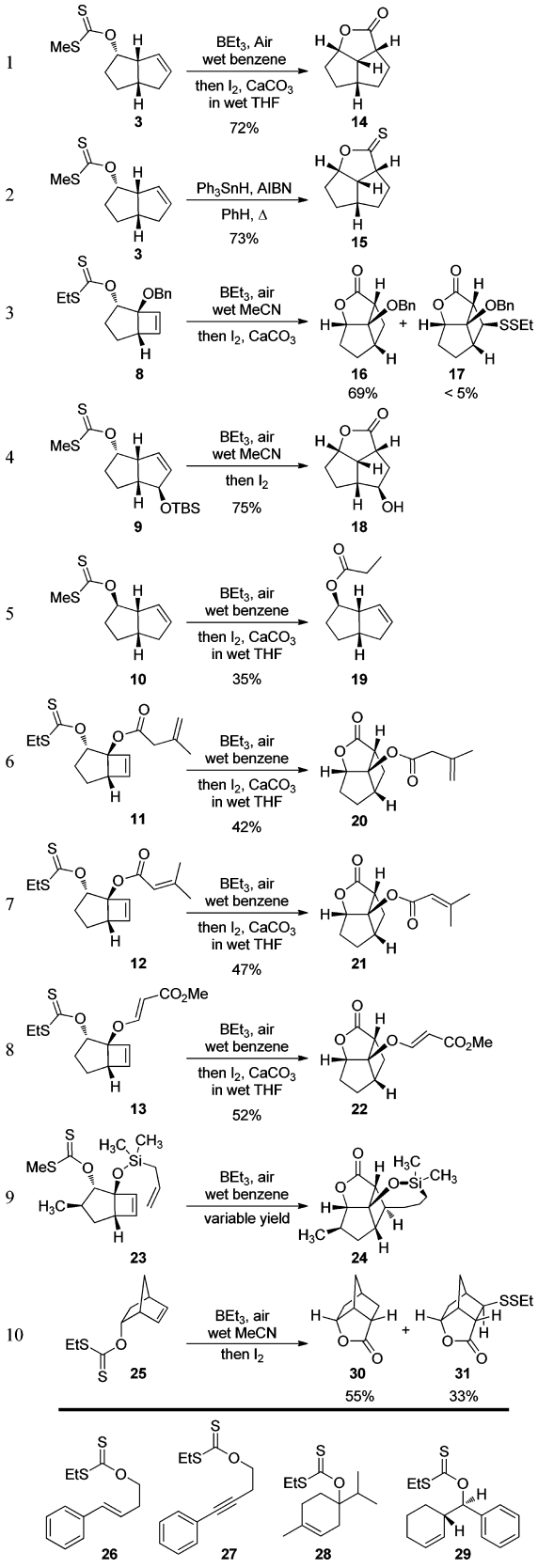
Table 1. Substrate Scope for the Lactonization of Bicycles



For comparison, we also treated **3** under standard tin radical conditions (Table 1, entry 2), which led to the formation of thionolactone **15** in 73% yield. Transformation of thionolactones to lactones (i.e., **O**→**G**, Scheme 1) is well-known,[12,13] but this represents an extra synthetic step. Thus, the tin-free method described here could represent a more efficient route to certain classes of lactone products.

Mindful of the possibility that deoxygenation would be competitive with ring-closure, we recognized that the precise placement of the radical-accepting alkene relative to the xanthate group might substantially influence the reaction outcome. In addition, therefore, to several less-constrained systems (vide infra), we sought to test the lactonization reaction for derivatives of bicylo[3.2.0]heptene **7** (Scheme 2). This more-constrained system (relative to **3**) greatly restricts the conformational flexibility of the alkene-containing ring, potentially increasing the synthetic challenge. At the same time, the tertiary alcohol in **7** provides the opportunity to tether additional alkene functions to the reacting core, allowing us to explore the possibility of cascade cyclizations.

We accessed **7** through a photochemical electrocyclic rearrangement of tropolone (**4**) to afford **5**,[23] followed by standard functional-group manipulations. Protection of the tertiary alcohol in **7** initially proved difficult, but reductive benzylation of **6** with benzaldehyde and triethylsilane[24] provided the benzyl-protected substrate **8** in good yield (Scheme 2).

Xanthate **8** underwent lactonization under the same conditions as **3** to afford the desired lactone **16** in 51% yield, together with a 16% yield of a second product, which was eventually identified as disulfide **17**. The use of dry benzene doped with methanol in place of wet benzene did not greatly affect the product distribution, while presaturation of the wet benzene solvent with oxygen shut down the reaction entirely, presumably by degrading the triethylborane too quickly. Attempts to use chloroform or tetrahydrofuran in place of benzene were likewise unsuccessful, leading principally to decomposition of the substrate. Fortunately, the use of wet acetonitrile as solvent (Table 1, entry 3) completely suppressed the formation of **17**, providing lactone **16** in 69% yield.

The fact that **16** could be isolated in similar yield to **14** (albeit following a reoptimization of the reaction conditions) indicated that the reaction was tolerant of both the decreased conformational flexibility present in the smaller scaffold and the presence of the benzyl protecting group. To further explore the degree of protecting-group compatibility, TBS-protected alcohol **9** was prepared via allylic oxidation[25] and silylation (Scheme 3). This substrate also cyclized effectively (Table 1, entry 4), but the TBS group was lost under the reaction conditions (even when $CaCO_3$ was eliminated from the workup step), providing alcohol **18** in 75% yield.

To evaluate the effect of positioning the xanthate group farther away from the alkene acceptor, we next synthesized **10** via Mitsunobu inversion of the secondary alcohol in **2** prior to xanthate formation. Exposure of **10** to our standard reaction conditions did not result in any cyclized product, likely due to the substantial strain that would be present in the resulting tricycle. While most of the substrate was presumably deoxygenated (and subsequently lost to evaporation following workup), we were surprised to observe a 35% yield of propionate **19** (entry 5).[26] We hypothesize that **19** arises from reaction of intermediate **S** with an ethyl radical (present as compound **R** in Scheme 1), followed by hydrolytic loss of the two sulfur substituents. Alternatively **S** may gain an ethyl group from reaction with borane species **P** or **U**.

The rate at which the radical quenching step (i.e., **V**→**W**, Scheme 1) takes place will dictate the likelihood of radical

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cascade reactions occurring. It is well-known for the corresponding tin-mediated step (i.e., **N→O**) that the rate for this intermolecular process can be reduced through slow addition of the tin hydride reagent, thereby favoring intramolecular cascade events. It was less clear what the rate of the quenching step would be in our tin-free system. Therefore, to evaluate the likelihood of radical cascades occurring alongside lactonization reactions, we sought to tether alkenes onto the bicyclic core through the tertiary alcohol in **7**.

Addition of 3,3-dimethylacryloyl chloride to **7** was expected to provide dimethyl acrylate **12** (Scheme 3). Surprisingly, however, the double bond moved out of conjugation with the carbonyl, resulting in a good yield of terminal alkene **11**, a possible substrate for a 7-*exo-trig* or 8-*endo-trig* cyclization following the initial closing of the lactone. The olefin could be reconjugated to the ester by treatment with DBU to access **12**, a possible substrate for a 6-*exo-trig* or 7-*endo-trig* cyclization.

To complete the series, we also synthesized vinyl ether **13**, a possible substrate for a 5-*exo-trig* or 6-*endo-trig* cyclization, by phosphine-mediated conjugate addition[27] to methyl propiolate.

When subjected to our lactonization conditions, each of these substrates underwent a single cyclization event (Table 1, entries 6−8), but none of them cyclized further, despite the fact that several favored pathways would have been open to them.[28] This suggests that the radical quenching step (**V→W**) is a fast process in this reaction system, even when water is not intentionally added to the benzene solvent, which limits the amount of presumed hydrogen atom-donor **U** present in solution.

Interestingly, an analogously prepared substrate[29] bearing an allylsilane function (**23**) *did* engage in a cascade cyclization through an apparent 8-*endo-trig* process to provide the architecturally impressive product **24** (Table 1, entry 9). The ability of the silicon atom to stabilize the intermediate β-radical[30] may play a role in enhancing the rate of this cyclization versus those possible for **11**−**13**. However, although **24** could be cleanly isolated and fully characterized, it was not stable to either the reaction environment or the usual workup conditions. As a result, the yield for this transformation was highly irreproducible.

Our primary aim was to design a tin-free lactonization that would be useful for converting functionalized bicycles to tricyclic lactones. Nonetheless, in an effort to probe the scope and limitations of the method more fully, we prepared several additional xanthates from readily available alkene−alcohol conjugates (**25**−**29**, Table 1) and evaluated their ability to react under our optimized conditions.

Compound **25**, which is similarly constrained to **3** or **8**, cyclized efficiently to provide the desired lactonization product (**30**) in 55% yield, as well as a further 34% of the corresponding disulfide product (**31**). Perhaps not surprisingly given the number of competing reactions that could take place in the relatively complex reaction environment, less constrained substrates **26**−**29** did not cyclize efficiently, and no clean lactone products were obtained.

EXPERIMENTAL SECTION

General Methods. Unless otherwise stated, all reagents were purchased from commercial suppliers and used without further purification. ^{1}H chemical shifts are reported in parts per million (ppm, δ scale) downfield from tetramethylsilane and are referenced to residual protium in the NMR solvent ($CDCl_3$: δ 7.24). Likewise, ^{13}C chemical shifts are referenced to the carbon resonances of the solvent ($CDCl_3$: δ 77.00). Accurate masses were obtained using an orbitrap MS unless otherwise noted. Infrared spectra were collected using an FT-IR spectrometer.

General Procedure for Xanthate Formation. To a solution of alcohol (1.0 equiv) in THF (0.5 M) was added CS_2 (2.0 equiv). The resulting solution was cooled to 0 °C, NaH (95%; 1.1 equiv) was added, and the mixture was slowly warmed to room temperature over 4 h. Iodoethane or iodomethane (4.0 equiv) was added, and the solution was stirred at room temperature for 12 h. A saturated solution of aqueous NH_4Cl was added and the organic phase was separated. The aqueous phase was extracted twice with Et_2O and the combined organic extracts were washed with brine, dried over anhydrous Na_2SO_4, filtered, concentrated, and purified by chromatography over silica gel.

General Procedure for Tin-Free Xanthate Lactonization. A solution of xanthate (1.0 equiv) in 4:1 MeCN−H_2O (8 mM) was sparged with argon. Triethylborane (1 M in hexanes; 5.0 equiv) was added dropwise. A 60-mL syringe was filled with air, and a syringe pump was used to slowly inject the air (ca. 5 mL/h) into the mechanically stirred reaction mixture. Upon completion of the injection, iodine (3.0 equiv) was added to the reaction mixture, and the solution was stirred open to air for a minimum of 3 h. To the dark brown solution was added a 0.5 M solution of aqueous $Na_2S_2O_3$ (approximately twice the reaction volume), and the mixture was stirred for 30 min, resulting in a disappearance of the dark brown color. Finally, the solution was extracted twice with dichloromethane, and the organic extracts were washed with brine, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure. Products were purified by chromatography over silica gel. In cases where both $CaCO_3$ and I_2 were used to effect hydrolysis, 3 equiv of each were added to a solution of the crude reaction mixture in 4:1 THF/H_2O.

Xanthate ***3****:* yellow oil (90% yield); 40:1 hexanes−ethyl acetate; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.84 (dd, J = 12.4, 6.2 Hz, 1H), 5.75 (dt, J = 5.8, 2.2 Hz, 1H), 5.45 (dt, J = 8.0, 2.2 Hz, 1H), 3.61−3.51 (m, 1H), 2.80−2.60 (m, 2H), 2.51 (s, 3H), 2.12 (ddd, J = 14.0, 5.1, 2.5 Hz, 1H), 2.00−1.74 (m, 3H), 1.46 (ddd, J = 15.6, 10.0, 5.3 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 215.4 (C), 132.7 (CH), 128.3 (CH), 87.1 (CH), 53.6 (CH), 41.5 (CH_2), 39.6 (CH), 30.9 (CH_2), 30.9 (CH_2), 18.8 (CH_3); IR (neat, cm^{-1}) 3051 (w), 1231 (s), 1213 (s), 1057 (s), 713 (m); HRMS (ESI) calcd for $C_{10}H_{14}OS_2$ + H^+ 215.0564, found 215.0560.

Xanthate ***8****.* Silyl ether **6** (prepared as indicated in Scheme 2; 122 mg, 0.403 mmol, 1.0 equiv) and benzaldehyde (59.1 mg, 0.504 mmol, 1.3 equiv) were dissolved in dry dichloromethane (6 mL), and the reaction was cooled in an ice bath. The subsequent addition of TMSOTf (2 drops) at 0 °C caused the pale yellow solution to turn reddish brown. After 1 h, triethylsilane (59.1 mg, 0.504 mmol, 1.3 equiv) was added and the reaction stirred overnight, acclimating to room temperature. Upon quenching with saturated NH_4Cl solution (5 mL), the crude mixture was extracted with Et_2O (3 × 10 mL), and the combined organic layer was washed with H_2O (2 × 10 mL) and brine (10 mL), dried over $MgSO_4$, filtered, and concentrated by rotary evaporation. The crude material was purified by chromatography (benzene−hexanes 1:3 to 1:1) to afford compound **8** (90.4 mg, 70%) as a yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.30−7.15 (m, 5H), 6.20 (d, J = 2.9 Hz, 1H), 6.18 (d, J = 2.9 Hz, 1H), 5.76 (dd, J = 7.1, 9.5 Hz, 1H), 4.60 (d, J = 12.2 Hz, 1H), 4.55 (d, J = 12.2 Hz, 1H), 3.13 (dd, J = 0.9, 5.9 Hz, 1H), 3.07 (q, J = 7.4 Hz, 2H), 2.47−2.38 (m, 1H), 1.73−1.40 (m, 3H), 1.32 (t, J = 7.4 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 214.6 (C), 139.2 (CH), 139.1 (C), 135.6 (CH), 128.3 (CH), 127.4 (CH), 127.2 (CH), 91.2 (C), 86.1 (CH), 67.7 (CH_2), 49.8 (CH), 30.1 (CH_2), 26.9 (CH_2) 20.8 (CH_2), 13.5 (CH_3); IR (neat, cm^{-1}) 3088 (w), 3033 (m), 2947 (m), 2864 (m), 1454 (m), 1313 (m), 1211 (s), 1137 (m), 1071 (s), 768 (m); HRMS (ESI) calcd for $C_{17}H_{20}O_2S_2$ + Na^+ 343.0797, found 343.0795.

Xanthate ***9****:* yellow oil (66% yield); 40:1 hexanes−ethyl acetate; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.85−5.74 (m, 2H), 5.69 (ddd, J = 5.7, 2.3, 0.9 Hz, 1H), 4.58 (dt, J = 2.9, 2.2 Hz, 1H), 3.75 (ddt, J = 7.5, 10.0, 2.3 Hz, 1H), 2.53 (s, 3H), 2.52−2.45 (m, 1H), 2.03−1.91 (m, 1H), 1.90−1.79 (m, 1H), 1.79−1.68 (m, 1H), 1.67−1.56 (m, 1H), 0.90 (s,

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9H), 0.09 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 215.4 (C), 135.9 (CH), 132.4 (CH), 86.5 (CH), 85.8 (CH), 52.3 (CH), 50.7 (CH), 30.2 (CH_2), 27.3 (CH_2), 26.1 (CH), 19.0 (CH_3), 18.4 (C), −4.3 (CH_3); IR (neat, cm^{-1}) 3058 (w), 1252 (s), 1212 (s), 1056 (s), 667 (m); HRMS (ESI) calcd for $C_{16}H_{28}O_2S_2Si$ + Na^+ 367.1198, found 367.1190.

Epimerization of ***2***. A solution of PPh_3 (3.37 g, 12.8 mmol, 1.6 equiv) in THF (20 mL) was cooled to 0 °C, and DEAD (40 wt % in toluene; 5.60 mL, 12.8 mmol, 1.6 equiv) was added dropwise via syringe. The resulting solution was stirred for 1 h at 0 °C, during which time a thick white precipitate formed in the flask. In a separate flask were combined **2** (1.00 g, 8.05 mmol, 1.0 equiv) and AcOH (0.738 mL, 12.8 mmol, 1.6 equiv) in THF (10 mL), and this solution was added to the DEAD−PPh_3 mixture via cannula at 0 °C. The combined mixture was stirred for 1 h at 0 °C and an additional 1.5 h at room temperature after which the solvent was removed via rotary evaporation and the crude material was chromatographed to provide 1.02 g (76%) of the desired epimer as the acetate ester: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.67 (dt, J = 7.9, 2.0 Hz, 1H), 5.60 (dt, J = 7.9, 2.0 Hz, 1H), 4.91−4.86 (m, 1H), 3.15−3.07 (m, 1H), 2.85 (ddt, J = 17.2, 8.2, 3.1 Hz, 1H), 2.66 (ddq, J = 17.2, 9.2, 2.0 Hz, 1H), 2.09−1.95 (m, 2H), 2.03 (s, 3H), 1.74−1.65 (m, 2H), 1.41 (ddd, J = 12.6, 6.4, 3.2 Hz, 1H).

The acetate (600 mg, 3.61 mmol, 1.0 equiv) was dissolved in MeOH (40 mL), and aqueous KOH (2 N; 10.8 mL, 10.8 mmol, 3.0 equiv) was added. After the mixture was stirred at room temperature for 4 h, aqueous 10% HCl (10.8 mL) was added, followed by excess saturated aqueous $NaHCO_3$. The product mixture was extracted with Et_2O (2 × 10 mL). Organic extracts were washed with brine, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure. Chromatography afforded *epi*-**2** (320 mg, 71%) as a colorless oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.65 (ddd, J = 5.6, 4.4, 2.0 Hz, 1H), 5.55 (ddd, J = 5.6, 4.4, 2.0 Hz, 1H), 4.08−4.03 (m, 1H), 3.09−3.01 (m, 1H), 2.88 (ddd, J = 17.3, 8.5, 2.9, 1H), 2.66 (ddq, J = 17.3, 9.4, 2.2 Hz, 1H), 2.16−1.97 (m, 2H), 1.73−1.51 (m, 3H), 1.45−1.35 (m, 1H).

Xanthate ***10:*** yellow oil (66% yield); 40:1 hexanes−ethyl acetate; ^{1}H NMR (360 MHz, $CDCl_3$) δ 5.71 (ddd, J = 5.6, 4.4, 2.1 Hz, 1H), 5.64 (ddd, J = 5.6, 4.6, 2.2 Hz, 1H), 5.59 (d, J = 2.3 Hz, 1H), 3.33 (d, J = 7.1 Hz, 1H), 2.90 (ddt, J = 17.3, 8.3, 2.9 Hz, 1H), 2.70 (dddd, J = 17.2, 9.4, 4.1, 2.1 Hz, 1H), 2.55 (s, 3H), 2.13−1.98 (m, 2H), 1.97−1.87 (m, 1H), 1.80 (dddd, J = 13.8, 11.7, 4.7, 6.9 Hz, 1H), 1.52 (dddd, J = 12.4, 6.6, 2.9, 2.7 Hz, 1H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 215.1 (C), 132.9 (CH), 130.0 (CH), 90.3 (CH), 58.2 (CH), 41.5 (CH_2), 39.1 (CH), 32.8 (CH_2), 30.6 (CH_2), 19.1 (CH_3); IR (neat, cm^{-1}) 3050 (w), 1221 (s), 1081 (s), 1047 (s), 716 (m); HRMS (ESI) calcd for $C_{10}H_{14}OS_2$ + H^+ 215.0564, found 215.0564.

Xanthate ***11***. Silyl ether **6** (154 mg, 0.507 mmol, 1.0 equiv) was dissolved in freshly distilled THF (5 mL) and cooled in an ice bath. A solution of TBAF (1.0 M in THF, 1.60 mL, 3.0 equiv) and acetic acid (121 mg, 2.03 mmol, 4.0 equiv) in dry THF (1 mL) was added dropwise and the reaction stirred for 2 h, acclimating to room temperature. Upon quenching with saturated NH_4Cl solution (5 mL), the crude mixture was extracted with Et_2O (3 × 10 mL), and the combined organic layer was washed with H_2O (2 × 10 mL) and brine (10 mL), dried over $MgSO_4$, filtered, and concentrated by rotary evaporation. The crude material was purified by chromatography (Et_2O−hexanes 1:5) to afford alcohol **7** (95.7 mg; 82%) as a yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.21 (d, J = 2.9 Hz, 1H), 6.11 (d, J = 2.9 Hz, 1H), 5.66 (dd, J = 9.9, 7.1 Hz, 1H), 3.04 (q, J = 7.4 Hz, 2H), 2.92 (d, J = 6.7 Hz, 1H), 2.92 (br s, 1H), 2.31 (dddt, J = 6.2, 7.0, 12.3, 0.9 Hz, 1H), 1.85 (ddt, J = 9.9, 7.0, 12.7 Hz, 1H), 2.31 (dddt, J = 12.3, 7.0, 6.2, 0.9 Hz, 1H), 1.85 (ddt, J = 9.9, 7.0, 12.7 Hz, 1H), 1.28 (t, J = 7.4 Hz, 3H). The alcohol (67.0 mg, 0.290 mmol, 1.0 equiv) was added to a flame-dried round-bottom flask and dissolved in 10 mL of dichloromethane. The solution was cooled to 0 °C, and then DMAP (3.5 mg, 0.0290 mmol, 0.10 equiv), freshly distilled triethylamine (88.3 mg, 0.873 mmol, 3.0 equiv), and 3,3-dimethylacryloyl chloride (51.7 mg, 0.436 mmol, 1.5 equiv) were sequentially added. After acclimating to room temperature while stirring overnight, the reaction was quenched with saturated NH_4Cl solution (5 mL), the crude mixture was extracted with Et_2O (3 × 10 mL), and the combined organic layer was washed with H_2O (2 × 10 mL) and brine (10 mL), dried over $MgSO_4$, filtered, and concentrated by rotary evaporation. The crude material was purified by chromatography (dichloromethane−hexanes 3:7 to 1:1) to afford **11** (62.4 mg, 69%; containing 16% **12**) as a yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.24 (d, J = 2.9 Hz, 1H), 6.23 (d, J = 2.9 Hz, 1H), 6.15 (dd, J = 7.4, 9.3 Hz, 1H), 4.89 (pen, J = 1.6 Hz, 1H), 4.82 (oct, J = 1.0 Hz, 1H), 3.27 (d, J = 7.1 Hz, 1H), 3.08 (dq, J = 2.4, 7.4 Hz, 2H), 3.00 (d, J = 1.0 Hz, 2H), 2.42−2.25 (m, 1H), 1.87−1.73 (m, 1H), 1.82−1.71 (m, 1H), 1.77 (t, J = 1.2 Hz, 3H), 1.50 (dd, J = 5.4, 11.5 Hz, 1H), 1.32 (t, J = 7.4 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 214.8 (C), 170.7 (C), 140.0 (CH), 138.3 (C), 133.8 (CH), 114.9 (CH_2), 89.7 (C), 83.3 (CH), 51.4 (CH), 43.5 (CH_2), 30.1 (CH_2), 27.9 (CH_2), 22.4 (CH_3), 21.4 (CH_2), 13.5 (CH_3); IR (neat, cm^{-1}) 3079 (w), 2933 (m), 2871 (m), 1738 (s), 1652 (m), 1447 (m), 1279 (m), 1207 (s), 1143 (s), 1083 (s), 1069 (s), 898 (w), 764 (w); HRMS (ESI) calcd for $C_{15}H_{20}O_3S_2$ + Na^+ 335.0746, found 335.0744.

Xanthate ***12***. Compound **11** (9.8 mg, 0.0313 mmol, 1.0 equiv) was dissolved in 3 mL of dichloromethane along with DBU (50.0 mg, 0.313 mmol, 10 equiv). The reaction was stirred at room temperature overnight prior to quenching with saturated NH_4Cl solution (2 mL). The crude mixture was extracted with Et_2O (3 × 5 mL), and the combined organic layer was washed with H_2O (2 × 5 mL) and brine (5 mL), dried over $MgSO_4$, filtered, and concentrated by rotary evaporation. The crude material (9.8 mg, 99%), a yellow oil, did not require additional purification: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.24 (d, J = 2.9 Hz, 1H), 6.23 (d, J = 2.9 Hz, 1H), 6.12 (dd, J = 9.3, 7.2 Hz, 1H), 5.63 (sep, J = 1.4 Hz, 1H), 3.31 (d, J = 6.0 Hz, 1H), 3.08 (dq, J = 1.4, 7.4 Hz, 2H), 2.47−2.38 (m, 1H), 2.12 (d, J = 1.2 Hz, 3H), 1.95 (qt, J = 12.5, 6.3 Hz, 1H), 1.86 (d, J = 1.3 Hz, 3H), 1.86−1.73 (m, 1H), 1.51 (dd, J = 12.6, 6.5 Hz, 1H), 1.32 (t, J = 7.4 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 214.6 (C), 165.7 (C), 157.4 (C), 139.8 (CH), 134.1 (CH), 116.0 (CH), 89.9 (C), 83.8 (CH), 51.4 (CH), 30.1 (CH_2), 27.9 (CH_2), 27.4 (CH_3), 21.4 (CH_2), 20.2 (CH_3), 13.5 (CH_3); IR (neat, cm^{-1}) 2962 (m), 2929 (s), 2855 (m), 1716 (s), 1649 (m), 1445 (w), 1234 (s), 1207 (s), 1142 (s), 1069 (s), 1035 (m); HRMS (ESI) calcd for $C_{15}H_{20}O_3S_2$ + Na^+ 335.0746, found 335.0744.

Xanthate ***13***. A solution of methyl propiolate (87.8 mg, 1.05 mmol, 4.0 equiv) in dry dichloromethane (3 mL) was added dropwise to a mixture of alcohol **7** (60.2 mg, 0.261 mmol, 1.0 equiv) and trimethylphosphine (1 M in THF, 0.130 mL, 0.50 equiv) in dry dichloromethane (5 mL). The clear colorless reaction turned dark brown as it stirred over 4 h. The reaction was concentrated by rotary evaporation and purified by chromatography (triethylamine-treated silica, dichloromethane) to afford **13** (59.4 mg, 72%) as a yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.59 (d, J = 12.1 Hz, 1H), 6.36 (d, J = 2.9 Hz, 1H), 6.24 (d, J = 2.9 Hz, 1H), 5.73 (dd, J = 9.4, 7.0 Hz, 1H), 5.41 (d, J = 12.1 Hz, 1H), 3.67 (s, 3H), 3.15 (d, J = 5.7 Hz, 1H), 3.09 (q, J = 7.4 Hz, 2H), 2.53−2.44 (m, 1H), 1.70−1.59 (m, 1H), 1.73−1.50 (m, 2H), 1.32 (t, J = 7.4 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 214.6 (C), 168.2 (C), 157.9 (CH), 141.4 (CH), 133.7 (CH), 100.0 (CH), 92.7 (C), 84.6 (CH), 51.3 (CH), 51.1 (CH_3), 30.4 (CH_2), 26.9 (CH_2), 20.7 (CH_2), 13.4 (CH_3); IR (neat, cm^{-1}) 2951 (m), 1717 (s), 1645 (s), 1435 (m), 1316 (m), 1257 (s), 1205 (s), 1176 (s), 1138 (s), 1081 (s), 957 (w), 771 (w); HRMS (ESI) calcd for $C_{14}H_{18}O_4S_2$ + Na^+ 337.0539, found 337.0545.

Lactone ***14:*** colorless oil (72% yield); 1:1 dichloromethane−hexanes; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.98−4.89 (m, 1H), 3.17 (ddd J = 9.5, 9.1, 7.2 Hz, 1H), 3.04 (ddd, J = 9.9, 8.4, 5.1 Hz, 1H), 2.69−2.55 (m, 1H), 2.19−2.02 (m, 3H), 1.94−1.76 (m, 3H), 1.57−1.36 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 181.3 (C), 84.9 (CH), 51.0 (CH), 46.4 (CH), 45.5 (CH), 34.8 (CH_2), 32.1 (CH_2), 32.0 (CH_2), 29.1 (CH_2); IR (neat, cm^{-1}) 1760 (s), 1179 (s), 1001 (s); HRMS (ESI) calcd for $C_9H_{12}O_2$ + Na^+ 175.0735, found 175.0733.

Thionolactone ***15***. A solution containing 30 mg (0.14 mmol, 1.0 equiv) of **3** in 15 mL of benzene (freshly distilled over CaH and degassed) was heated to reflux. A separate solution containing Ph_3SnH (74 mg, 0.21 mmol, 1.5 equiv) and AIBN (2.3 mg, 0.014 mmol, 0.10 equiv) in 2 mL of benzene (distilled and degassed) was drawn into a syringe and slowly injected via syringe pump (0.34 mL/h) into the

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refluxing solution of **3**. After 8 h, the reaction mixture was cooled to room temperature, concentrated under reduced pressure, and purified by chromatography (silica, hexanes−ethyl acetate, 9:1) to afford 17 mg (73%) of light yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.38−5.32 (m, 1H), 3.52 (ddt, J = 0.6, 9.7, 6.7 Hz, 1H), 3.22 (dt, J = 9.2, 7.0 Hz, 1H), 2.63 (ddt, J = 16.1, 5.4, 7.7 Hz, 1H), 2.34−2.17 (m, 3H), 1.98−1.79 (m, 3H), 1.53−1.45 (m, 1H), 1.45−1.35 (m, 1H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 229.1 (C), 95.8 (CH), 61.5 (CH), 52.3 (CH), 46.4 (CH), 36.3 (CH_2), 34.7 (CH_2), 31.8 (CH_2), 29.3 (CH_2); IR (neat, cm^{-1}) 1298 (s), 1255 (s), 1206 (s), 1154 (s); HRMS (ESI) calcd for $C_9H_{12}OS$ + H^+ 169.0687, found 169.0684.

Lactone **16:** colorless oil (69% yield); 1:1 to 1:0 dichloromethane−-hexanes; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40−7.25 (m, 5H), 4.92 (dd, J = 3.1, 6.3 Hz, 1H), 4.49 (s, 2H), 3.14 (ddd, J = 1.7, 4.2, 11.4 Hz, 1H), 2.94−2.82 (m, 1H), 2.70 (ddd, J = 10.1, 11.4, 12.9 Hz, 1H), 2.30−2.14 (m, 1H), 2.21−2.03 (m, 1H), 2.07−1.97 (m, 1H), 1.78−1.66 (m, 1H), 1.54 (dt, J = 12.9, 4.2 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 177.9 (C), 137.2 (C), 128.6 (CH), 128.1 (CH), 127.4 (CH), 92.4 (C), 88.3 (CH), 67.5 (CH), 39.1 (CH), 37.8 (CH_2), 32.8 (CH_2), 31.2 (CH_2), 23.7 (CH_2); IR (neat, cm^{-1}) 3033 (w), 2958 (m), 2866 (m), 1771 (s), 1455 (m), 1350 (m), 1298 (m), 1267 (m), 1190 (m), 1102 (m), 1029 (m), 739 (m), 702 (m); SMB-IAA-GC−MS (EI) confirmed molecular formula $C_{15}H_{16}O_3$ with a matching factor of 998.[31]

Disulfide **17:** light yellow oil (16% yield); 2:5 Et_2O−hexanes; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.38−7.25 (m, 5H), 4.92 (dd, J = 6.1, 2.8 Hz, 1H), 4.57 (s, 2H), 3.25 (dd, J = 2.0, 3.5 Hz, 1H), 2.97 (t, J = 3.7 Hz, 1H), 2.95−2.88 (m, 1H), 2.75 (q, J = 7.3 Hz, 2H), 2.32−2.19 (m, 1H), 2.23−2.11 (m, 1H), 2.04 (dddd, J = 5.9, 7.7, 13.7, 3.1 Hz, 1H), 1.91−1.81 (m, 1H), 1.32 (t, J = 7.3 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 175.0 (C), 137.1 (C), 128.6 (CH), 128.1 (CH), 127.4 (CH), 90.1 (C), 88.6 (CH), 68.3 (CH_2), 48.2 (CH), 46.4 (CH), 45.4 (CH), 32.7 (CH_2), 32.6 (CH_2), 30.5 (CH_2), 14.6 (CH_3); IR (neat, cm^{-1}) 3032 (w), 2957 (m), 2925 (m), 2854 (m), 1771 (s), 1455 (m), 1374 (w), 1350 (m), 1295 (m), 1256 (m), 1182 (m), 1137 (m), 1096 (m), 1041 (m), 1002 (m), 736 (m), 698 (m); SMB-IAA-GC−MS (EI) confirmed molecular formula $C_{17}H_{20}O_3S_2$ with a matching factor of 992.31.

Lactone **18:** colorless oil (75% yield); 1:2 hexanes−ethyl acetate; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.01 (dd, J = 5.4, 6.6 Hz, 1H), 4.30 (s, 1H), 3.49 (ddd, J = 7.5, 8.3, 10.2 Hz, 1H), 3.28 (ddd, J = 10.2, 6.7, 10.0 Hz, 1H), 2.60−2.47 (m, 1H), 2.37−2.19 (m, 2H), 2.16−2.05 (m, 1H), 1.96−1.83 (m, 1H), 1.82−1.66 (m, 1H), 1.32−1.15 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 181.1 (C), 84.9 (CH), 78.3 (CH), 55.4 (CH), 49.4 (CH), 43.5 (CH), 40.0 (CH_2), 34.7 (CH_2), 26.9 (CH_2); IR (neat, cm^{-1}) 3407 (m), 1760 (s), 1191 (m), 989 (m); HRMS (ESI) calcd for $C_9H_{12}O_3$ + Na^+ 191.0684, found 191.0685.

Lactone **20:** colorless oil (42% yield; containing 20% **21**); dichloromethane; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.93 (br s, 1H), 4.84 (br s, 1H), 3.23 (ddd, J = 1.8, 4.5, 11.2 Hz, 1H), 3.02 (d, J = 1.0 Hz, 2H), 3.00−2.92 (m, 1H), 2.85 (ddt, J = 10.0, 0.9, 11.6 Hz, 1H), 2.46−2.34 (m, 1H), 2.31 (ddd, J = 13.4, 6.5, 16.1 Hz, 1H), 2.08 (ddd, J = 3.2, 7.2, 14.5 Hz, 1H), 1.81−1.76 (m, 1H), 1.78 (t, J = 1.0 Hz, 3H), 1.57 (td, J = 4.4, 12.4 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 176.9 (C), 170.4 (C), 137.6 (C), 115.4 (CH_2), 90.3 (C), 89.0 (CH), 43.0 (CH_2), 40.9 (CH), 38.9 (CH), 33.0 (CH_2), 31.5 (CH_2), 24.5 (CH_2), 22.4 (CH_3); IR (neat, cm^{-1}) 3081 (w), 2949 (m), 2866 (m), 1778 (s), 1741 (s), 1650 (m), 1445 (m), 1346 (m), 1267 (m), 1224 (m), 1151 (s), 1033 (s), 974 (m); SMB-IAA-GC−MS (EI) confirmed molecular formula $C_{13}H_{16}O_4$ with a matching factor of 997.31

Lactone **21:** colorless oil (47% yield); dichloromethane; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.63 (sep, J = 1.3 Hz, 1H), 4.95 (dd, J = 3.2, 6.9 Hz, 1H), 3.24 (ddd, J = 1.8, 11.2, 4.5 Hz, 1H), 3.00−2.92 (m, 1H), 2.84 (ddd, J = 9.9, 11.2, 12.4 Hz, 1H), 2.44 (dddd, J = 5.2, 7.0, 9.1, 14.3 Hz, 1H), 2.31 (tdd, J = 6.8, 13.5, 9.3 Hz, 1H), 2.14 (d, J = 1.3 Hz, 3H), 2.09−2.00 (m, 1H), 1.90 (d, J = 1.4 Hz, 3H), 1.76 (dddd, J = 7.9, 2.3, 5.4, 13.2 Hz, 1H), 1.57 (td, J = 4.5, 12.4 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 177.4 (C), 165.3 (C), 159.8 (C), 114.8 (CH), 89.5 (C), 89.1 (CH), 40.9 (CH), 39.1 (CH), 33.1 (CH_2), 31.5 (CH_2), 27.6 (CH_3), 24.7 (CH_2), 20.4 (CH_3); IR (neat, cm^{-1}) 2943 (m), 2861 (m), 1777 (s), 1719 (s), 1646 (m), 1445 (m), 1343 (m), 1266 (m), 1224 (m), 1141 (s), 1032 (m); SMB-IAA-GC−MS (EI) confirmed molecular formula $C_{13}H_{16}O_4$ with a matching factor of 978.31

Lactone **22:** colorless oil (52% yield); dichloromethane; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.35 (d, J = 12.3 Hz, 1H), 5.36 (d, J = 12.3 Hz, 1H), 4.91 (dd, J = 3.2, 6.2 Hz, 1H), 3.65 (s, 3H), 3.23 (ddd, J = 1.7, 4.3, 11.5 Hz, 1H), 3.00−2.91(m, 1H), 2.80 (ddd, J = 10.2, 11.4, 12.8 Hz, 1H), 2.35−2.19 (m, 1H), 2.22−2.13 (m, 1H), 2.12−2.01 (m, 1H), 1.81 (dddd, J = 2.8, 5.7, 7.0, 12.6 Hz, 1H), 1.59 (td, J = 4.3, 12.9 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 176.2 (C), 167.2 (C), 156.2 (CH), 101.9 (CH), 93.5 (C), 88.1 (CH), 51.4 (CH_3), 40.3 (CH), 38.5 (CH), 32.9 (CH_2), 31.2 (CH_2), 23.8 (CH_2); IR (neat, cm^{-1}) 2953 (m), 2870 (m), 1778 (s), 1716 (s), 1646 (s), 1437 (m), 1331 (m), 1293 (m), 1267 (m), 1192 (m), 1135 (s), 1030 (m), 970 (w), 843 (w); SMB-IAA-GC−MS (EI) confirmed molecular formula $C_{12}H_{14}O_5$ with a matching factor of 998.31.

Xanthate **23:** yellow oil (88% yield); 1:1 dichloromethane−pentane; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.19 (d, J = 2.9 Hz, 1H), 6.16 (d, J = 2.9 Hz, 1H), 5.87 (d, J = 9.7 Hz, 1H), 5.71 (ddt, J = 10.2, 16.9, 7.9 Hz, 1H), 4.84 (ddt, J = 1.2, 10.4, 1.7 Hz, 1H), 4.80 (ddt, J = 2.2, 4.2, 1.1 Hz, 1H), 2.92 (d, J = 6.7 Hz, 1H), 2.55 (s, 3H), 2.18 (dqd, J = 9.7, 6.7, 18.3 Hz, 1H), 1.58−1.54 (m, 2H), 1.59−1.52 (m, 1H), 1.39 (ddd, J = 12.0, 13.2, 6.7 Hz, 1H), 1.02 (d, J = 6.5 Hz, 3H), 0.08 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 216.5 (C), 138.9 (CH), 136.9 (CH), 134.1 (CH), 113.5 (CH_2), 92.5 (CH), 87.7 (C), 53.4 (CH), 35.6 (CH), 29.4 (CH_2), 25.8 (CH_2), 19.1 (CH_3), 16.6 (CH_3), −0.6 (CH_3), −0.7 (CH_3); IR (neat, cm^{-1}) 3042 (w), 2958 (s), 2982 (m), 2872 (m), 1630 (m), 1455 (w), 1299 (m), 1260 (s), 1221 (s), 1159 (s), 1109 (s), 1063 (s), 888 (m), 839 (m), 801 (m); HRMS (EI) calcd for $C_{15}H_{24}O_2S_2Si$ 328.0987, found 328.0988.

Lactone **24.** A solution of xanthate **23** (21.0 mg, 0.0640 mmol, 1.0 equiv) in benzene (3 mL) was sparged with argon for 45 min. Triethylborane (1 M in hexanes, 0.320 mL, 0.320 mmol, 5.0 equiv) was added dropwise. A 60-mL syringe was filled with air, and a syringe pump was used to slowly inject the air (ca. 5 mL/h) into the mechanically stirred reaction mixture. The reaction was concentrated by rotary evaporation and purified by chromatography (Et_2O−pentane 1:5 to 1:1). The concentrated fractions were allowed to stand at room temperature, exposed to the atmosphere for 48 h. Lactone **24** (4.1 mg, 25%) was obtained as a colorless oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.33 (s, 1H), 2.84 (dd, J = 2.5, 3.6 Hz, 1H), 2.66−2.57 (m, 1H), 2.42 (qd, J = 7.1, 7.4 Hz, 1H), 2.08 (ddd, J = 1.4, 13.8, 9.6 Hz, 1H), 2.05−2.02 (m, 1H), 2.00−1.85 (m, 4H), 1.78 (td, J = 6.4, 13.8 Hz, 1H), 0.92 (d, J = 7.5 Hz, 3H), 0.85−0.78 (m, 2H), 0.14 (s, 3H), 0.12 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.6 (C), 94.9 (CH), 87.3 (C), 46.3 (CH), 45.1 (CH), 41.9 (CH), 40.7 (CH), 39.8 (CH_2), 33.7 (CH_2), 19.0 (CH_2), 17.0 (CH_2), 16.8 (CH_3), 0.29 (CH_3), 0.12 (CH_3); IR (neat, cm^{-1}) 2962 (s), 2919 (s), 2873 (s), 1771 (s), 1463 (m), 1342 (m), 1259 (s), 1192 (m), 1154 (m), 1102 (m), 1020 (s), 905 (m), 829 (m), 750 (m); HRMS (EI) calcd for $C_{14}H_{22}O_3Si$ 266.1338, found 266.1338.

Xanthate **25.** Prepared from commercially available 5-norbornen-2-ol (mixture of *endo* and *exo* isomers) using the general procedure given above: yellow oil (70% yield of combined *endo* and *exo* xanthates, which were separable by chromatography); 40:1 hexanes−ethyl acetate; desired *endo* product; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.38 (dd, J = 5.6, 2.9 Hz, 1H), 6.02 (dd, J = 5.6, 2.9 Hz, 1H), 5.97 (ddd, J = 8.0, 2.8, 3.8 Hz, 1H), 3.35−3.29 (m, 1H), 3.03 (q, J = 7.4 Hz, 2H), 2.92−2.87 (m, 1H), 2.25 (ddd, J = 12.9, 7.9, 3.8 Hz, 1H), 1.52 (dddd, J = 8.8, 3.8, 2.1, 2.0 Hz, 1H), 1.40−1.34 (m, 1H), 1.30 (t, J = 7.4 Hz, 3H), 1.11 (ddd, J = 12.9, 2.6, 3.8 Hz, 1H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 214.6 (C), 139.0 (CH), 131.8 (CH), 84.8 (CH), 47.7 (CH_2), 46.0 (CH), 42.4 (CH), 35.1 (CH_2), 29.9 (CH_2), 13.8 (CH_3); IR (neat, cm^{-1}) 3065 (m), 1219 (s), 1066 (s), 726 (s); HRMS (ESI) calcd for $C_{10}H_{14}OS_2$ + H^+ 215.0564, found 215.0564.

Lactone **30.** Prepared from xanthate **25** according to the general procedure given above: white solid (55% yield); 4:1 dichloromethane−hexanes; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.78 (dd, J = 7.9, 5.3 Hz, 1H), 3.22−3.16 (m, 1H), 2.53 (ddt, J = 11.4, 4.7, 1.5 Hz, 1H), 2.48−2.42 (m, 1H), 1.96 (ddt, J = 13.0, 11.3, 3.3 Hz, 1H), 1.80−

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1.69 (m, 2H), 1.61−1.49 (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 181.6 (C), 81.0 (CH), 46.6 (CH), 39.2 (CH), 38.2 (CH_2), 38.0 (CH_2), 36.6 (CH), 34.6 (CH_2); IR (KBr, cm^{-1}) 1770 (s), 1187 (s), 1166 (s), 1002 (s), 983 (s); HRMS (ESI) calcd for $C_8H_{10}O_2 + Na^+$ 161.0578, found 161.0578.

Disulfide ***31***. Isolated as a byproduct during the synthesis of **30**: light yellow oil (33% yield); 4:1 dichloromethane−hexanes; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.80 (dd, J = 7.9, 4.7 Hz, 1H), 3.24−3.17 (m, 2H), 2.75 (q, J = 7.3 Hz, 2H), 2.64−2.58 (m, 2H), 2.09 (dtd, J = 11.4, 0.9, 3.5 Hz, 1H), 1.94 (ddd, J = 14.3, 7.9, 3.8 Hz, 1H), 1.59−1.50 (m, 2H), 1.34 (t, J = 7.3 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.4 (C), 80.3 (CH), 55.4 (CH), 46.5 (CH), 46.2 (CH), 42.2 (CH), 38.4 (CH_2), 35.4 (CH_2), 32.8 (CH_2), 14.6 (CH_3); IR (neat, cm^{-1}) 1772 (s), 1172 (m), 1028 (m), 987 (m); HRMS (ESI) calcd for $C_{10}H_{14}O_2S_2 + Na^+$ 253.0333, found 253.0333.

■ ASSOCIATED CONTENT

Supporting Information

^{1}H NMR, ^{13}C NMR, and ^{13}C-DEPT135 NMR spectra for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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